The Geology and Mass Mining (GMM) project

Six-monthly Technical Report

Review of the utilisation/potential of geophysical methods in the development and monitoring of block-cave mines [underground mass-mining]

Travis Murphy

November 2014
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Executive Summary</td>
<td>01</td>
</tr>
<tr>
<td>1 Introduction</td>
<td>02</td>
</tr>
<tr>
<td>2 Geophysics in Metalliferous Mining – the Status Quo</td>
<td>03</td>
</tr>
<tr>
<td>3 Geophysical Methods</td>
<td></td>
</tr>
<tr>
<td>3.1 Magnetics</td>
<td></td>
</tr>
<tr>
<td>3.2 Gravity</td>
<td></td>
</tr>
<tr>
<td>3.3 Seismic</td>
<td></td>
</tr>
<tr>
<td>3.3.1 Seismic reflectance/refraction method</td>
<td>11</td>
</tr>
<tr>
<td>3.3.2 Cross-hole Seismic Tomography</td>
<td>16</td>
</tr>
<tr>
<td>3.3.3 P-wave velocity</td>
<td>18</td>
</tr>
<tr>
<td>3.4 Electromagnetic methods</td>
<td></td>
</tr>
<tr>
<td>3.4.1 Conductivity</td>
<td>25</td>
</tr>
<tr>
<td>3.4.2 Radio frequency EM (RFEM, RIM)</td>
<td>27</td>
</tr>
<tr>
<td>3.4.3 Ground Penetrating Radar</td>
<td>28</td>
</tr>
<tr>
<td>3.4.4 Magnetotellurics (MT/AMT)</td>
<td>32</td>
</tr>
<tr>
<td>3.4.5 Emission of electromagnetic radiation during rock failure – potential application to cave back monitoring</td>
<td>33</td>
</tr>
<tr>
<td>3.5 Resistivity</td>
<td>33</td>
</tr>
<tr>
<td>3.6 Natural Gamma</td>
<td>35</td>
</tr>
<tr>
<td>3.7 Neutron logging</td>
<td>37</td>
</tr>
<tr>
<td>3.8 Spectral Gamma-Gamma (SGG, density log)</td>
<td>38</td>
</tr>
<tr>
<td>3.9 Neutron Activation logging</td>
<td>39</td>
</tr>
<tr>
<td>4 A note on ‘Joint Inversion’ and applicability to the cave mining industry.</td>
<td>40</td>
</tr>
<tr>
<td>5 Discussion: Geophysical methods/techniques showing most promise for pre- and syn- development rock mass assessment and monitoring of block cave mines.</td>
<td>43</td>
</tr>
<tr>
<td>6 Conclusions</td>
<td>45</td>
</tr>
<tr>
<td>7 References</td>
<td>47</td>
</tr>
</tbody>
</table>
Executive Summary

Geophysical methods have wide-ranging applications and span industry sectors including mineral/petroleum exploration, mining (coal and metalliferous) and civil engineering. There is a clear underutilisation of geophysics in metalliferous mining even when compared to our coal-mining counterparts. This underutilisation is considered to stem from a lack of thorough understanding of geophysical methods, recent advances, and emerging technologies; and the potential unconventional application of the same to resolve mining related problems.

Several methods are summarised and their potential applicability to the underground mass-mining operation are discussed, with examples where available. For some methods and emergent technologies, there are case studies of successful proof of concept work but these need field-application in hard-rock mines before they can be embedded into the mining workflow.

Potentially value-adding geophysical methods are identified which could be employed in block cave mining, or require further development to be readied for cave-mining application. The key methods as determined by this review include:

- **Interpretational aids**: Ground Penetrating Radar and down-hole seismic tomography
- **Rock mass characterisation**: Seismic wave velocity (P & S), measurement of anisotropy of geophysical response, neutron-logging for density determination;
- **Mine monitoring and prediction**: Measurement of electromagnetic radiation emitted due to mining-induced fracturing, 4D P-wave velocity measurement as indicator of a change in stress conditions.

There is potential for a step-change in the use of geophysics in mining provided targeted, yet conceptual; and justified, yet unconventional; application of methods are correlated with known physical parameters. Geophysics should then be used to fill gaps where sampling via drilling is sparse, or if possible, replace some proportion of the drilling. However, no one geophysical method has the unique solution to mining related problems and the effectiveness of the geophysical methods employed will be realised when coupled, or jointly inverted; with other geoscientific data.
1 Introduction

In order to both maximise data density in a large deposit and improve the dollar costs per unit of data, alternative methods of investigation should be considered which exist outside of the traditional methods which include:

1. **Drilling.** This activity is cost intensive, and there is a limit of achievable spacing when drilling from surface/long holes. Interpolation will always be required between the holes, independent of spacing.

2. **Development mapping.** Data and interpretations of the same are required well in advance of the development mine phase in order to optimise design parameters for long-lived capital infrastructure. Put simply, we cannot wait for development to be established before gaining the required level/confidence in the geology (inclusive of geotechnical parameters) of the deposit/resource to be mined.

Geophysics, defined as ‘a subject of natural science concerned with the physical processes and physical properties of the Earth……and the use of quantitative methods for their analysis’ (Wikipedia, 2014), is well utilised in exploration for ore-deposits where some methods commonly employed (but not limited to) include:

- Electromagnetic (EM)
- Magnetic
- Induced Polarisation (IP)
- Gravity
- Radioactivity

These methods (Table 1) allow the geologist to ‘map’ the subsurface for changes in physical properties associated with lithologies, structures, and ore deposits themselves (dependent on physical properties of the mineralisation). This stage of exploratory investigation is often a pre-cursor or contemporaneous with on-ground drilling of target areas and either ‘guides’ these follow-up activities or enables lateral/vertical extension of geological observations into the surrounding areas to build a 3D framework of the geological setting with little drill-data. This is effectively modelling the macro-scale rock-mass with the aim of defining features which will generally be on a scale of or larger than the ore-deposit. Note that there is scale dependence of geophysical data, i.e. there is a proportionality between the spacing of data and the resolution/size of feature that can be determined/located.

In the civil engineering industry (Table 1), geophysical methods are employed to determine rock mass stability and quality through a range of shallow surface methods and down-hole (borehole) logging methods. These applications generally are not required to look far into the rock mass as is required in the exploration and mining industry. The civil industry has borne a variety of hand-held and laboratory-based non-destructive techniques (NDT) which are finding application in mining operations through ‘geometallurgical’ or ‘orebody knowledge’ channels.
In general, mining operations (Table 1) are the least pro-active users of geophysics in the exploration (regional) > exploration (prospect) > mining > civil (excavation) spectrum. This review will assess the current methods employed across multiple applications/industries and will determine which geophysical methods show greatest promise for mine-based application. The application must involve detection of one, or preferably several, of the following (see Table 1):

- Major structures/faults
- Fracture zones
- Lithological variation
- Voids
- A physical property deemed useful to inform mining and mineral processing activities. This will fall under the ‘rock mass characterisation’ banner.

For the purposes of determining suitability of geophysical methods to underground mass-mining project development, the terms ‘direct’ and ‘indirect’ will be used to classify the application of a method to a purpose (Table 1). Intuitively, a direct method is one that can detect the contrasting physical properties of a fault or rock type and ‘map’ the feature. Conversely, an indirect method cannot detect the fault as a unique solution but can use offsets in mappable stratigraphy as an indicator of the presence of the fault. Similarly, the indirect method may obtain data which proves useful as a proxy for rock response.

Geophysical methods can also be classified by penetrative capability dependent on application. In this sense, methods can be used as ‘sensing’ or ‘detecting’ tools. The distinction being the distance of transmission of, for example, current (IP) or an AC magnetic field (EM) through a rock mass over several hundreds of metres (kilometres when using MT/CSAMT) which is considered ‘sensing’ rather than recording a rock response at or with limited penetration into, the surface of the rock. Examples of this include borehole logging methods including Neutron logging, and the semi-quantitative borehole geochemical analysis tools (e.g. NAA, SGG).

Each geophysical method will herein be discussed in terms of:

- The physical property measured,
- The surveying method
- Current applications
- Potential applications to the development of a deep block cave mine or more generally, the underground mass-mining operation.

2 Geophysics in Metalliferous Mining – the Status Quo

While geophysical methods have been applied successfully to the definition of bulk resources (e.g. coal, iron ore) and well utilised in locating/defining large remote fluid systems (petroleum), application to metalliferous projects has been limited. Limited largely to an exploration tool in the metalliferous sector, the energy sector utilise geophysics to inform and quantify the size, value, and production capabilities of the resource (Mutton, 1997). This is
in part due to the diversity of commodities and geological environments, including complexity and variety of rocktypes, in the metalliferous sector, and a record of limited cost-effective application (Fullagar, 2000). Exceptions exist where good geophysical analysis and interpretation of metalliferous deposits has been undertaken (Mutton, 1997) for an open-cut resource, however few similarly comprehensive underground applications are recorded. This is in part because the shallower, open-cut mines make use of the existing exploration geophysics database and interpretations.

Mine applications of geophysical methods differ from exploration usage in that greater resolution of data is required and, due to abundant available drill-holes and access, borehole logging methods have dominated (Fullagar, 2000). However, it is not only a matter of scale or resolution of data and interpretations. The desired outcomes of a geophysical programme designed by the exploration geologist are fundamentally different to that of the mine geologist/geotechnical engineer. The exploration geologist must be focussed on the use of geophysics to facilitate and assist vectoring toward discovery of a mineral resource, whereas the mine-based personnel require information regarding rock mass characterisation including defect spacing and orientation, rock strength, and better definition of lithological variation and the orebody.

