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Geophysics in Metalliferous Mines for Ore Body Delineation and Rock Mass Characterisation

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ABSTRACT

Over the last few decades geophysics has become firmly established as a vital component of modern exploration programmes for metals and minerals. The new frontier of geophysics is the mine site. Geophysics now offers a means for more cost-effective ore body delineation and rock mass characterisation during resource definition, mine development, and production.

Geophysical methods can be divided into two broad categories: logging and imaging. Logging systems record in situ physical properties of the borehole wall rocks, while geophysical imaging techniques can map features at tens or hundreds of metres from the sensors. Imaging methods are predominant in exploration, but logging is well suited to resource definition and mining given the high spatial density of holes and the need for detailed information. Density, natural gamma radiation, magnetic susceptibility, and conductivity are the principal in-mine logging parameters because they can be recorded in both dry and water-filled holes. Sonic velocity is the premier geotechnical logging parameter, given its sensitivity to rock strength, stress, porosity, and degree of fracturing.

Conventional downhole EM and borehole magnetics are used for near-mine exploration, but the higher resolution offered by seismic, radio imaging, and radar is usually necessary to effectively delineate ore bodies and map structures, or to geotechnically characterise the rock mass and identify hazards. Imaging methods can be applied in open pits, or underground from individual holes, between holes, or from hole to mine opening.

Geophysics is already playing an important role in a number of metalliferous mines around the world, especially for ore boundary delineation, delivering benefits measured in millions of dollars per year in some cases. The benefit may be direct, e.g. as savings from substitution of core drilling with percussion drilling plus borehole logging, or it may be indirect, e.g. in the form of reduced dilution arising from a more accurate mine model. There is potential for the role of geophysics to expand into automated geological logging, blasting optimisation, and grade estimation.

During resource definition and mine development, an appropriate combination of surface and crosshole imaging and borehole logging sometimes has the potential to delineate and geotechnically characterise the ore and host rocks in three (or four) dimensions. Interpretation of the geophysical data in conjunction with all existing geological and geotechnical information can provide a firmer basis for major design and development decisions.

Appropriately applied, geophysics can reduce uncertainty in mine design and production, thereby enhancing safety, lowering costs, and increasing revenue. The greatest impediment to expanded use of geophysics at mines, however, is the low level of awareness of geophysics on the part of most mine geologists, engineers, and managers.

Integration of geophysics with drilling will be a key innovation during the next ten years, guaranteeing access to all holes, simplifying logistics, and eliminating the delay between drilling and interpretation. Measurement-while-drilling technology, used in drill performance monitoring, represents a source of geotechnical information. Slimline logging-while-drilling technology for delivery of petrophysical and imaging data is in its infancy. Interfacing geophysical modelling and imaging software with mine modelling systems will expedite integrated interpretation of all data. These developments, in combination with other technologies such as high bandwidth communications, will usher in a new paradigm in mining, characterised by vastly higher information flows and substantially lower risk factors.

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INTRODUCTION

Metalliferous mines must continue to enhance their profitability, improve their safety performance, and reduce their environmental impact in order to remain in business. These wide-ranging challenges must be met as metal prices continue to decline at approximately 3% per annum in real terms (Eager, 1992). More than savage cost-cutting or incremental improvements to conventional mining practices is demanded. There is a need for innovation.

Excluding commodity price and sovereign risk, uncertainty about ore geometry and rock quality are the principal threats to mine performance. In mine development, major capital expenditures are committed on the basis of sparse information. Likewise during mining, local inaccuracies in mine models based on incomplete data sets are not infrequently the root cause of unexpected and sometimes costly production shortfalls, through lost ore or bad ground. Geophysics has the potential to reduce these risks in mine development decision making when suitable physical contrasts exist, via timely and cost-effective mapping of the ore body and its environment. Geophysics, appropriately applied, can underpin mine performance improvements in a number of spheres, including cost per tonne, safety, and environmental impact.

Benefits arising from a geophysics implementation may be direct, in terms of immediate cost reduction, or indirect in the form of an improved ore body model, better mine design, or a timely recognition of safety hazards. The scale of the economic benefits is often difficult to quantify, not only because companies are often reluctant to share their commercial information but also because the benefits are relative to "would have been" scenarios and are therefore difficult to calculate. In million tonne per annum operations the economic benefit can run to millions of dollars per year (King *et al.*, 1994; Williams, 1996), sufficient to drive an operation down the cost curve, and maintain its competitive position.

Geophysical techniques are already employed extensively in petroleum reservoir engineering (e.g., McWhorter and Torguson, 1995) and in coal mining (e.g., Davies, 1992). Despite this, and notwithstanding the important role of geophysics in mineral exploration, the metalliferous mining industry as a whole has been slow to introduce geophysics into mines. Although the metalliferous geological environment is relatively more complex, the barriers to greater acceptance of geophysics in mining are more "cultural" than technical, due principally to the historical divisions between exploration, feasibility, and production teams. Educating mine managers, engineers, and geologists as to the benefits of geophysics at metalliferous mines is therefore an essential pre-requisite for wider implementation of geophysical techniques.

Nonetheless, several major metalliferous mining companies are now successfully integrating geophysics into their mining operations, including Outokumpu (Lappalainen and Lehto, 1995), INCO (King *et al.*, 1994; Fullagar and Livelybrooks, 1994; Fullagar *et al.*, 1996a), WMC (Williams, 1996; Turner *et al.*, 1996), MIM (Jackson *et al.*, 1996), Noranda (McCreary *et al.*, 1992), and JCI and others in South Africa (Campbell, 1994). Geophysical techniques can be applied at almost any scale and at any stage of a mining operation, to provide a performance benefit. Four broad classes of application can be recognised:

- *ore body delineation*, to maximise ore recovery and minimise dilution;
- *rock mass characterisation*, to guarantee safety and to optimise mine design;
- *exploration* and *ground sterilisation* (e.g., King *et al.*, 1994; Kowalczyk *et al.*, 1996);
- *environmental monitoring* (e.g., King and Pesowski, 1993).

In this paper the state-of-the-art geophysical ore body delineation and rock mass characterisation will be briefly reviewed using examples from around the world. Factors determining the rate of expansion of in-mine geophysics are identified: education of mining personnel, acquisition of geophysical data during drilling, automated interpretation, and integration of geophysical and geological modelling.

OVERVIEW OF GEOPHYSICAL TECHNIQUES

Introduction

Geophysical methods can be classified into two broad categories: *borehole logging*, for determination of in situ physical properties in the immediate vicinity of a drill hole; and *geophysical imaging*, for mapping features located tens or even hundreds of metres from the sensors. *Imaging* as used here encompasses all the methods applied routinely in mineral exploration for geological mapping and ore detection, e.g. magnetics, electromagnetics (EM), gravity, etc., as well as the less common high resolution techniques, namely seismic, radio imaging, and ground probing radar.