As stated by Fullagar (2000) “…uncertainty about ore geometry and rock quality are the principal threats to mine performance.”, and yet geophysical methods are rarely employed as a data collection and interpretation mechanism despite decades of research, development, and commercialisation of tools and techniques.

In the context of a large underground, mass-mining operation; likely to employ personnel with operational focus, the challenge becomes education-oriented in that “…the greatest single impediment to expanded use of geophysics at mines has been the low level of awareness of geophysics on the part of most mine geologists, engineers, and managers…” (Fullagar, 2000) and the lack of knowledge of the physical properties of the ore and host rocks which may be exploitable through investigation with geophysics (Mutton, 1997).

In the context of the use of geophysics in civil engineering, Fell (1990) comments on observed technical disconnect between engineers (geotechnical), geophysicists, and geologists; and states the requirement that “the geophysicist and geologist be trained in the engineering application of their disciplines”. It could well be argued that reciprocal training of the engineer in the appropriate requirements for collection, analysis, interpretation, and communication of geoscientific data; is required.

There are perceived logistical difficulties in executing a geophysical programme in an operational environment (Mutton, 1997) and the general view that it is expensive and perhaps superfluous to comprehensive/exhaustive drill-outs of a resource. The reality is that a completed drill-hole, excluding the core, has little value except for the potential subsequent acquisition of geophysical data, which inherently adds value to the drill-programme. The mine technical team first need to justify the employment of the geophysical method through an understanding of the physical properties of interest and through a proof-of-concept survey, for which there is generally more appetite in the exploration stage as opposed to the
development/operational phase. McIntosh (2009) describes the potential role of geophysics in the pre-feasibility/feasibility/operational phases to complement investigation into the key areas of:

- Improving/optimising ore body knowledge
- Reduction of geometrical uncertainties
- Increase in confidence in key physical properties (e.g. density)
- Acquiring adequate geotechnical knowledge
- Examination of the situation away from the known resource, i.e. brownfields exploration.

Cultural discrepancies arising due to “historical divisions between exploration, feasibility, and production departments.” (Fullagar, 2000) cause both a loss of knowledge and know-how across what are effectively blurred and transitional project phase boundaries. It is well known that a data-critical phase of an operation occurs during ‘handover’ from the exploration to feasibility/development/production stage, and managing the transfer of data and knowledge is challenging given the differing focus of the disciplines. However, we must remember that it is the one body of rock which is investigated by all parties and it is only logical that the geophysical methods which assisted in discovery of the deposit may actually have application, albeit at higher resolution, to the ongoing assessment of the ore deposit in the mining context.

As stated above, a geophysical method can only be selected and applied if there is underlying knowledge of the physical parameter to be exploited and it is important to have an understanding of the different types of geophysical methods and their capabilities; and as such, a brief, high-level description of common methods follows and is summarised in Table 1. For in-depth detail of the outlined methods, refer to the listed references herein. It is important to keep an open mind as to unconventional application of some of the discussed methods if mine geophysics is to effect a step-change in geoscientific understanding of large scale ore deposits suited to block-cave mining and the broader mining industry.

3 Geophysical Methods

Both land-based and downhole applications will be discussed in the context of block cave mining. It is considered that intensively developed levels in large-scale mines be considered as a suitable platform for ‘ground-based’ geophysical programs to resolve geological features both above and below that level. However, for the purposes of informing the decision making process in the lead up to developing the block-cave mine, downhole techniques will offer the lead time required to determine optimum design considerations of the key extraction and undercut levels and associated long-life capital infrastructure.
<table>
<thead>
<tr>
<th>METHOD</th>
<th>APPLICATION</th>
<th>DETECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td><strong>Data acquisition mode</strong></td>
<td><strong>Exploration Regional</strong></td>
</tr>
<tr>
<td><strong>Physical property measured</strong></td>
<td><strong>Airborne</strong></td>
<td><strong>Ground</strong></td>
</tr>
<tr>
<td>Magnectics</td>
<td>Measure of the response of rock-types to the Earth's and locally applied magnetic fields. Magnetic susceptibility is the significant variable.</td>
<td>Airborne</td>
</tr>
<tr>
<td><strong>Gravity</strong></td>
<td>Distribution of rock densities. Slimline down-hole probe, or surface probe, contains gravimeter sensors. Data transfer to operator via wireline.</td>
<td>Airborne</td>
</tr>
<tr>
<td>Seismic (Reflection, Refraction, Interferometry, Velocity)</td>
<td>P and S wave velocities. First-arrival travel times between source and receiver are recorded. 2D Diffraction tomography between holes and full waveform inversion.</td>
<td>Ground</td>
</tr>
<tr>
<td>Electromagnetics (conductivity)</td>
<td>Measurement of the decay of a local magnetic field and presence of eddy currents in secondary field associated with conductive rock-types.</td>
<td>Airborne</td>
</tr>
<tr>
<td>Other EM (GPR, RFEM, MT/AMT/CSAMT)</td>
<td>Application of EM radiation as a wave, similar to seismic.</td>
<td>Downhole</td>
</tr>
<tr>
<td>Resistivity (IP, SP)</td>
<td>Measure of the resistance of the rockmass or rock-types to the passage of electrical current; and the charge retained by the rock during current shut-off.</td>
<td>Ground</td>
</tr>
<tr>
<td>Natural Gamma</td>
<td>Measures naturally emitted gamma rays from wallrocks of drillhole.</td>
<td>Downhole</td>
</tr>
<tr>
<td>Neutron</td>
<td>Measures loss of energy of neutrons through wallrocks of drillhole.</td>
<td>Downhole</td>
</tr>
<tr>
<td>Spectral Gamma-Gamma/Neutron Activation</td>
<td>Measured loss of energy and change in amplitude of gamma rays, and the characteristic, element-specific energy emissions.</td>
<td>Downhole</td>
</tr>
</tbody>
</table>

Table 1. Geophysical methods by sector and detection capability. Colours in the ‘Application’ section refer to the prevalence of use (hot colours= almost always, green= almost never), and colours in the ‘Detection’ section refer to ability/capability of the method (D= direct detection, D/I= both direct and indirect detection, I= indirect detection, N/A= the method cannot detect).
The geophysical methods discussed herein should also be reviewed in terms of better understanding of geology rather than purely geotechnical/stability detection. With further development, it is possible that some methods may enable reduction in the number of drill-holes required, thereby increasing spacing between holes.

### 3.1 Magnetics

The Earth’s geomagnetic field is responsible for the bulk of magnetization (density of aligned dipoles per cubic metre) of rocks through induction of the present magnetic field (Telford et al., 1990). Rocks which have a permanent or remnant magnetic field acquire this through formation in the presence of a strong local magnetic field and/or abundance of magnetic minerals including magnetite and pyrrhotite.

Subsurface geological features can be ‘mapped’ by observing distortions to the magnetic field which alter the texture, continuity, and intensity of magnetic response (Figure 1). The magnetic response is measured via airborne, ground, down-hole, and handheld means (Table 1).

Magnetic susceptibility is the significant variable in magnetics (Telford et al., 1990) and is a measure of a rocks response to a local applied magnetic field, defined by the ratio between the induced magnetization of the rock and the inducing magnetic field (Ferre et al, 1999). Magnetic susceptibility has been used to map rock types, structural zones, and alteration associated with conditions of formation and hydrothermal (Figure 2, 3) (Hrouda et al, 2009); and to determine the structural history of complexly deformed rocks (Pares and van der Pluijm, 2002).

Magnetic surveys and collection of magnetic susceptibility data are routinely performed in exploration and advanced exploration projects. As such, it is important to fully utilise the data and extract all possible applications of the data, whether directly or as proxies for rock behaviour.

Measurement of the anisotropy of the magnetic susceptibility (AMS) tensor has been shown to quantify the rock fabric or texture, recognizing that the AMS is sensitive to proportions of magnetic minerals, the shape and orientation of these, and the 3D distribution of magnetic minerals through a rock (Borradaile and Henry, 1997). Clustering of magnetic grains/crystals may cause an alignment heterogeneity, with a long axis, which influences the anisotropy of the magnetic susceptibility (Hargraves et al, 1991). In turn, fracture and microfracture distribution and orientation can be shown to be related to the pre-existing tectonic magnetic fabric of the rock mass as preserved in the magnetic susceptibility anisotropy (Rathore and Mauritsch, 1982). Correlation between AMS and the elastic anisotropy (measured using acoustic spectroscopy) in sedimentary and metamorphic rocks lead Lebedev et al (2012) to infer a like-origin of the anisotropies, linked to the rock fabric/texture (including microfractures).
This process could therefore be useful for domaining a rock mass according to the dominant orientation of heterogeneity at the textural scale, with likely links to fracture propagation orientation and irregularity, intact rock strength, and comminution response at the processing plant. The AMS would be considered a useful addition to numerical modelling of rock mechanics as applied to mass-mining.

Magnetic susceptibility is measured on outcrops or rock samples and as such does not record the bulk susceptibility of a rock mass (Telford et al., 1990). However, just as assay data does not represent the bulk, the data can be used as a downhole variable for interpretation and modelling.
No recommendations are made in Takahashi et al (2006) guidelines for use of borehole geophysics in rock engineering, for the application of magnetic methods; although a down-hole magnetometer and magnetic susceptibility meter (SUSLOG 403-D) developed by the International Ocean Drilling Program has been used successfully and the tool has a 75mm diameter which could be accommodated in conventional HQ drill-holes. This tool would record data at a coarser resolution than prior AMS studies mentioned above, but this is considered appropriate for the scale of observations required to characterise the rock mass in block-cave mines.

In a geometallurgical/deposit knowledge context, the presence/absence of magnetic minerals such as pyrrhotite and magnetite can impact on processing performance. Whereas pyrrhotite may be a diluent in leaching operations and require additional leachates to maintain production efficiency, magnetite content can impact on grindability of ore in terms of energy consumption (Jankovic et al., 2010) and reflects rock-strength at the grain scale. A good knowledge of the proxy relationship between magnetic susceptibility and the mining-processing response of rock can facilitate prediction and forecasting of variability in parcels of ore in a large operation.

Figure 2. Down-hole trace of magnetic susceptibility vs rock type (Hrouda et al, 2009)
3.2 Gravity

The use of gravity prospecting in geophysics involves the measurement of variations in the Earth’s gravitational field (Telford et al., 1990). Rocks have variable densities as measured routinely in the geological function of mining operations. Local variation in the densities of rocks near the surface cause minute changes to the gravity field (Telford et al., 1990). Density distributions in the shallow crust produce observable signals in gravity surveys (Jacoby and Smilde, 2009) and, similar to the 2D interpretation of magnetic data; areas of varying texture, geometry, and intensity of the gravity response inform the geologist and geophysicist as to the subsurface lithology and structure.

Gravity surveys are conducted via airborne, ground, and downhole techniques; and are sensitive to the following effects (Nind and MacQueen, 2013):

- Gravimeter drift: requiring revisiting a reference point to maintain statistical representivity.
- Lunar and Solar tides: effects of which are removed using software algorithms
- Free air and Bouger Slab: the borehole gravimeter log is dominated by the gravity of the entire Earth and the geoid model employed.
- Latitude
- Surface topography: requiring accurate topographic models of the survey area.
- Underground workings
- Regional gradient.

As such, the gravity measurements recorded are usually relative to a standard or
reference location and relative-gravity measurements are used rather than absolute gravity (Jacoby and Smilde, 2009).

Gravity interpretation can be ambiguous and it is either the combination with other datatypes or use of gravity data to fill gaps to fully utilise the data (Jacoby and Smilde, 2009).

Gravity is useful for both predictively mapping density variation away from drill-holes to map geology and detect off-hole excess mass. This also provides quantifiable density determinations of rocktypes intersected by the drillhole (Figure 4) improving resource estimation (Siegel et al, 2008; Nind and MacQueen, 2013). A case study using the gravilog system at Sudbury, deployed in NQ holes, successfully recorded the density variation associated with disseminated and massive mineralization, including internal variability in the mineralized intercept (Figure 5) (Siegel et al, 2008). Commonly used laboratory (and coreshed) based density determinations can derive variable results when methods are compared side-by-side. A recent study by Makhuvha et al. (2014) at the Los Bronces porphyry Cu-Mo deposit in Chile demonstrated density variances between two measurement techniques of between 3.5% and 6.1%. It is important to put this in context of the economics of a mining operation, a 5% change in the density of the ore through calculation variance, affects the ounces of contained gold and/or the tonnes of contained copper metal by 5%. There is therefore some vigilance required in accurate density determination but this is seldom the case in practice and it is often seen as a time-consuming additional task which can be adversely affected by human error. Collection of reliable and abundant density data by using a down-hole gravity tool may be a solution, albeit at additional cost.

No recommendations are made in Takahashi et al (2006) guidelines for use of borehole geophysics in rock engineering, for the application of gravity methods to mining. The benefits of comprehensive mapping of density would be a useful input into numerical modelling as well as the obvious resource-oriented application. It is possible that density may be used as a proxy for rock strength and/or comminution response, also.

3.3 Seismic

The seismic methods encompass a variety of techniques, data collection modes, and interpretation/analysis processes. The following is a subset of these and intended to highlight those techniques which may have potential application in underground mass-mining. Other seismic techniques may also be applicable.

All seismic methods require a source mechanism (transmitter), whether caused by man-made devices or naturally-occurring, and measurement of the transit time of the produced acoustic wave to receivers (geophones) located on surface or in drill-holes; and attempt to determine characteristics of the rock types and attitudes by reconstructing the wave path (Telford et al., 1990).
Figure 4. Gravity response of rocks types and mineralisation (Nind and MacQueen, 2013).

Figure 5. Borehole density data (Siegel et al, 2008).
Seismic wave paths can be classified as:

- Reflected: the overall path of the wave is essentially at a high angle to the features being investigated
- Refracted: the principal portion of the wave path is focussed along the interface between stratigraphic boundaries and the path is essentially parallel to the features being investigated (Telford et al., 1990).

### 3.3.1 Seismic reflectance/refraction method

Seismic surveys are traditionally executed using a line of receivers and a source transmitter (Figure 6) and as such are 2D (Peters, 2005). With the advent of 3D seismic survey capability, where, instead of a line of receivers, a grid is employed; 3D mapping of the subsurface is possible and benefits the geological modelling of underground mines (Peters, 2005; Malehmir et al., 2012). Note that while surface seismic surveys are suitable for mapping gently to moderately dipping features (reflectors), steeper oriented features are better defined by downhole survey and in-mine methods (Malehmir et al., 2012). The 3D seismic survey volume comprises data of all geological boundaries and structures as a function of the two-way reflection time (Peters, 2005) which can be reduced to parameters including:

- Travel time gradient
- Seismic amplitude, and
- Instantaneous frequency.

Analysis of these data types can yield detailed structural maps, stratigraphic anomalies, and locate faults (Peters, 2005). There is known ambiguity in seismic interpretation results (Peters, 2005) and measures of uncertainty in location are applied to modelled features reflecting error in spatial location.

![Schematic diagram of seismic reflection and two-way travel time in trace gathers](Salisbury and Snyder, 2007).
The two factors which determine whether a geological feature will be detected and imaged by seismic reflection are (Salisbury and Snyder, 2007):

- Acoustic impedance \((Z)\) \((Z=\text{density} \times \text{P-wave velocity})\) of adjacent lithotypes, and
- Geometry of the feature relative to the survey specifications

According to Salisbury and Snyder (2007), a reflection co-efficient \((R)\) \((R=|Z_1-Z_2|/(Z_1+Z_2))\) of 0.06 is required to produce a strong reflection if the geometry is favourable. As displayed on Figure 7, the contrast in acoustic impedance at Ridgeway Deeps is unlikely to be significant enough to enable determination of lithological boundaries using seismic reflection. However, other underground mass-mining operations are sure to have appropriate contrast for this method to be employed. It is advisable to conduct field and/or laboratory measurements of velocities of the various rock types in a deposit to determine if a seismic programme is suitable or not (Salisbury and Snyder, 2007). In an exploration context, contrasting acoustic impedance of sulphide deposits and their host rocks make them suitable for detection using seismic methods, however disseminated deposits usually lack sufficient contrast for mineralization location purposes (Salisbury and Snyder, 2007). Salisbury and Snyder (2007) discuss the exploration potential for a range of deposits using seismic reflection, but little emphasis on the determining rock mass characteristics of the mineralization and host. In the context of underground mass-mining, Salisbury and Snyder (2007) indicate that while the ore minerals in porphyry-copper style deposits have significantly higher impedance than the felsic host rocks, the deposits themselves are unlikely to be detectable using seismic methods due to the low tenor of mineralisation. However, if pyrite is sufficiently abundant in the alteration halo around a porphyry deposit, and the surrounding rocks are entirely felsic to intermediate, the haloes would then represent significant targets as the felsic rocks would be relatively acoustically transparent (Salisbury and Snyder, 2007).

Down-hole methods of seismic surveying typically have higher resolution than surface data and are better suited to delineating fracture and fault zones for mine planning purposes (Malehmir et al., 2012). Vertical seismic profiling (VSP) utilises a single drill-hole with multiple receivers arranged down-hole, and a single surficial source (Hornby and Yu, 2007) and has commonly been applied to investigating the location of the flanks of salt domes. Other configurations of the VSP survey are illustrated in Figure 8. VSP records not only the direct waves to the receiver but also reflections and multiples (Figure 8) (Telford et al., 1990). The VSP method is best suited to locating features that were a ‘near-miss proximal to a drill-hole and for collecting additional data as interpretational aids (Telford et al., 1990). The VSP single-drillhole imaging scenario with both receivers and virtual sources in the same hole, removes many of the assumptions required in seismic surveying such that only the velocities of the rocks in the immediately around the borehole are required (Hornby and Yu, 2007). Although the contrast between salt and host sediments is significant and not analogous to the contrasts in a typical underground metalliferous mine, the single-hole method is capable of detecting complex geometries up to 500m from the drill-hole (Hornby and Yu, 2007), and may suit some metalliferous applications. The generally high velocities and densities in metalliferous deposits restrict the sensitivity of velocity analysis due to low attenuation of wave velocity and low

Confidential to Sponsors of the Geology and Mass Mining (GMM) project and to SMIBRC
reflection co-efficients (Malehmir et al., 2012). Multiple reflections may occur but exist below the noise threshold in this instance (Malehmir et al., 2012).

Refinement of the 3D boundaries of the Diavik Kimberlite Pipe (Canada), for resource calculation and design purposes; was achieved using side-scan downhole seismic (Malehmir et al., 2012). The acoustic impedance of kimberlites is low compared with igneous, metamorphic, and most sedimentary rocks and this makes the boundary of kimberlite pipes a potentially strong reflector and ideally suited to definition using downhole seismic methods (Salisbury and Snyder, 2007). Salisbury and Snyder (2007) list the application of seismic to many deposit styles in an exploration context, many of which however are not amenable to mass-mining.