Rock property determination and borehole logging

Geophysics rests fundamentally on the existence of contrasts in rock properties. Petrophysical properties can be determined either from discrete rock samples in a laboratory or continuously in situ via borehole logging. Petrophysical laboratory analysis of representative ore and host rock samples is highly desirable prior to collecting geophysical data at a new site. Electrical and electromagnetic survey design and equipment selection is especially problematical without such petrophysical orientation data, given that conductivity often varies over several orders of magnitude in metalliferous mines. No single system is suitable over the entire range.

Knowledge of rock density and strength has always been a necessity at mines, for ore reserve estimation and mine design respectively. Density is routinely measured for samples submitted for geochemical assay. Sampling for rock strength testing is often more limited, sometimes raising concerns as to the representivity of the results. The capacity of calibrated borehole logging to provide continuous in situ density and rock strength determinations has been largely ignored.

Petrophysical contrasts can be exploited to discriminate ore from waste, or in some cases estimate grade, during resource definition, production, or processing. Natural gamma activity is routinely logged at uranium deposits for ore delineation and grade control (Conaway and Killeen, 1978), and magnetic susceptibility has long been recognised as a direct grade indicator at magnetite mines (Virkkunen and Hattula, 1992). Discrimination of ore from waste between mine and mill, by exploiting contrasts in natural radioactivity (Bohme, 1983), conductivity (Balint, 1975), or optical properties (Maughan, 1974), eliminates the costs of grinding and processing mullock, and reduces the volume of tailings. Similarly, petrophyiscal classification of ore types can introduce a greater degree of consistency into mill feed via blending, thereby enhancing metal recovery, albeit at the cost of additional handling.

Slimline borehole logging probes are available from a number of manufacturers to measure a wide range of physical properties (e.g., Fallon *et al.*, 1997). Some systems, such as the Outokumpu OMSLOGG, have stiffened cable to permit logging of holes oriented upwards. The principal applications of borehole logging in minerals mines are:

1. geological interpretation (hole-to-hole correlation);
2. ore boundary definition;
3. grade estimation;
4. geotechnical characterisation of the rock mass.

Examples of each application will be described briefly in subsequent sections below.

For geological interpretation and ore boundary definition, qualitative interpretation of logs is often adequate. If, however, borehole logs are to be used as a basis for quantitative modelling, be it for ore reserve determination or geomechanical analysis, petrophysical calibration of probe responses is a prerequisite.

Absolute calibration establishes the relationship between probe readings and physical standards, e.g. between gamma-gamma response and density. This is usually performed at government facilities, such as the GSC radiometric test site in Ottawa, where holes have been drilled through synthetic materials with prescribed properties (Killeen, 1986).

Core-based calibration relates a probe response to a property of the core (from the same location) as determined in a laboratory, e.g. sonic velocity to UCS.

Petrophysical properties measured in situ by a calibrated borehole probe can differ from laboratory determinations on the drill core taken from the same location for a number of reasons. Fundamentally, the measurements relate to different material, namely that removed from the hole and that which remained in situ. Furthermore, the borehole probe value is representative of a far larger volume of rock than the corresponding core sample. The probe may have been calibrated in a hole of different diameter. Other factors to consider include the in situ rock stress (which mainly affects porosity and sonic velocity), salinity and temperature of interstitial fluid (which affect electrical conductivity), and drill-induced porosity, permeability (fracturing), and magnetisation.

Geophysical imaging

A variety of geophysical techniques is available for detecting and delineating features at ranges up to hundreds of metres from the sensors. Many of these techniques are applied routinely in mineral exploration. The effective radius of investigation and achievable resolution are dependent on the technique adopted, the survey specifications, the local rock properties, and ambient noise conditions. Geophysical imaging data can be collected in open pits or underground from mine drives and boreholes in a variety of survey configurations: single hole, hole to hole, hole to surface, drive to drive, etc.

Conventional downhole EM and borehole magnetics are normally selected for in-mine exploration and ground sterilisation (e.g., Jackson *et al.*, 1997, Kowalczyk *et al.*, 1996). The focus in this paper will be on the higher resolution imaging techniques required for ore body delineation and rock mass characterisation.

Some imaging techniques require access to a single hole or roadway only, e.g. downhole EM, borehole magnetics, reflection seismic or radar, and gravity. In crosshole imaging, the spatial distribution of a physical property (e.g., velocity, attenuation, resistivity) can be mapped by recording signals transmitted from one hole or opening to another. Tomographic techniques similar to those used in medicine are commonly employed, based on the assumption that the energy propagates in almost straight paths between the transmitter and receiver.

Seismic is inherently attractive for both exploration and production in-mine applications because, in principle, it can provide resolution of a few metres over ranges from tens to hundreds of metres. In-seam seismic has proved to be an effective tool in some coal mines (e.g., Mason *et al.*, 1980), and the application of seismic in metalliferous mines is being actively researched (e.g., Cao and Greenhalgh, 1995). The principal disadvantage of seismic is the need for mechanical coupling of both source and receiver with the ground. This coupling adds to the cost of seismic surveys, especially if geophones are grouted and sacrificed. Hydrophones can be used in water-filled holes, but at the expense of directional information.

Ground penetrating radar (GPR) offers comparable resolution to seismic, but usually over a limited range. Radar is, however, effective over long ranges in salt mines (Eisenburger *et al.*, 1993). Radar data can be collected more readily than seismic, and there is no restriction to water-filled holes. Massive sulphide ore bodies in resistive host rocks are an excellent target in principle, behaving as perfect radar reflectors. This has provided the rationale for the on-going borehole radar trials by WMC for delineation of nickel shoots at Kambalda, Western Australia. However, minor amounts of disseminated sulphide in the host rocks can significantly attenuate radar signals, severely reducing its effective range (Fullagar and Livelybrooks, 1994).

The radio frequency electromagnetic method (RFEM) is intermediate in range and resolution between conventional electromagnetic exploration methods and ground penetrating radar. In principle, therefore, RFEM has the potential to play a role in both exploration and mining. Radio frequency surveys are usually undertaken in a crosshole configuration, with hole separations constrained by operating frequency and local conductivity. Conductive zones between the holes attenuate the radio signals, and massive sulphide bodies can give rise to "radio shadows". The technique has been implemented successfully in coal and potash mines, and is under investigation in metalliferous mines in Australia (Anderson and Logan, 1992), South Africa (Wedepohl, 1993), and Canada (Fullagar *et al.*, 1996a).

ORE BODY DELINEATION

Introduction

An accurate knowledge of ore body geometry and grade is fundamental to mining. The examples below illustrate how geophysics can contribute to cost-effective and timely ore body delineation, and hence improve the economic performance of mines. More precise ore body delineation can also translate into reduced environmental impact. Reduced dilution, for example, not only increases the head grade but also reduces the energy expended hauling, crushing, and treating waste rock, and minimises the volume of tailings.

Ore boundary definition

Defining the limits of mineralisation to high accuracy is the most common application of borehole logging in mines. Geophysical definition of mineralisation boundaries is cost-effective because the net cost of drilling and logging percussion or reverse circulation is less (by about $30/m) than the cost of diamond drilling. The economic benefit may be realised as a direct drill cost saving (if the same total meterage is drilled), and/or as an improvement in mine performance flowing from a higher number of ore body drill intercepts (if more holes are drilled for the same net expenditure on drilling). These more economical drilling techniques do have their limitations, but these limitations can often be largely overcome by the logging, as indicated in Table 1.

In some cases the advent of logging can alter the economics of a resource, and hence add to ore reserves and mine revenue. At Zinkgruvan, Sweden, for example, borehole logging was a crucial

Table 1: ***Enhancement of percussion drilling effectiveness with borehole logging.***

Limitation of percussion & RC drilling	**Logging solution**
Poor sample quality for geological logging	Accurate, complete single or multiparameter logs
Sampling error for geochemistry: mislocation, smearing, contamination	Mineralisation boundaries accurate. Possible empirical grade estimates from log analysis
Loss of structural & geotechnical information	Some structural & geotechnical information, e.g. from sonic logs
Rig capacity restricts length of holes	Cannot compensate

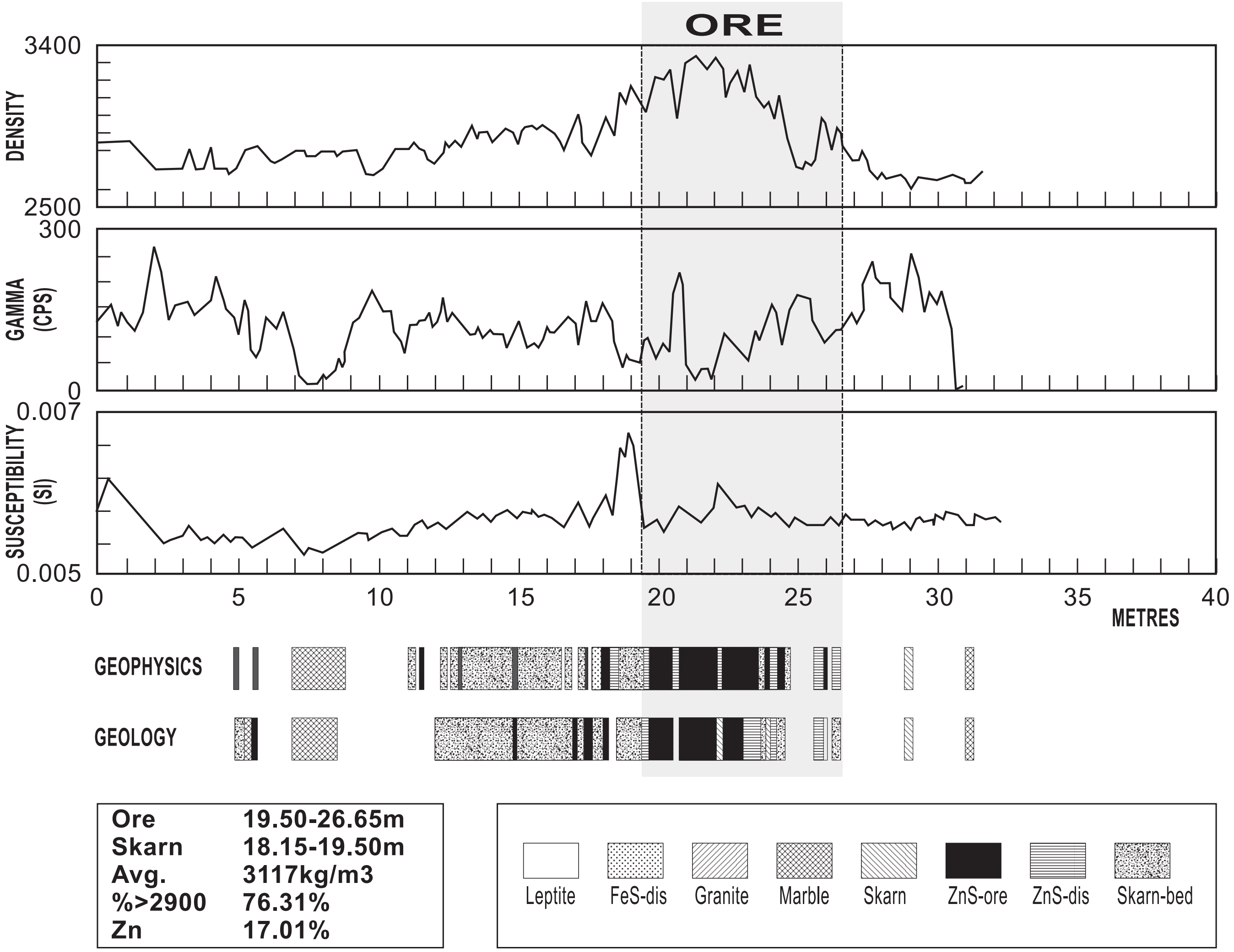

Figure 1: *Comparison between the geological log and an automated interpretation based on density, natural gamma, and magnetic susceptibility logs at Zinkgruvan, Sweden (after Wanstedt, 1992).*

component in the modification of a traditional mining method, undertaken to permit economic extraction of an isolated ore lens adjacent to the main lode (L. Malmstrom, pers. comm.). The ore lens was not sufficiently large to support the cost of additional development which would normally have been required for conventional sub-level stoping. Nor was the grade sufficiently high to tolerate significant dilution. By logging cablebolt holes drilled from the existing development drift, the ore boundaries were defined very accurately, permitting precise placement of charges to minimise overbreak. More than one petrophysical parameter was required for reliable discrimination of ore from waste (Wanstedt, 1992): the ore was uniquely characterised by low susceptibility, high conductivity, and high density (Figure 1).

Blast holes can be logged to refine charge placement, size, and sequencing. King *et al.* (1994) described the use of simple conductivity probes to discriminate ore from waste in blast holes in vertical retreat mining stopes at Stobie Mine, Sudbury. The economic benefit was approximately C$20 M in 1993, comprised of increased revenue from enhanced ore recovery (Figure 2a), as well as cost savings from reduced dilution (Figure 2b). The conductivity log is interpreted in a binary fashion: "ore" for responses above a previously determined cutoff value. The implementation of borehole logging for ore boundary delineation need not be expensive or complicated: the system used at Stobie can be carried by one person, and the original purchase price of the conductivity probes was Cdn $6000.