![Diagram](image)

Figure 7. Figure obtained from Salisbury and Snyder (2007) illustrating the relationship of P-wave velocity (Vp) and density, expressed as the Nafe-Drake curve of acoustic impedance. Domains for common rock-types (coloured) and ore-assemblages (fields to the right of the Nafe-Drake curve) are shown. Note the five yellow dots approximately coincident with the ‘granodiorite’ ellipse, these represent the five lithologies at Ridgeway Deeps appended to the diagram.
3.3.2 Cross-hole Seismic Tomography

Placing of a seismic source in one drill-hole and receivers in another, provides multiple raypaths between the holes, the travel-times and amplitudes of which provide tomographic data (Telford et al., 1990). Distribution of velocities and amplitude loss within the survey area between the drill-holes are investigated so as to identify geological features and improve the geological model of the region (Telford et al., 1990).

![Diagram of Cross-hole Seismic Tomography](image)

**Figure 8.** Variations of VSP: (a) Zero-Offset VSP; (b) Offset VSP; (c) Walk-Away VSP; (d) Reverse VSP (Takahashi et al., 2006).

Cross-hole Tomography can be classified into three categories (Patella and Patella, 2009):

- **Velocity**, where the traveltime of the first arrival of the seismic impulse is measured in the inter-well space;
- **Attenuation**, where the focus is on the amplitude of the first arrivals, with the objective of measuring absorption of seismic energy between boreholes;
- **Elastic**, where the entire wavefield is processed, with the scattered wavefield providing additional information (Patella and Patella, 2009).
Cross-hole systems developed for mining applications comprise two frequency ranges (Thill et al., 1989):
- 20kHz for close spaced drill-holes (2-20m), and
- 1-2kHz for drill-holes spaced at 40-300m.

Cross-hole seismic systems permit ray path views of geological targets in multiple orientations (Figure 9) that would be unobtainable by conventional surface seismic techniques (Thill et al., 1989) and due to the ability of locating both source and receiver down the drill-holes, signal quality can be maintained. Mining applications of cross-hole seismic include determination of (Thill et al., 1989):
- elastic and deformational properties
- anisotropy
- porosity
- rock quality
- geologic anomalies
- water content
- stress state

The resolution of cross-hole tomographic image depends on the wavelengths and receiver separations (Jackson and McCann, 1997) with the highest resolution obtained using smaller wavelengths and closely spaced receivers. Short wavelengths coupled with large receiver spacing may not adequately test the whole rock-mass as data will be obtained proximal to the ray-paths only, and in this case the survey is unlikely to detect geological features of size comparable to the wavelength (Jackson and McCann, 1997).

Case-studies of ore-body imaging by crosswell seismic methods are dominated by application to massive sulphide deposits including nickel sulphide orebodies (Xu and Greenhalgh, 2010; Greenhalgh and Mason, 1997). The acoustic impedance contrast between massive sulphides and silicate hosts makes for a good seismic reflector and success has been had in imaging these deposits.
3.3.3 **P-wave velocity**

P-waves are the primary body wave, or first received, during transmission of seismic energy through a medium and comprise a compressional waveform (Telford et al., 1990). The velocity of P-waves are recorded as ‘m/s’ or ‘km/s’, and occasionally as travel time ‘µs/ft’ (Figure 10).

Underground blast-sourced seismic surveys have been used to map velocity tomography, relating velocity domains to areas of induced seismicity (Maxwell and Young, 1996). There is the possibility that data can be collected from seismic monitoring systems to build the velocity model, without requiring additional survey expense (Maxwell and Young, 1996). Repeated velocity measurements along selected raypaths over time could detect changes in the rock mass and complement standard geomechanical observations and measurements (Maxwell and Young, 1996).

Lower velocities have been recorded in directions perpendicular to microcracks in laboratory and numerically modelled testwork (Hazzard and Young, 2004). Anisotropy of microcrack development (preferred alignment of cracks) indicates that orientation of the cracks is critical, particularly within the 3-dimensional stress tensor. Application of stress
perpendicular to the crack orientation causes cracks to close and a proportional increase in wave velocity (Hazzard and Young, 2004). Stesky (1985) recognised a relationship between fractures and decrease in wave velocities and found the effect was greater at lower stresses. It was observed through experimental work, that P-wave velocities increased with increased confining pressure (up to 200MPa) and that this is largely attributed to the closing of fractures due to applied stress (Stesky, 1985) and is equivalent to approximately 100m/s velocity difference between the 100 and 200MPa thresholds (Maxwell and Young, 1998). An important observation of the work by Stesky (1985) is that the curves of wave velocity vs confining stress indicate that not all rock types respond the same to the increase in confining stress and this is likely reflecting a textural (and perhaps mineralogical) response to the stress application. This is one example where ‘loss’ of rock type due to imposition of a numerical geotechnical classification scheme may have a material effect on numerical simulation of the rock response.

Just as there is a demonstrated relationship between increasing P-wave velocity and confining stress, a relationship between P-wave velocity and yield point of the UCS test is also observed in a variety of rock-types (Figure 10) including granitic rocks (Tugrul and Zarif, 1999), limestone (Tugrul and Zarif, 2000), sedimentary rocks (McNally, 1990, 1987; Oyler, 2010; Altindag, 2012), metamorphosed rocks (Sharma and Singh, 2008), mixed rock types (Kilic and Teymen, 2008), and concrete (Turgut, 2004). The relationship has been exploited in coal operations to predict in situ rock strength, often through development of site-specific correlations (Butel et al., 2014). Similarly, UCS can be found to have an inverse relationship to the A*b parameter considered important in characterising material in terms of crushability in the context of comminution (Starkey, 2007) and there may be potential for sonic logging to inform rock response during comminution.

![Figure 10. P-wave velocity : UCS relationships. Left, Sedimentary rocks from an Australian coal mine (McNally, 1987) and right, mix of sedimentary, metamorphosed, and intrusive rocks (Kilic and Teymen, 2008).](image)

[Note: UCS in PSI and P-Wave velocity recorded as µs/ft, the inverse relationship of m/s or km/s]
Small-scale (~1m) cross-hole velocity tomography adjacent to a test tunnel in the Canadian Underground Research Laboratory demonstrate conclusively the relationship between in situ stress and P-wave velocity (Meglis et al., 2005) whereby high stress state corresponds to high velocity. This is not measuring damage or defects, but the in situ stress state. Maxwell and Young (1998) take this observation further and confirm/predict stress patterns proximal to underground workings using P-wave velocity tomography. Areas of induced fracturing were shown to have decreased velocity, and a region of relatively high velocity was spatially related to a high stress region; with induced seismicity located in the transition between these high and low velocity domains (Maxwell and Young, 1998). Similarly, reduced velocities corresponded with regions of tensile stresses, suggesting micro-cracking, associated with extension, have weakened the rock mass (Maxwell and Young, 1998). Maxwell and Young (1998) observed that, in high-stress environments, both the active-source and passive-source surveys indicated velocities higher than those of intact rock, suggesting anisotropy of velocity due to disturbance of the stress field around excavations. This is assumed to be degradation of in situ strength, as a result of the stress conditions, proximal to the excavation; and achieves a minima comparable to the long term average testwork results on core samples, i.e. de-stressed and unconfined (Read et al., 1998). Similarly, significant variance between velocity measurements from core vs down-hole (in situ) is recognised (Maxwell et al., 1998) and both datasets cannot be combined without recalibration.

Retrospective passive seismic tomography of the Ridgeway Deeps Block Cave (Westman et al., 2012) using only mine-induced seismicity, resulted in velocity tomography which clearly delineates the seismogenic zone above the cave void and concentration of stresses through the diminishing pillar between the block cave and overlying sub-level cave void (Figure 11). Limitations in the method include the reliance on mine-induced sources of seismic energy and the non-ideal wave-paths that may result (Westman et al., 2012) however installation of fixed sources could overcome this and the method clearly would add value to planning and operation of the block cave if this analysis was conducted in real time as opposed to the back analysis.

Correlation of RQD with P- and S-wave velocities (Figure 12, 13, 14) exhibits a robust relationship supporting the experimental observations regarding the effect of fractures on velocity, mentioned above. Barton (2007) and Sjogren (1979) recognize the relationship between P-wave velocity, fracture frequency, and RQD (Figure 12); and Barton (2007) establishes a correlation between P-wave velocity and the ‘Q’ geotechnical parameter (Figure 14). Barton (2007) seeks to bolster the standard measures of RQD, RMR, Q, and GSI with fundamental characterization parameters such as rock stress, water pressure, permeability, seismic velocity; in an attempt to inspire cross-disciplinary rock-mass characterization.
Figure 11. Velocity tomography of the Ridgeway Deeps block cave at March 2010 (Westman et al., 2012) with a clearly defined seismogenic zone as indicated by the arcuate higher velocity zone above the cave (RH image).

Figure 12. Relationship between P-wave velocity, fractures per metre, and RQD; from predominantly hard-rock sites. Data trends compiled from 113km of seismic profiles and 2.9km of core logging. (Barton 2007, data from Sjogren, 1979)
Figure 13. Correlation of RQD with P- and S-wave velocities (Takahashi et al., 2006)
However, in the context of the work by Maxwell and Young (1998), these observations are time dependent in that the effect of an encroaching mine void will alter the stress field (Figure 11). This highlights the multipurpose use of the data in that the first pass sonic log informs as to the rock strength and condition, and subsequent logging of the hole informs as to changes in the local stress-field and damage to the rock mass through microfracturing.

Potential measurement of persistence of joints and joint sets may be achieved through detailed cross-hole velocity tomography. Coupled with detailed logging and televiwer data, it may not be possible to determine the persistence of individual joints but distinct joint sets may have a measurable effect on the P-wave velocity between holes. This would have significant impact on numerical modelling of cave propagation phenomena given the reliance on joint persistence.