Ore boundaries can be defined within centimetres down-hole with geophysical logging, but the achievable 3-D positional accuracy, hence the geometrical validity of any model, will be governed by the exactitude of the logging depths and the quality of the borehole trajectory data. Killeen *et al.* (1995) have reviewed borehole survey technology.

High resolution geophysical imaging is used for remote ore boundary definition. Radar has been applied in underground tunnels in the Witwatersrand to map pyritic auriferous reefs at ranges up to 30 m (Campbell, 1994). Detailed geophysical ore delineation from underground development is especially attractive for deeper reefs, given that its position is under-sampled for any affordable surface drill hole spacing.

Dyer and Fawcett (1994) describe an application of seismic tomography for exploration and delineation of chromite pods at Shurugwi, Zimbabwe. Shooting detonators from mine drives, their survey successfully defined a pod, outlined previously from drilling, as a high velocity zone and also highlighted a low velocity talcose block in the talc-carbonate host. Tomographic definition was achieved for 30% of the funds and in 9% of the time expended for conventional drill definition. While this comparison takes no account of the importance of the grade information provided by the drilling, it nonetheless serves to establish the viability of seismic tomography for exploration and delineation from drifts.

Ore continuity

Recognition of ore disruptions, due to pinch-outs, fault displacements, or intrusives, is vital for mine planning.

In sedimentary environments, faulting can sometimes be inferred from hole-to-hole stratigraphic correlation based on geophysical logs. Kerr *et al.* (1994) demonstrate the use of natural gamma logs for interpretation of faulting and the development of a structural model for iron ore in the Pilbara, Western Australia.

Establishing continuity of ore lenses can be crucial during both delineation and production phases. For conductive ores in resistive

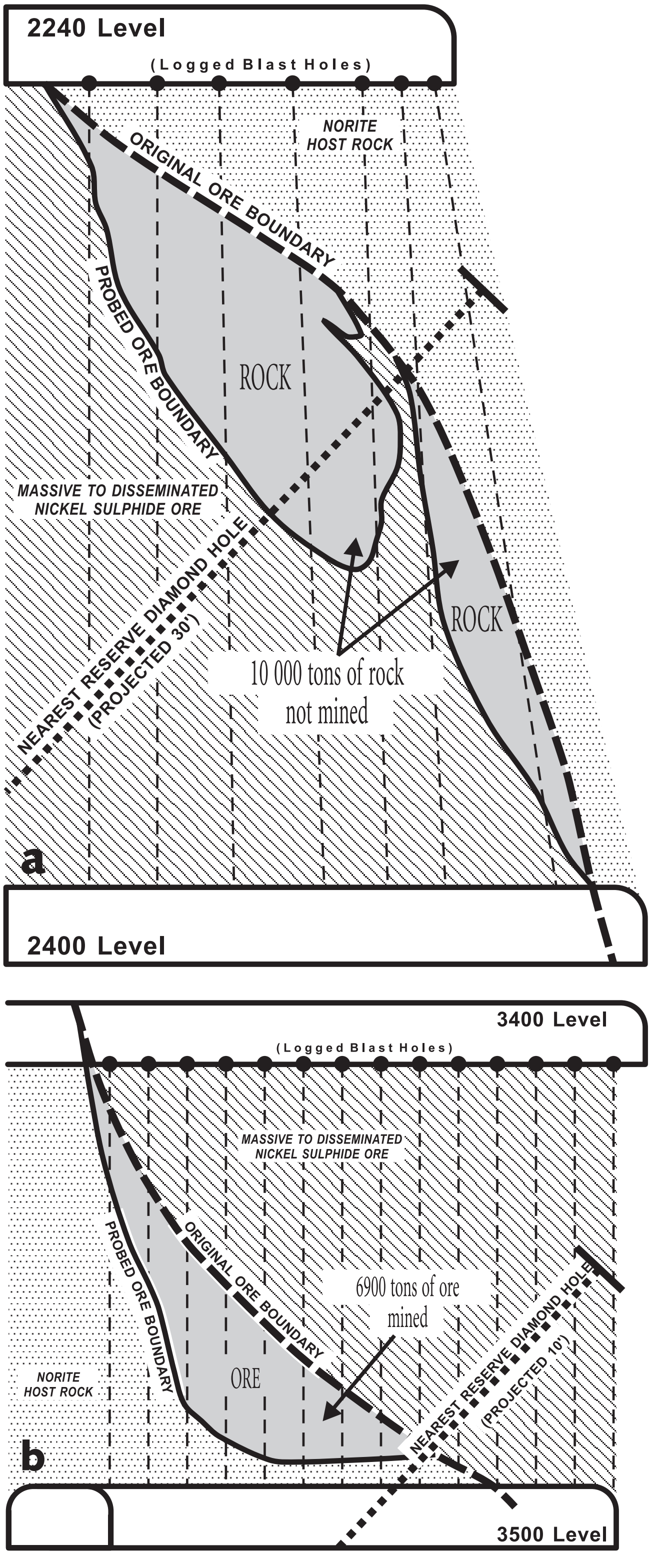

Figure 2: *Refinement of ore boundaries based on conductivity logging in vertical retreat mining stopes at Stobie Mine, Sudbury, has proved effective prior to charging for (**a**) minimising ore dilution and (**b**) enhancing ore recovery (after King et al., 1994).*

hosts, electrical methods may provide a straightforward indication of continuity. In 1982 WMC employed mise-a-la-masse to establish continuity of nickel shoots at Blair, Western Australia (Williams, 1996). More recently, Inco applied a crosshole resistance technique in the footwall at Levack (North Range, Sudbury) to test the continuity and establish the plunge of nickel-copper lenses (A. King, pers. comm.).

The deeper the ore, the stronger the case for all-of-mine imaging, given the prohibitive cost of closely spaced drilling. 3-D seismic techniques pioneered by the petroleum industry have been employed to generate structural models of auriferous reefs in the Witwatersrand (Campbell, 1994). Confidence in the seismic-based model at South Deep is such that it is used as the basis for siting mine pillars. South Deep is the first major deep Witwatersrand gold ore body to benefit from 3-D seismic, and the technique is readily transferable to other seam or reef type mines.

Radio frequency tomography has been successfully applied to nickel-sulphide ore boundary definition at Sudbury (Fullagar *et al.*, 1996a) and to detect copper ore lenses missed by 40 m-spaced evaluation drilling at the CSA Mine, Cobar, New South Wales (Thomson *et al.*, 1996). In both of these cases the host lithology is very resistive and the ore is highly conductive, providing an optimal geoelectrical environment.

More generally, metalliferous environments include zones of both economic and non-economic sulphides which may or may not have consistent spatial relationships. This is epitomised at George Fisher Mine, Queensland, where the polymetallic zinc/lead ore occurs with pyrite and pyrrhotite gangue as a series of stratiform massive sulphide lenses hosted by shale (Forrestal, 1990). Radio tomography at a frequency of 50 kHz clearly outlines the massive sulphide mineralisation, but the ore boundary is less certain (Figure 3).

Towards geophysical grade estimation

When correlated with geochemical assays, rock properties can sometimes provide a basis for grade estimation. Petrophysical grade estimation via automated interpretation of geophysical logs offers attractive benefits:

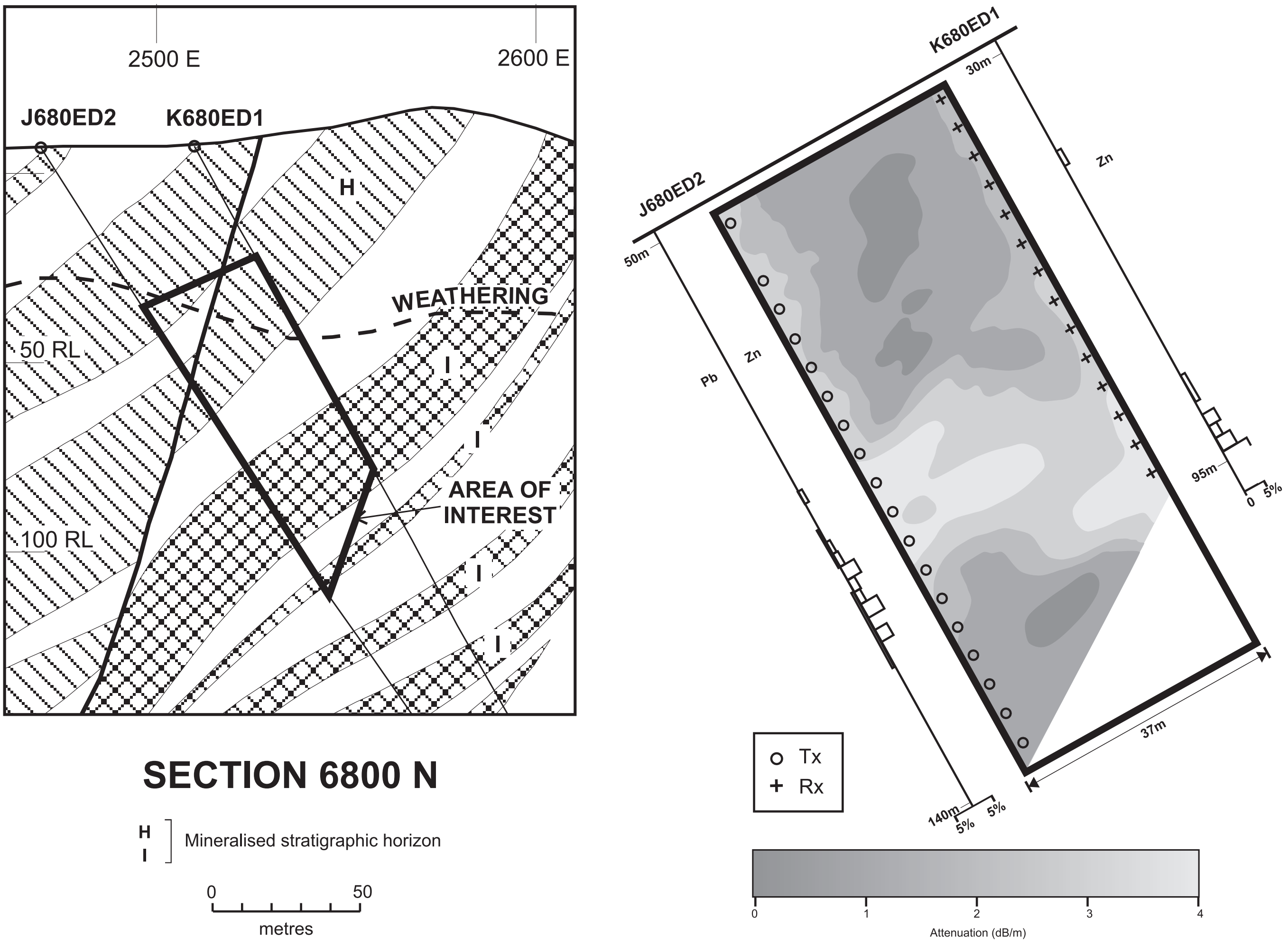

Figure 3: *Radio frequency attenuation tomogram (50 kHz) defining continuity of zinc-lead sulphide I Lens between holes at George Fisher Mine, Mt. Isa, Australia. H Lens is transparent to radio frequencies at this location due to poorly developed mineralisation and variable weathering (per favour MIM).*

1. reduced reliance on core drilling;
2. lower core handling and assaying costs;
3. shorter turn-around times.

Given the inherent sampling problems with percussion and reverse circulation drilling, and hence the poor reliability of chip and sludge assay results, the amount of core delineation drilling which can be foregone (in favour of more economical drilling plus geophysical logging) expands considerably when grade can be reliably inferred from petrophysical logs.

For some ore types there is a close correlation between petrophysical properties and grade. Magnetic susceptibility is a well-known measure of iron grade in magnetite ore bodies (e.g., Virkkunen and Hattula, 1992) and natural gamma activity is an effective indicator of uranium grade (e.g., Conaway and Killeen, 1978). Conductivity correlates closely with grade for some base metal sulphide deposits, e.g. Enonkoski nickel deposit in Finland (Figure 4). Spectral gamma-gamma (e.g., Killeen and Schock, 1991) and neutron activation (e.g., Eisler *et al.*, 1977; Borsaru *et al.*, 1994) are also of potential value for grade estimation. However, there are practical problems restricting wider implementation, not the least being the general reluctance displayed by some companies to deploy radioactive source probes, for safety and logistical reasons.

For virtually all gold deposits and many base metal deposits, the abundance of the target commodity and/or the petrophysical contrast of its host mineral is insufficient to permit grade estimation by direct detection. However, in some cases a strong mineralogical association exists between ore and a mineral which is readily detectable. In some Witwatersrand Basin mines, for example, a correlation between uranium content and gold grade permits prediction of gold grades using natural gamma in logging or face scanning modes (Campbell, 1994). In other cases grade estimates are based on multiple parameters, e.g. copper grade at an oxide deposit in Arizona is estimated from a linear combination of density (gamma-gamma), natural gamma, and neutron activation log values (Nelson and Johnston, 1994).