Hildyard et al., 2005 recognise potential applications of understanding the degree of fracturing proximal to underground workings and in monitoring of the stress conditions proximal to underground development using microseismic and active ultrasonic survey, Young and Collins (2001) recognised a measurable decrease in P-wave velocity with increasing crack-density.

There are clear differences in the P-wave velocity and amplitude of waves due to different degrees of fracturing, and measurements are geometry-dependent. P-wave velocity, as correlated with the anisotropy of magnetic susceptibility tensor, is also affected by textural variability of the rock-types and testing of material is orientation dependent (Song et al., 2004; Amadei, 1996; Vishnu et al., 2010). Vishnu et al (2010) suggest acquiring knowledge as to the anisotropy of magnetic susceptibility and P-wave velocity anisotropy.
to better inform the selection of samples, emphasising orientation; for geotechnical
testwork. According to Fullagar and Fallon (1997), “Sonic logging is the premier
gеоph ysical tool for rock mass characterisation, since seismic velocity and attenuation
are sensitive to rock stress, strength, degree of fracturing, porosity, and the nature of the
material occupying the voids.”.

Sonic logging of P-wave velocity has advantages over individual tests on core samples as
it is able to provide a continuous record of the rock character in situ (Fullagar and Fallon,
1997) and at the current stress state. A limitation of hand-held core-testing methods is
that these cannot test broken rock and as such only test the velocity of the intact rock and
introduces sample selection bias (Fullagar and Fallon, 1997). Sonic logging is able to
test the wholistic rock-mass incorporating fractures and discontinuities.

Full waveform sonic logging captures shear wave (S-wave) velocities in addition to the P-
wave velocity. S-waves are the slower than the accompanying P-wave (Figure 13), and
are also known as ‘shear’ waves having transverse waveforms (Telford et al., 1990). The
dynamic elastic moduli and Poisson’s ratio can be calculated using both the P- and S-
wave velocities (Figure 15, 16) and are critical parameters of rocks indicating the
elasticity and ratio of strain to applied stress. The variations in rock engineering
properties on a fine scale within rock units are required inputs into rock mechanics
modelling programs (Fullagar and Fallon, 1997). Estimation of these moduli using widely
distributed and continuous data obtained from drill-hole logging across a deposit could
capture variability and enable more appropriate inputs into numerical modelling.

![Figure 15. Dynamic elastic constants derived from sonic and density logs, Witwatersrand Basin, South Africa. Fine scale variations in rock strength are evident within the weak Westonaria formation, the Hangingwall to the Ventersdorp Contact Reef (Fullagar and Fallon, 1997; after Campbell, 1994)](image)
3.4 Electromagnetic methods

An electromagnetic wave is created in a fluctuating electric field and has the form of mutually reinforcing oscillating electric and magnetic fields at right angles to each other, and with the same frequency (Figure 17). The energy of the wave (radiation) is proportional to the frequency of the wave (Allaby, 2008) (Figure 17). Unlike seismic (mechanical) waves, EM waves can travel through empty space and at the speed of light (Telford et al., 1990). The spectrum of EM waves (Figure 17) includes radiowaves, microwaves, Infrared, visible light, UV, x-ray, and gamma rays. Geophysical applications involve waves generally at radio frequencies and below (Figure 17).

3.4.1 Conductivity

Electromagnetic (conductivity) methods involve the propagation of continuous-wave (frequency-domain EM) or transient electromagnetic fields (Time-domain EM) in and over the earth with the aim of detecting conductive sulphide deposits within contrasting resistive host-rocks (Telford et al., 1990). The method is employed as airborne (helicopter and fixed-wing), ground, and down-hole surveys and generally involves inductive energising of the ground using a wire loop connected to an AC power source, thereby creating a local (primary) magnetic field through the subsurface (Telford et al., 1990). During periods of source cut-off, and elimination of the primary field, detection of a secondary field (occurring as eddy currents) and measurement of the time rate of change of the secondary field may indicate the presence of a conductive rock-type within or proximal to the survey area (Telford et al., 1990). This is the traditional use of EM methods in mineral exploration.

Resistivity (inverse of conductivity) of common rock-types indicates that there is a general trend from igneous rocks having the highest resistivity, sediments the lowest, and metamorphic rocks having an intermediate resistivity (Telford et al., 1990). However, there is considerable overlap and porosity (water content) is a major factor in variability of a given rock type.

\[
E = \rho_{\text{bulk}} V_p^2 \left( \frac{1 - 2\nu}{1 - \nu} \right) \left( \frac{1 + \nu}{1 - \nu} \right),
\]

\[
\nu = \frac{(V_p/V_s)^2 - 2}{2[(V_p/V_s)^2 - 1]} = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)},
\]

Figure 16. Modulus calculation using wave velocities. \( E \) = dynamic Young’s modulus, \( \nu \) = Poisson coefficient, \( V_p \) and \( V_s \) are wave velocities, and \( \rho_{\text{bulk}} \) is the bulk density of the material (Martinez-Martinez et al., 2012)
EM methods can therefore be employed to ‘map’ rock types, similarly to magnetic surveys, given recognised variability across rock-types and recognized geometries and textures in the derived imagery. This is largely the domain of the exploration geologist, and as such the potential for the underground mass-mine is limited to application to near-mine exploration; and not contributing to enhanced knowledge of the rock mass characteristics of the deposit.
<table>
<thead>
<tr>
<th>Rock-type</th>
<th>Resistivity (ohm-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite Porphyry</td>
<td>Min: 4,500</td>
</tr>
<tr>
<td></td>
<td>Max: 1,300,000</td>
</tr>
<tr>
<td>Porphyry</td>
<td>60</td>
</tr>
<tr>
<td>Basalt</td>
<td>10</td>
</tr>
<tr>
<td>Tuff</td>
<td>2,000</td>
</tr>
<tr>
<td>Gneiss</td>
<td>68,000</td>
</tr>
<tr>
<td>Graphitic schist</td>
<td>10</td>
</tr>
<tr>
<td>Slate</td>
<td>600</td>
</tr>
<tr>
<td>Quartzite</td>
<td>10</td>
</tr>
<tr>
<td>Shale</td>
<td>20</td>
</tr>
<tr>
<td>Sandstone</td>
<td>1</td>
</tr>
<tr>
<td>Conglomerate</td>
<td>2,000</td>
</tr>
<tr>
<td>Limestone</td>
<td>50</td>
</tr>
<tr>
<td>Dolomite</td>
<td>350</td>
</tr>
<tr>
<td>Clay</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2. Resistivity values and ranges for some common rock-types (after Telford et al., 1990)

3.4.2 Radio frequency EM (RFEM, RIM)

Versatility of electromagnetic methods in terms of frequencies used and loop geometries/applications is demonstrated through the application of radio-frequency EM (RFEM/RIM). When applied in a cross-hole configuration at the Callide Coal Mine in Queensland (Miller and Nichols, 2001), data can be collected up to a maximum spacing of 120m between drillholes, with varying frequency (12 – 300kHz) used according to drill-spacing. Traveltime and amplitude of RFEM radiation are recorded from source to receiver detectors and, through assessment of wave attenuation affecting both velocity and amplitude, information regarding geological features along the raypaths can be discerned. In the example discussed in Miller and Nichols (2001), there is sufficient contrast in the rock-types such that the coal seam can be traced in excess of 100m between the drill-holes and fault offsets as small as 4m can be imaged (Figure 18). Stolarczyk et al. (1988) successfully predicted the orientation and locations of cross-cutting dykes in a longwall panel of the Kemira colliery as confirmed by mapping. It should be noted that the contrasts in physical properties are likely to be extreme in these situations and have facilitated successful imaging, however, due to generally low contrast between rock-types commonly associated with underground mass-mining operations, including porphyry-related systems; the method may have limited effectiveness.
Figure 18. Cross-hole electromagnetics tomography (RIM2) from the Callide Coal Mine. The blue, low attenuation rate layer represents the coal seam with dislocations of only 4m detectable by the method, with >100m between drill-holes. (Miller and Nichols, 2001).

3.4.3 Ground Penetrating Radar

Ground Penetrating Radar (GPR) is a non-destructive and non-invasive subsurface imaging method that utilises low-power, non-sinusoidal wide-band radio EM waves with frequencies from 10MHz to 4GHz (Yelf, 2007). GPR systems are utilised in pulse or continuous wave (multi-frequency) modes (Yelf, 2007). Similar to seismic, GPR can be operated in reflection or refraction modes; however GPR provides higher spatial resolution than equivalent seismic and electrical survey methods (Yelf, 2007). Variation in the radar signal travel time and amplitude of the received signal, through the inter-borehole space, enables interpretation of the geology in the survey area (Yelf, 2007); and can be employed in a number of configurations (Figure 19). The technique is used to examine and locate interfaces where features in the bedrock show as a distinct radar reflector according to the contrasting dielectric constant of the feature compared to the host strata (Wanstedt et al, 2000). The propagation of electromagnetic waves through rock is mainly a function of the dielectric constant and the electrical conductivity of the material (Wanstedt et al., 2000). Changes in the rock types also produce strong reflections but these are smaller and more subtle than reflections from fracture zones, cavities, and rock-air interfaces (Dezelic, 2007).
According to Yelf (2007), there is a direct relationship between the transmitter frequency and the resolution, and an inverse relationship between frequency and penetration depth.