In order to define the correlation between petrophysics and grade, a control study must be undertaken. Since petrophysical data is normally recorded at intervals of a few centimetres, it is necessary to derive a petrophysical value representative of the coarser (1–2 m) geochemical sampling interval, a process termed *upscaling* in the petroleum literature (e.g., Yang *et al.* 1994). Simple averaging will not always be appropriate, e.g. if the petrophysical parameter is related non-linearly to grade.

If rules relating petrophyiscal responses to grade can be codified, automatic grade estimation is achievable using a variety of techniques, including multi-variate statistics (e.g., Emilsson, 1993) and neural networks (e.g., McCreary and Wanstedt, 1995). The assumption underlying automated interpretation is that the relationships between petrophysics and grade established in control holes are valid for other holes some distance away. Often it will be necessary to invoke different control data sets in different sections of a mine.

The chemical and spatial resolution of petrophysical grade estimation need not be high in order to be useful. For example, within the ore intervals it may be possible to reliably distinguish high grade from low grade zones on the basis of logs, without necessarily providing accurate geochemical abundance estimates within those zones. At Outokumpu's Tara lead-zinc mine in Ireland, for example, gamma-gamma logging of in-fill percussion delineation holes is used not only to refine contact geometry, but also to rank the grade of ore blocks within individual stopes (J. Ashton, pers. comm.). The combined zinc+lead grade estimates derived from geophysical logs at Tara are in fact fairly reliable, but are not used for ore reserve calculations. Similarly at the Kemi chromite mine in Finland, Outokumpu performs gamma-gamma logging in all production holes for ore sorting and grade estimation (J. Lehto, pers. comm.).

The instrumental requirements and acquisition procedures for grade estimation, or any quantitative interpretation, are more stringent than for qualitative ore boundary delineation. Regular multipoint precision checking of the probe over a wide dynamic range is essential to guarantee consistent results. Likewise, acquisition procedures must be

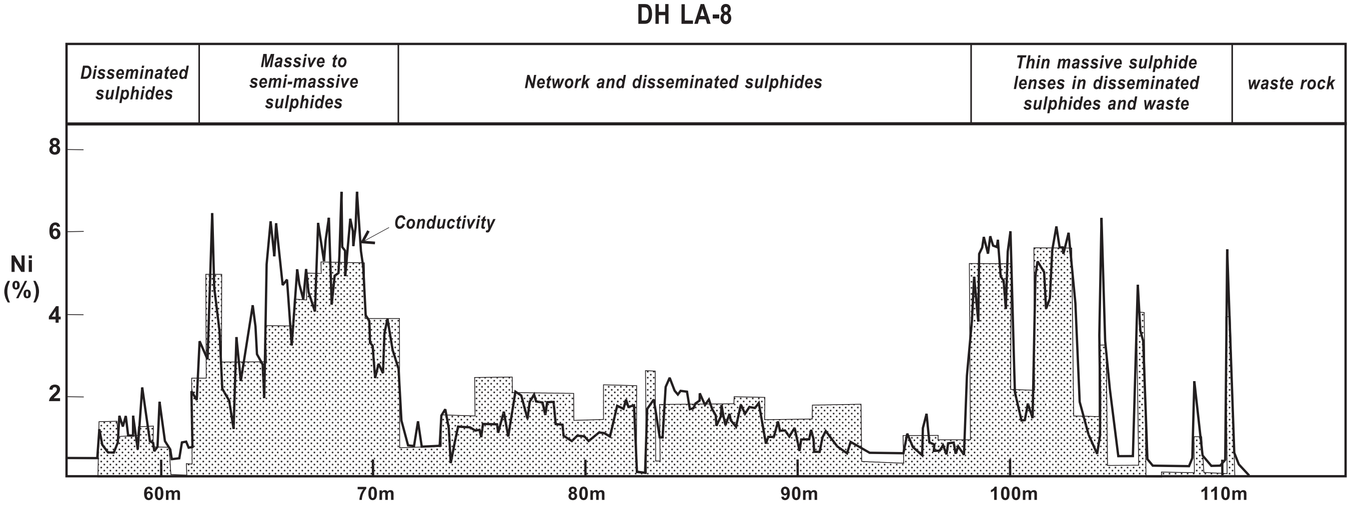

Figure 4: *Nickel grade (stippled) superimposed on OMSLOGG conductivity log from Enonkoski Mine, Finland, revealing a close correlation (after Hattula, 1992).*

devised to minimise the effects of borehole environment variations, e.g. moisture characteristics, temperature, and pressure.

Grades estimated from petrophysics are rarely if ever accepted as a basis for ore reserve estimation, even in mines such as Laisvall (Sweden) where the correlation between density and lead grade is well established. However, the validity of petrophysical grade estimates for modelling should not be judged purely in terms of geochemical accuracy because the sampling volume or *support* (per unit length of drill hole) associated with borehole logs is approximately two orders of magnitude greater than the volume of core. It is possible, therefore, that ore reserve models based on geophysical logs could be superior to assay-based models in some cases.

ROCK MASS CHARACTERISATION

Introduction

The strength and integrity of the rock mass is fundamentally important in mine design and blasting optimisation. Geophysics is poised to enhance mine economics and safety by providing the input data for more detailed and complete geomechanical models on which to base crucial mine design decisions.

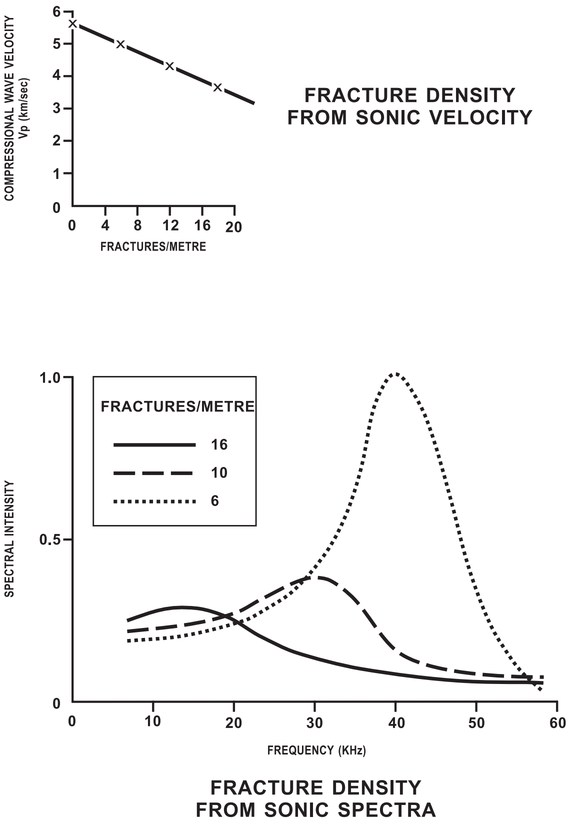

Figure 5: *Sensitivity of acoustic parameters to variations in fracture frequency in a pegmatite: compressional velocity (top) and full waveform sonic spectra (after King et al., 1978). Velocity decreases and high frequencies are more strongly absorbed as fracture density increases.*