![Variations in GPR bore-hole GPR survey configurations](image)

**Figure 19.** Variations in GPR bore-hole GPR survey configurations (Yelf, 2007).

Similar to the seismic velocity tomography and logs discussed earlier, radar velocity has a relationship to fracture frequency and it is found that areas of competent rock have higher than average velocities (Serzu et al., 2004). Conversely, areas of lower velocity correspond to fractured rock with associated attenuation of wave velocities due to the additional interfaces (Serzu et al., 2004). Tomography between the two drillholes in Figure 20 was possible across the 80-100m inter-hole distance and correlates well with the observed fracture frequency. Fractures, joints, and rock degradation (due to oxidation/alteration/chemical breakdown) result in lower velocity values, and therefore, the final velocity model can be used to evaluate rock integrity and to locate zones with poor rock-mass quality (Pipan et al., 2004).

GPR is very effective for detecting fractures or discontinuities in resistive rocks (Gregoire and Halleux, 2002) and is one of the few geophysical methods that is capable of imaging individual millimetre wide fractures away from boreholes (Dorn et al., 2011). Dorn et al (2011) have modelled fractures with limited extents suggesting that this method may, in time, be useful in determining persistence of joint sets in a given rock mass, a continuing conundrum for the numerical modelling of block-cave mine propagation. Numerical modelling of synthetic DFN models suggests that increased salinity of fluid in permeable fractures decreases the amplitude of reflections due to increased conductivity, and that more information can be acquired regarding fracture properties from reflection-mode data as opposed to transmission (refraction) mode data (Liu, 2005). Faster velocity of radar waves in air compared with water-filled fractures results in variable radargrams based on interpreted fracture-fill (Liu, 2005).
Figure 20. Cross hole GPR tomography between holes MF1 and 2 at the URL. Radar velocity gridded data and fracture frequency represented by blue histogram (Serzu et al., 2004).

Spatial orientation of reflectors (fractures) is possible using GPR in single hole mode (Figure 21) and tomographic inversion of multiple single-hole GPR logs can yield plots of velocity and amplitude distributions in the tomographic plane (Figure 21) consisting of the inter-hole area (Wanstedt et al., 2007). Again, low velocity or high attenuation characterises fracture zones intersecting that plane (Figure 21). Connection, through interpretation, of features between holes becomes less ambiguous using the tomographic data as compared to the two single-hole reflector interpretations (Wanstedt et al., 2007; Figure 21).

A tow-along geo-radar system employed in a gneiss quarry in Switzerland has enabled detailed 3D mapping of fractures and a fault zone (Figure 22), to a depth of 30m below the survey path, thereby providing useful rock quality information to the operation (Grasmueck, 1996). In the underground mining context, data collection along drives of the undercut and extraction level could provide very useful structure location and orientation information which may be difficult to acquire in the active operational environment where shotcreting limits the time-window of exposure to map in detail. Also, magnetic interference associated with magnetite alteration often affects the collection of useable orientation data. This method, modified to enable wider line spacing, has potential to create a robust 3D model of this critical volume of the block-cave mine.
Applications of GPR to orebody delineation are largely based on case studies at massive sulphide deposits and as these are seldom sub-level or block-cave mined, these may not have direct application to the underground mass-mining operation. For more information on these case studies refer to the following: Hellyer Zn-Pb-Ag-Au deposit (Zhou and Fullagar, 2000, 2001), McConnell Ni deposit (Bellefleur and Chouteau, 2001), and Western Australian Ni (Turner et al., 2001).

One application of relevance to mass-mining and block-caving is that at the Kimberlite hosted Finsch Diamond Mine (Wolmarans et al., 2005). During this proof of concept study, a small region of the Kimberlite was successfully defined using GPR and improvements to the geological model were made using the GPR data (Wolmarans et al., 2005).

GPR has been useful in the detection of old abandoned mine workings proximal to current mining activity at Cripple Creek and KCGM mining operations (Dezelic, 2007) and predicting conditions ahead of the current mining areas. Applications of GPR to detection of shallow natural cave systems (Beres et al., 2001; McMechan, 1998) indicate that the method is useful for the purpose, although these case studies are generally <20m below...
surface. Nevertheless, there is potential to reconfigure the methodology to be more suited to monitoring the propagation of a block-cave void.

Figure 22. 3D view of interpreted fractures (white) and fault zone (red boundaries) below the quarry surface (green). (Grasmueck, 1996)

3.4.4 Magnetotellurics (MT/AMT)

The magnetotelluric methods are natural source methods which utilise low-frequency (in the order of 10Hz to 10kHZ) (Queralt et al., 2007), large scale earth currents induced by the Earth’s magnetic field (Telford et al., 1990). Controlled-source AMT (CSAMT) is preferable in the near surface (down to 500m) where the source is controllable and the survey can be designed to address/test a hypothesis (Queralt et al., 2007).

The natural source MT methods are capable of testing several kilometres below surface but often at the expense of resolution. This method is better suited to exploration geology and detection of groundwater systems/flow as applied to assessment of a nuclear waste repository in Great Britain (Unsworth et al., 2000) but cannot provide sub-100m interpretations of the sub-surface geology for mine assessment purposes. An interesting
A body of work utilizing MT resistivity data to constrain kriging of RMR obtained from drillholes (Seokhoon et al., 2004) utilises geostatistics to infer a relationship between resistivity and RMR where both are co-located along the drill-hole trace. The relationship is then used to estimate RMR values in unsampled regions between drill-holes and at depth. The project aimed to determine rock-mass characterisitcs for a planned tunnel at a depth of 200m (Seokhoon et al., 2004).

CSAMT was successfully employed at Century Mine, Queensland; to detect geotechnically unfavourable detached blocks of shale within limestone which had potential to affect pit-slope stability, and to determine the extent of water-bearing limestone for hydrological consideration (Mutton, 1997).

### 3.4.5 Emission of electromagnetic radiation during rock failure – potential application to cave back monitoring

Recognition of the release of high frequency electromagnetic radiation (EMR) in the lead up to roof failures (Figure 23) in coal mines has potential to be used as a monitoring tool in the mass-mine and possibly complement the conventionally applied micro-seismic arrays (Frid and Vozoff, 2005). EMR is generated due to fracture nucleation prior to a fall of ground with fractures in the order of 1-2cm inferred as the main source (Frid and Vozoff, 2005). Comparison with conventional acoustic emission records indicate that anomalous EMR activity occurs much earlier than acoustic emission (Frid and Vozoff, 2005) and therefore has improved predictive capability (Figure 24).

Electromagnetic radiation emission has been correlated with both the area of a crack, and the crack width; in the experimental environment (Rabinovitch et al., 2007). Rabinovitch et al. (2007) indicate that EMR is emitted long before earthquakes occur and that the reasoning behind lack of employment of this method as a predictor of seismic events is due to the lack of knowledge in the mode of generation of the EMR, for which they infer EMR as being generated by oscillatory waves of dipoles moving as a surface wave on both sides of the crack.

There is distinct potential of using this method to complement conventional seismicity in predicting/measuring/monitoring the passage of the seismogenic zone above the cave-back and for locating the cave-back : void interface.

### 3.5 Resistivity

Resistivity refers to electrical resistance of a material, i.e. the ratio of the voltage applied to the current that flows through the rock mass (Telford et al., 1990).
Figure 23. Increase in EMR activity building to the point of failure denoted by the response in Richter magnitude (Frid and Vozoff, 2005)

Figure 24. Relationship of EMR amplitude to the timing of a collapse failure event (Frid and Vozoff, 2005)

The resistivity of some common rock types was tabulated in Table 2 in the Electromagnetics section (3.4.1) of this report in the context of conductivity, the inverse of resistivity.

Induced Polarisation (IP) is the most commonly applied method of ground-based and down-hole survey and measures the decay voltage between electrodes in connection with the ground, measured during abrupt cut-off of the current (Telford et al., 1990). The
decay and build-up of charge on restart of the current, as a function of time, informs the geophysicist as to physical properties of the rock types through which the current has passed.

A coupled EM-IP method employed at the El Arco porphyry Cu deposit, Mexico; has been used to characterise the deposit according to mineralization types (Flores and Peralta-Ortega, 2009) according to the relationship between chargeability and the texture (both grain size and mode of distribution, Figure 25) and sulphide concentration as a function of time (Pelton et al, 1978). This could add significant value to a mass-mining operation in terms of geometallurgical mapping of the deportment of sulphides, at deposit scale, using a geophysical sensing method.

A relationship between P-wave velocity and resistivity has also been recognized (Ikeda et al., 2008) and is illustrated on Figure 26. This is likely to reflect a textural anisotropy in the rock-mass involving preferred orientation and/or distribution of minerals. Herwanger et al. (2004) recognise that coincident highly resistive regions in 2D tomographs exhibit high seismic velocities and the directions of symmetry of electrical and seismic anisotropy correspond well.

2D resistivity tomography applied to the identification of faults and fracture zones as verified by mapping of a tunnel approximately 100m below surface, was found to be more successful than very low frequency (VLF) EM and seismic tomography (Ganerod et al., 2006). A significant fault zone (approximately 2m wide with gouge infill) was identified and orientation established. Limit of depth penetration of the system applied was 130m.

Imagery of borehole walls using micro-resistivity measurements from a ‘formation microscanner’ (FMS) has been used to replicate lithological logging and map textural variation (Linek et al., 2007; Jungmann et al., 2011). This has potential application to the non-core drilling techniques in a mass-mining context. Drilling may be completed faster and still obtain textural data which would complement optical and acoustic televiewer application.

### 3.6 Natural Gamma logging

Natural Gamma logging is a down-hole detection tool which has the ability to identify changes in lithology continuously along the length of the hole (Cripps and McCann, 1999). The gamma ray probe, or ‘sonde’, contains a detector which measures the gamma radiation emanating from the immediate surrounds of the borehole (within 30cm of the borehole wall), with count-rate indicating lithological variation (Cripps and McCann, 1999). The gamma ray activity normally reflects the Potassium-40 content, however gamma ray activity is also attributed to isotopes of Uranium and Thorium (Ellis and Singer, 2008). Gamma logs are useful for mapping clay rich strata e.g. shales (Cripps and McCann, 1999) and feldspar-bearing rocks given that feldspar has a Potassium-rich end-member (Ellis and Singer, 2008). The natural gamma log does not record a unique response according to lithology but the response of rock types is internally consistent (Figure 27) within a single geological area (Cripps and McCann, 1999).
Figure 25. Diagram relating chargeability to sulphide texture and concentration (after Pelton et al. (1978). Red arrow indicates increasing sulfide concentration (after Flores and Peralta-Ortega, 2009).

Figure 26. Relationship between P-wave velocity and resistivity (Ikeda et al., 2008)
Use of a combination sonde at Zinkgruvan Mine in Sweden has enabled the refinement of geological horizons and, through the combination of density, natural gamma and magnetic susceptibility; ore grades can be estimated from the logs within an error limit still useful for ore delineation and mining purposes (Wanstedt, 1992). It is likely, however, that the density log is the more significant component of the algorithm for calculating the estimated-grade from the combination log of the sulphide mineralization.

The use of natural gamma logging in the mass-mining context is really the case for enhancing the confidence in geological modelling given the inherent broader spaced drill-pattern that large orebodies attract. Any method that validates models and interpretations in this way is useful but the draw-back is that the technique does not provide the sensing-component between drillholes that allows prediction of rock-types and physical characteristics in areas not sampled by the drill-hole.

### 3.7 Neutron logging

In this down-hole logging method, high-energy neutrons from a source in the sonde bombard the rock in the borehole wall and lose energy on transit to the detector part of the sonde (Telford et al., 1990). The rate of energy loss is proportional to the density of protons and the response is primarily due to Hydrogen content. The neutron method therefore detects the amount of liquid-filled porosity (Hydrogen index) of the wall-rock
strata within a 20-60cm range, dependent on porosity of the rock-type (Telford et al., 1990).

Correlation of the neutron log/Hydrogen index with a fracture index (logarithm of 1/number of fractures per unit length') in coal measures (Staffordshire, U.K.) enabled prediction of fracture density and the relationship was extended to UCS (Halker et al., 1982). A continuous log of estimated-UCS was derived from the neutron log following establishment of the site-specific relationship.

Similarly, Elkington et al. (1982) derived relationships between the point-load strength (Is[50]) and gamma response, wave velocity, and neutron-neutron response. The neutron response was observed to have the best correlation with the point-load index for the sedimentary rocks in U.K. coal measures.

It is possible that the relationships observed in the relatively undeformed and unmetamorphosed sedimentary rocks will not extend to crystalline rocks common to underground mass-mining operations.

3.8 Spectral Gamma-Gamma (SGG, Density log)

The density log is another down-hole logging method to determine porosity, and similar in configuration to the neutron probe, the density logging sonde passes gamma rays from source to detector through the adjacent wall of the drill-hole. Most of the signal comes from the first 8cm depth into the wall and the maximum penetration is approximately 15cm (Telford et al., 1990). The only rock property affecting the detector response is the density of electrons (Killeen, 1997) and the detected gamma-ray intensity is an exponential function of rock density (Telford et al., 1990).

The significance of accurate measurement of density to the mass-mining operation was discussed in the ‘Gravity’ methods section above. Bias or error in the density estimation associated with a mineral resource could cause significant discrepancy in the estimated contained metal of the resource. A reliable down-hole method which can record data for numerous drill-holes will have internal consistency and map variability. The logging method can be repeated for a given hole for quality control purposes.

For orebodies which contain minerals with distinct density to the host or gangue mineralogy, a continuous downhole density log can provide an estimate of grade, as demonstrated with magnetite iron in Charbucinski (1983). In that study, physical parameters which influence the gamma-ray spectra, and can therefore be quantified; included the heavy element content, density, grain size, and borehole diameter. Killeen (1997) demonstrates a strong relationship between the SGG ratio (ratio of count rates in two energy windows: high and low) and Pb grade for the Yava lead deposit (Figure 28), Canada (Killeen, 1997).

Note also, that the combination of density determination and acquisition of sonic wave velocity data can yield several important physical properties of rocks including the
dynamic elastic modulus, shear modulus, and Poisson’s ratio. These are required inputs into rock mechanics computational modelling and better understanding of the variability of these parameters across a deposit would reduce error in associated modelling.

![Figure 28. SGG ratio vs Pb grades in the Yava lead deposit, Nova Scotia, Canada (Killeen, 1997).](image)

### 3.9 Neutron Activation logging

The neutron activation logging method or ‘prompt gamma neutron activation analysis’ (PGNAA) measures the energy of the gamma rays and the ‘activation gamma rays’ emitted by the decaying isotopes in the survey volume (Killeen, 1997). The energy emitted is characteristic of the emitting element (Killeen, 1997) and the spectral intensities are proportional to the elemental content (Molnar et al., 2000). A catalogue of 79 elements (between Hydrogen and Uranium) for which the gamma-ray spectra has been defined (Molnar et al., 2000) and application to mining and mineral exploration include a field trial of the method at the Chuquicamata mine, Chile (Figure 29); in testing copper grade in blast-holes (Charbucinski et al., 2004). This proved highly successful and
resulted in a robust predictor of copper grade with standard error of 0.14% (Charbucinski et al., 2004).

![Figure 29. Plot of copper assays vs PGNAAN-log derived copper values at Chuquicamata Mine (Charbucinski et al., 2004).]

Again, while not a ‘sensing’ tool to predict conditions in the inter-hole space, the PGNAAN method technique could be applicable in situations where turnaround of assays is critical (e.g. grade control application in blast holes) and may complement non-core drilling techniques in their application in underground drilling.

4 A note on ‘Joint Inversion’ and applicability to the cave mining industry.

There is no one geophysical method which is the silver bullet given the intricacies of the geology of individual deposits and any logistical and economic constraints on the programmes (Fullagar, 2000). The preceding discussion regarding the various geophysical methods and applications identifies the fact that the method must be applied to address an unknown parameter, and tailored implementation of geophysics to provide mining solutions. Due to the inherent complexity of mineralized systems, it is likely that:

a) More than one geophysical method may provide useful vectoring, diagnostic, or quantification of physical parameters of the deposit, and
b) No single method will provide all of the required parameters for numerical modelling inputs, design decisions, monitoring of operations.

As an exploration geologist working in the Pilbara Iron Ore province approximately 10 years ago, self-organising map processing was applied to airborne geophysical data (gravity and magnetics) to define areas with high gravity and diminished magnetic response as targets for iron enrichment. Geophysical inversion of the resultant data provided a very useful 3D targeting tool for the exploration geologist. To bring this into the mining context, we are no
longer talking about processing of largely 2D data and now need to apply analogous ‘joint inversion’ processes (Figure 30) to elucidate geophysical relationship with important physical parameters of the mineral resource for mining and processing purposes.

![Figure 4.30 Schematic process of joint inversion of magnetic and gravity data](http://www.hpxploration.com)

“All geophysical inversion methods are fraught with the problem of non-uniqueness” (Moorkamp et al., 2011) and it is often a paradox that the geologist must provide interpretations of the geology of a region to constrain geophysical inversion, in order to achieve sensible and usable inversion products. This is recognised by Jacoby and Smilde (2009) in that “the problem of gravity interpretation can be ‘solved’ by inversion, especially by ‘Bayesian inversion’ which attempts to achieve the best compromise between all pieces of available information within their particular uncertainty limits, usually called ‘errors’”. In other words, a geophysical technique will provide the answer if accompanied and interpreted in context of all other available data. This is a reasonable and logical statement but so often a single geophysical technique is used, possibly due to cost constraints or knowledge gaps, and the errors associated with the interpretation of the data are not always fully understood by the downstream users.

Joint inversion is defined as the process of reducing a set of acceptable models by combining multiple geophysical datatypes in a single inversion scheme with the aim of the resulting model explaining all data simultaneously (Vozoff and Jupp, 1975). This methodology is underpinned by recognition that different methods have different resolving kernels and the null space for one type of data can be resolved by another (Julia et al., 2000) as illustrated on Figure 31, and that sources of noise will differ for different geophysical methods and complementary data may reduce the effects of noise and error in the data (Moorkamp, 2011).
Published examples of joint inversion include:

- 3D joint inversion of seismic, magnetotelluric, and gravity data (Moorkamp et al., 2013)
- 3D stochastic joint inversion of gravity and magnetic data (Shamsipour et al., 2012)
- 3D joint inversion of MT, gravity, and seismic refraction data (Moorkamp et al., 2011)
- 2D joint structural inversion of cross-hole electrical resistance and GPR (Bouchedda et al., 2012)
- Zonal (domaining) joint inversion of cross-hole P-wave, S-wave, and GPR (Linder et al., 2010)

Each of the above outlines the algorithms and processes used but are not applied to mining related problems. The method almost appears like a solution looking for a problem. It is required that relationships between geophysical methods/datatypes and physical parameters useful to mining practices need to be determined such that the key geophysical and other (e.g. geotechnical, geochemical, mineralogical) data types can be selected for joint inversion. The combinations of geophysics and all other datatypes collected at a mining operation are significant and the key will be to identifying those datatypes which account for the bulk of the variability in the chosen physical response being investigated. It will also be key that a significant proportion of overlap is required for the inversion to be successful/meaningful.