Sonic logging is the premier geophysical 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 velocity can be related to mechanical parameters such as hardness and uniaxial compressive strength (UCS) (e.g., McNally, 1990, Ohkubo and Terasaki, 1977). The effect of an increase in the number of fractures per unit length on the compressional velocity has been documented by King *et al.* (1978) (Figure 5). Seismic attenuation is more pronounced in fractured rock, especially at high frequencies, as witnessed by the variations in full waveform sonic spectra with changing fracture frequency (Figure 5).

Sonic logging has distinct advantages over testing individual core samples insofar as it provides a continuous record of rock character in situ. At the very least, sonic logs can be used to optimise core sample selection for testing and hence calibration. Ideally, the sample suite should fully and evenly span the strength range for each rock type. Properly calibrated, sonic velocity data can provide rock strength information in weak zones, which are not amenable to core testing due to core fragmentation and loss. Thus sonic logging offers a means for overcoming sample selection bias which is difficult to avoid in conventional core testing.

Full waveform sonic logs allow determination of the shear wave velocity, V_s, in addition to the usual compressional velocity, V_p. Alternatively, the shear wave velocity can sometimes be estimated from the compressional velocity and the density of the rock (Entwisle and McCann, 1990). The dynamic elastic moduli and Poisson's ratio can be calculated from V_p, V_s, and density (e.g., McCann and Entwisle, 1992). Figure 6 shows logs of shear, bulk, and Young's moduli derived from sonic and density logs for a hole passing through the Ventersdorp contact reef (VCR) in the South Deep gold mine, South Africa (Campbell, 1994). The talcose Westonaria (lava) which directly overlies the VCR is a relatively soft, weak rock, in contrast to the competent Witwatersrand quartzites in the footwall. There are significant variations in rock engineering properties on a fine scale within the rock units, probably due to local fracturing.

The dynamic and static elastic moduli are almost equal for high strength rocks, but for weaker rocks large differences can arise if the high strains (approximately 10^{-3}) imposed during testing cause permanent deformation (McCann and Entwisle, 1992). Thus it may not be appropriate to simply interchange dynamic moduli for static moduli in rock mechanics modelling programs.

Sonic and density logging are by no means the only geophysical options for rock mass characterisation. Dipmeter logs, for example, can indicate joint and fracture orientation as well as intensity. For highly detailed structural analysis, increasingly sophisticated acoustic televiewers and borehole scanners are becoming available (e.g., Elkington, 1996). Single-hole reflection radar is effective for extrapolation of structures beyond the hole in resistive environments (Olsson *et al.*, 1992).

Blasting optimisation

Major savings have been realised in the past in open pit operations using seismic refraction to define velocity and hence indicate blastability. Heinen and Dimock (1976) determined the relationship between velocity and powder factors at the Ely open pit mine in Nevada. They estimated that a 17% reduction in drilling and blasting costs was obtained by exploiting the seismic information. The capital outlay and operating costs were insignificant in comparison with the cost reductions.

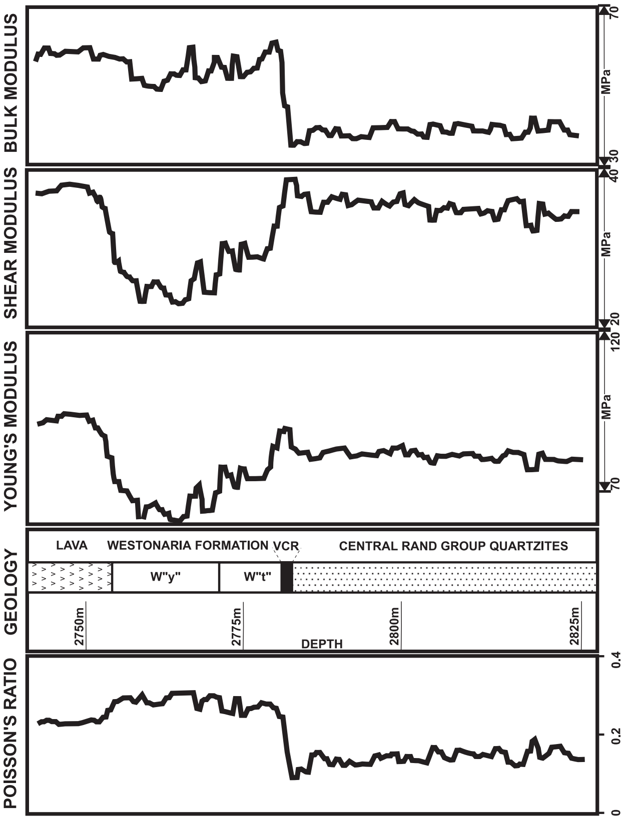

Figure 6: *Dynamic elastic constants derived from sonic and density logs, Witwatersrand Basin, South Africa. Fine scale variations in rock strength are evident within the weak Westonaria formation, the hanging-wall to the Ventersdorp Contact Reef (after Campbell, 1994).*

Hazard detection

Seismic velocity increases with an increase in in situ stress. In order to minimise safety risks posed by rock burst and/or collapse events, seismic monitoring equipment has been installed in many coal and metalliferous mines, e.g. Maxwell and Young (1993). While it is not usually possible to predict individual failures, zones of high risk can be defined. In addition, microseismic monitoring contributes to overall understanding of the mechanisms for rock failure.

Ground penetrating radar has been deployed at a number of mine sites for detection of cavities, e.g. for timely identification of historic mine workings beneath new open pit mines at Kalgoorlie (Williams, 1996). At Inco's Stobie Mine, GPR recorded in drifts, mapped the surface of an ore pass which was advancing due to erosion of wall rocks (Fullagar and Livelybrooks, 1994). The inferred range to the ore-pass at closest approach indicated that the wall had eroded 15 feet beyond its expected position.

The presence of fracture aquifers can be revealed as zones of anomalously high conductivity and/or dielectric constant in otherwise resistive formations. In the Witwatersrand, radar is recorded in development tunnels to map potentially hazardous water-filled fracture zones (Campbell, 1994).