A logical starting point would be thorough analysis of the geological/geotechnical database in the context of some proof-of-concept/trial geophysical datasets. If a robust regression can be established for, say, rock strength; which hypothetically might incorporate P-wave velocity, S-wave velocity, and RQD; then additional geophysical data could then be acquired to ensure representative data distribution, and joint inversion could utilise these variables. A systematic multi-disciplinary approach would be required to determine the key parameter to be investigated, and employ sound geoscientific means, employing the most appropriate geophysical method, to derive an outcome.
5 Discussion: Geophysical methods/techniques showing the most promise for pre- and syn- development rock mass assessment and monitoring of block cave mines (refer to the body text for relevant references)

As stated in the opening paragraph of the preceding section, there is no singular geophysical panacea which will answer all mining related problems or be the sole geoscientific input into numerical modelling of geomechanical behaviour.

However, given the vast choice of geophysical tools and methods, there are some which stand out as offering particular advantages to the mass-mining operation in particular, and should be considered as a starting-point in the application of geophysical methods to a new mining operation.

Firstly, **P-wave (and S-wave) velocity** has a long-lived history of application in the coal mining sector but has been largely underutilised in metalliferous mining. The benefits of collecting seismic wave velocity data are numerous and have been discussed in the body of this document, but are again summarised below.

From the literature, seismic wave velocity (both P & S-wave) is correlatable with, can be used as a proxy for, or can be used in the calculation of, the following:
- rock strength
- density
- lithological variation
- alteration (hydrothermal, fault halo etc)
- discontinuity frequency/RQD
- 4D stress distribution
- resistivity
- comminution response
- shear modulus
- P-wave modulus
- Poisson’s ratio
- Dynamic Young’s modulus

This is an impressive list of physical parameters and rock response variables that can be gleaned from a single technique. Collection of seismic wave velocity data can include ground survey (depth limited but also consider utilising key development levels of the underground operation), down-hole, cross-hole, and from core samples. The preference would be for the use of full-waveform sonic logging of drill-holes and the associated tomography in the first instance, with the application of reflection/refraction techniques in selected areas of the deposit where further data is required to assist geological interpretation. Down-hole sonic logging can indicate in situ stress conditions and variations through time, however hand-held techniques may be better applied to characterisation of rock-types in terms of comminution response and correlation with UCS testwork. Drill-core represents the rock in its de-stressed state analogous with ore delivery to a surface stockpile, and the stick of core loaded into the conventional UCS equipment.
In terms of interpretational aids in 3D modelling of geology and faults/fracture zones, the most applicable method to resolve the geology of the inter-hole region is ground-penetrating-radar (GPR). This method could be utilised to complement geological mapping and 3D modelling from drill-hole data and can be employed as either a down-hole and cross-hole survey, or as a tow-along configuration. The application to inter-hole tomography is clear and the ability of the method to detect fractures and obtain 3D orientations of the same, is a particularly pertinent application. The method has been used to refine lithological boundary modelling and, in some cases, this may represent refinement of the boundary of mineralization for design and mining purposes. The tow-along version of GPR may provide confirmatory analysis of the region between the undercut and extraction levels in the block-cave mine, a zone for which geoscientific knowledge must be maximised to ensure longevity of the key development/capital infrastructure, and to provide geohazard information relevant to ensuring safety of personnel working on these levels. GPR data acquisition data may be obtained below the extraction level also, given that this area can experience significant stresses during establishment and during operation of the cave and it is useful to understand the 3D geology in some detail to prepare for and/or prevent any ground response to the mining activity.

The importance of accurate density determination was stressed in the ‘gravity’ section of the document. Error in density directly affects contained metal in a resource as equally as error in grade estimation. However, in the mining industry density-sampling/determination occurs at coarse spacing and the effect of variability and accurate estimation is often neglected. The Neutron logging sonde is a down-hole density tool which could facilitate rapid collection of abundant reliable data. There is further potential of using this data in rock strength determination.

Observation of the emission of electromagnetic radiation (EMR) related to rock failure in the lead up to falls of ground in coal mining has potential as an alternative mine monitoring method. The methodology has been applied in a mining situation and experimentally, and suggests that during nucleation of cracks, EMR is emitted and that this builds to the point of failure (seismic event). The measurement of EMR emission gives significantly more lead time to the moment of failure than conventional acoustic-based microseismic monitoring. In the underground mass-mine, prediction and monitoring of cave back propagation is paramount and this method may complement the existing technologies, albeit with required upscaling for use in block-cave mines.

Televiewing tools and nuclear ‘geochemistry’ logging devices really come into their own if the decision to reduce the amount of core-drilling in a mining operation is made. In a surface operation, these can give rapid turn-around of geological and geochemical data required for operational purposes, however in the underground mass-mine, the significant lag time between drill-out of a resource and commencement of mining doesn’t require the ‘real-time’ acquisition of data. Detection limits and logistical issues will continue to reduce the effectiveness of the down-hole geochemistry loggers, however televiewers (acoustic or optical) can be an alternative method to collecting oriented measurements of geological
features, and be employed as an alternative to, or calibration of, conventional core-orientation methods.

Some thought should be given to measurement of the **anisotropy of geophysical parameters** in the appropriate unit of rock volume. Anisotropy is evident in magnetic, velocity, and resistance data and reflects textural and/or mineralogical variation in three dimensions (a tensor). Texture at, and below, the scale of the hand-specimen (e.g. grain boundaries, foliation/cleavage, fabric/mineral alignment, existing microfractures) is likely to be a critical control on fracture propagation, but is not captured in numerical modelling other than the general effect of texture on rock-strength testwork and the related modulus indices. Intuitively, rock texture will influence the orientation, rate of propagation, connectivity, and strength of fractures nucleating in the rock mass. Methods for measurement of anisotropy are laboratory based, however there may be some potential development of a 'bulk'-anisotropy measurement whereby this textural heterogeneity of the rock-mass can be accounted for in predictive numerical modelling. Even laboratory-based measurements of representative samples would be value-adding dependent on systematic and logical domaining of structurally constrained litho-types.

Relationships are found to exist between the 3D tensor for velocity, magnetic susceptibility, and resistivity; so it may be possible to infer the direction of anisotropy of a parameter by measurement of an alternative as a proxy. This approach may be complemented by X-ray CT analysis of the same rock, thereby recording the 3D geophysical anisotropy and determining the mineralogical abundance/distribution phenomenon effecting the heterogeneity. The X-ray CT data can then be used for metallurgical/geo-metallurgical investigations of the ore types providing information on grain-size, grain-shape, deportment, associated mineralogy, and volumetric abundance; of ore and deleterious minerals in a non-destructive test.

### 6 Conclusions

Geophysics is a field which is constantly on the move, and, with the advent of more powerful computing ability, significant advances have occurred over the past decade. Appropriate employment of a geophysical method often polarizes geoscientists, and can make for difficult justification of a program, particularly in the operational environment. It is the responsibility of mining companies to continue the professional development of their technical personnel, and as such generate knowledgeable well-rounded professionals with a competent understanding of applicable geophysical techniques. This may require an element of training/exposure to geophysical methods which might not have an immediate application to the mining operation, but a geologist requires the knowledge and to have the ability to apply one of an arsenal of tools to resolve technical problems or test hypotheses as required. It is important to stay abreast of new methods and improvements to established techniques so as to fully exploit any geophysical method with value-adding capability in the context of mining geology.
There are many geophysical methods applicable to mining-related issues, and, as with other emergent technologies, these require case-studies of successful implementation and value-addition before a wave of routine application is propagated through the mining industry. Some of the case studies presented in this document should be followed up if pertinent to the increased understanding of a suitable ore deposit. Trial or proof-of-concept surveys should be conducted initially to establish correlation with the desired physical properties.

Of the many geophysical methods in existence, and the subset of those discussed in this document; some stand out as having direct applicability to the underground mass-mining operation in terms of building more robust geological models and the estimation of rock mass characteristics. The use of seismic velocity data for geological modelling and prediction of rock mass characteristics appears to be a significant, value-adding method. No other single geophysical data type yields an equivalent list of physical parameters and rock response indexes and it is surprising that the metalliferous mining sector has been slow to catch on to this method, employed by the coal mining sector for some time. For locating fractures/fracture zones/faults/lithological contacts in the inter-hole area, ground penetrating radar appears to offer the most valuable data to augment the current modelling using geological mapping and drill-hole data. The importance of accurate and appropriate distribution of density data is raised. There are suitable tools for this purpose (e.g. Neutron logging) and perhaps more effort should be made to understand variability of density across a deposit. When reconciliation problems occur, we often look to the assay data for explanation, but neglect to be equally critical of density estimation, given its clear effect on contained metal within the ore-deposit. An emergent technique in measuring electromagnetic radiation as a ‘predictor of time to imminent mining-induced rock failure’ has particular relevance to cave-mining. One of the key phenomena required in the cave-mine, dominantly for safety purposes, is knowledge of the location of the cave-back to within <10m accuracy. If the electromagnetic radiation emission technique is a useful predictor of crack nucleation and failure, it is possible to redeploys this technique as a cave back monitoring system similar to the conventional microseismic arrays used in modern mass-mines. The technique requires more research and field-application to determine suitability to the geometries and scale of cave mining.

Finally, for geophysics to be routinely adopted by operational personnel, this requires education of mining technical personnel across multiple disciplines in the range of geophysical methods, and freedom to apply a method unconventionally to test for relationships and perhaps develop a step-change in prediction of physical properties in the mass-mining operation.
7 References