EMERGENT TECHNOLOGIES

Measurement-while-drilling (MWD)

Currently geophysical logging is performed after drilling is complete. This represents a serious limitation when re-entry is denied, e.g. due to a blockage. Logging after drilling is also logistically unattractive, involving as it does mobilisation of personnel and equipment to the drill holes. To overcome these difficulties, and to shorten the time between drilling and interpretation, there is a strong incentive to collect data during drilling.

Measurement-while-drilling (MWD) technology was originally developed to monitor drill performance, in order to optimise production and to schedule maintenance. However, MWD is also a source of geomechanical information.

The relationship between penetration rate and rock strength is not always straightforward since other factors are involved, e.g. penetration rate normally decreases as drilling proceeds in any given hole. In practice the determination of rock strength involves statistical analysis of a number of drill performance parameters (Schunnesson, 1990a). The statistical basis for interpretation must be developed during a prior control study.

If ore is mechanically distinct from its host, MWD can be used to define ore boundaries. At Zinkgruvan, MWD consistently defined the contact of the softer sulphidic ore zone to approximately 5 cm accuracy (Schunnesson, 1990b).

Currently, the major limitation in the application of computer modelling to blast planning and optimisation is the lack of adequate physical property measurements. Unlike sonic logging, MWD is not restricted to water-filled holes. Blastability inferred from drill performance monitoring could facilitate optimisation of blasting patterns within sections of each bench, potentially delivering cost-benefits of millions of dollars per year for a modest small capital outlay.

Logging-while-drilling (LWD)

Drill performance is not sensitive to all rock properties, neither is interpretation of MWD data always unambiguous. There is therefore a need for logging-while-drilling (LWD) technology, to record petrophysical data during drilling. LWD is available for a range of parameters in petroleum wells (e.g., McDonald and Ward, 1976, Allen *et al.*, 1989), but only for hole declination and inclination in slimline holes.

Automated log interpretation

One of the advantages of borehole logging is that it is amenable to automated interpretation, in real time if necessary. Thus detailed lithological, geochemical, and geotechnical information can be rapidly derived from logs rather than via labour-intensive, time-consuming analyses of core. Auto-interpretation of LWD data opens the way for real time updating of the mine model.

Automated interpretation of petrophysical logs is commonplace in the petroleum context (e.g., Baldwin *et al.*, 1990; Coudert *et al.*, 1994) and has been addressed in hardrock environments in a number of recent studies, e.g. Urbancic and Bailey (1988), Wanstedt (1992), Emilsson (1993), Nilsson (1995), McCreary and Wanstedt (1995), Fullagar *et al.* (1996b). These authors explored a range of techniques, including application of simple "if" tests based on scatter plots, principal component analysis, factor analysis, discriminant analysis, neural networks, and cluster analysis.

The most crucial phase of log interpretation is selection and pre-processing of petrophysical parameters. Parameters used for interpretation can be functions of the original parameters. The permutations and combinations are endless if several logs have been recorded. However, geological insight can provide powerful guidance. A quotient between natural gamma and density was devised to highlight ore zones at Zinkgruvan, for example (Wanstedt, 1993).

Integrated geological and geophysical modelling

In grass roots exploration, geophysical imaging techniques are invoked for mapping and for ore body detection on a coarse scale. Quantitative interpretation of geophysical data is usually couched in terms of simple geometric bodies such as plates and prisms, both for reasons of numerical expediency and because the details of the local geology are neither known nor of paramount importance. In mining applications, on the other hand, the geological context is usually very well defined. The existing geological mine model is therefore the starting point for the interpretation of the geophysical data.

Integration of borehole logging data into the mine model does not pose any fundamental difficulties to existing mining software, given that the data is drillhole-based and the interpretation is statistical in nature. Few mine modelling packages include software for editing and automated interpretation of borehole logs, however.

Existing mining and geophysical modelling software is far less well adapted for interpretation geophysical imaging data, which entails exchange of two- and three-dimensional information. Kowalczyk *et al.* (1996) have illustrated the way forward by inputting mine models into magnetic modelling software to model borehole magnetic data. A greater ability to capture and manipulate geological interpretations for geophysical modelling will also expedite survey design and interpretation in exploration.

CONCLUSION

Thoughtfully applied, geophysics can significantly enhance the economic, safety, and environmental performance of metalliferous mines. Fundamentally, the benefit of geophysics flows from risk reduction, via more complete characterisation of the ore body and its geomechanical setting. Usage of geophysics at mines will continue to expand during the next ten years as mining companies respond to increasing commercial, moral, and statutory pressures, and as emerging technologies mature.

Borehole logging is a mature technique which could be cost-effective if utilised for one or more applications at virtually all metalliferous mines. The most common economic rationale for logging is that it permits substitution of some core drilling with cheaper percussion drilling. The existing equipment is reasonably satisfactory and affordable, and can be operated by mine personnel. Interpretational aids are in a relatively advanced state. Requirements for successful implementation of borehole logging are a commitment from mine management, a local champion, and adherence to acquisition procedures which ensure high quality data.

Borehole EM is employed at a number of mines for in-mine exploration and ground sterilisation, but high resolution geophysical imaging is still at a fairly early stage of evolution at metalliferous mines. The application of three-dimensional seismic in stratiform environments, e.g. Witwatersrand, is an exception, building as it does on established petroleum industry practice. Whereas technical staff at mines are able to collect logging data, erratic demand and sophistication of the equipment will decree that imaging surveys are performed by contractors in the main. Likewise, processing and interpretation often demands high levels of skill, not least because the requisite software often does not exist. Lack of integrated mine modelling and geophysical modelling software represents a significant impediment to wider use of imaging.

The future of mining geophysics lies very much with its closer integration with drilling. Fundamentally, MWD and LWD technology guarantees access to drill holes for the sensors. In addition it reduces the movements of equipment and personnel, and compresses the time scales, required for collection and interpretation of drill-hole data. MWD technology is already available for slimline drill rigs but slimline LWD is limited to down-hole surveying at present.

The rate of acceptance of geophysics at mines is governed by, amongst other things, company culture. While in-mine geophysics is rapidly gaining credibility in some companies, it has no profile in others. We hope that this paper will go some way towards heightening the awareness of in-mine geophysics. Once aware, mine management must also be convinced that the up-front costs of implementing geophysics, in terms of dollars and management effort, are justified in terms of the performance benefits which ensue. The implementation of geophysics must be tailored at each mine, to deliver the correct information in the appropriate form at the opportune time for the right price.

We can glimpse a different future, in which automated drills and mining machines seek and extract ore using geophysical senses, in which risks to personal safety and corporate capital are minimised, and in which the balance between ore recovery and dilution is optimised with respect to economic and environmental criteria. Appropriately applied, geophysics is very much a part of this Brave New World of high baud rate, low risk mining.

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