THE APPLICATION OF GEOPHYSICS DURING EVALUATION OF THE CENTURY ZINC DEPOSIT

Mutton, A.J.[1]

---

1. RTZ-CRA, Australia, Spring Hill, Queensland, Australia

ABSTRACT

RTZ-CRA Group companies in Australia have undertaken experimental programs using high resolution geophysics at several operating mines and advanced evaluation projects in the last five years. The primary aim of this work has been to investigate the application of geophysical technology to improving the precision and economics of the ore evaluation and extraction processes. Geophysical methods used for this purpose include:

- *borehole geophysical logging to more accurately characterise ore and rock properties for improved correlations between drillholes, quantification of resource quality and geotechnical information;*
- *imaging techniques between drillholes to directly map structure or locate geotechnical problems ahead of mining;*
- *high resolution surface methods to map ore contacts and variations in ore quality, or for geotechnical requirements.*

The use of geophysics during evaluation of the Century zinc deposit in northern Australia demonstrates the potential value of these methods to the problems of defining the lateral and vertical extent of ore, quantitative density determination, prediction of structure between drillholes, and geotechnical characterisation of the deposit. An analysis of the potential benefit of using a combination of borehole geophysical logging and imaging suggests that a more precise structural evaluation of the deposit could be achieved at a cost of several million dollars less than the conventional evaluation approach based on analysis from diamond drillhole logging and interpolation alone.

The use of geophysics for the Century evaluation has also provided substance to the possibility of using systematic geophysical logging of blast holes as an integral part of the ore extraction process. Preliminary tests indicate that ore boundaries can be determined to a resolution of several centimetres, and ore grade can be directly estimated to a useable accuracy. Applying this approach routinely to production blastholes would yield potential benefits of millions of dollars annually through improved timeliness and accuracy of ore boundary and quality data, decreased dilution, and improved mill performance.

Although the indications of substantial benefits resulting from the appropriate and timely use of geophysics at Century and other RTZ-CRA Australian mining operations are positive, some barriers remain. These largely relate to acceptance by the mine operators and the integration of the technology with the mining process. Some effort by mine management will be required to address these issues before the use of geophysics will be accepted as a routine component of evaluation and mining.

INTRODUCTION

Geophysics has primarily been used by the metalliferous mining industry as a tool for exploration. By contrast, the petroleum and coal industries have exploited geophysics to a far greater extent in terms of using the data to quantify the value, size, or production capabilities of their resource. In general, the application of geophysics to mineral deposit evaluation and mining is not well developed. Some possible reasons are:

- little knowledge by the mining managers, engineers, and operators of the existence of geophysical methodologies, coupled with a "high tech–high cost" perception of geophysics;
- perceived infrastructure and logistical difficulties in using geophysics in a working mine environment;
- lack of knowledge of the physical properties of the ore and host rocks which may be exploitable in a mining environment;

In "Proceedings of Exploration 97: Fourth Decennial International Conference on Mineral Exploration" *edited by* A.G. Gubins, 1997, p. 599–614

- limited research effort applied to standard geophysical methods to develop higher resolution acquisition or interpretation tools applicable to mining applications, rather than tools applicable to exploration;
- lack of geophysicists with access to mine problems, or with sufficient knowledge of mining 'culture' or operational requirements, to champion the use of geophysics in this area.

CRA in the last few years has undertaken to investigate opportunities to develop and test geophysical applications directly related to resource definition and mining problems. Using some examples of results obtained during the evaluation by CRA of the Century zinc deposit in northern Australia, this paper describes the opportunities available, and the rationale for applying geophysics beyond the exploration stage of mineral development.

WORK UNDERTAKEN

A range of geophysical surveys, some conventional and some adapted for specific problems, have been trialed in recent years at several CRA evaluation projects and mining operations for the purpose of enhancing ore boundary definition and recoveries. The surveys fall into several categories, including:

- high resolution surface surveys to 'remotely' map the lateral and vertical limits of ore or other geotechnical parameters required for mine design. Successful application of such methods can potentially reduce the number of closely spaced expensive drillholes generally needed for these requirements, and also enables improved reserve calculations and mine design. Examples of such work incorporate the use of standard methods such as magnetics, electromagnetics (EM) and IP/resistivity utilising improved modelling and data enhancements, or 'new generation' methods such as borehole EM imaging and ground penetrating radar (GPR);
- geophysical logging of evaluation drillholes to quantify mineralogical, geotechnical and structural parameters of ore and host rocks *in situ*. Many of the standard suite of petroleum logging tools, such as density, sonic and dipmeter, have been successfully adapted to the hard-rock environment, along with developments in new tool technology such as magnetic susceptibility and conductivity. Improved confidence and demonstrated success with this approach is aimed mainly at providing significant cost savings by the future routine use of non-core rather than core drilling;
- inter-borehole imaging methods using electromagnetic or seismic sources. Examples of such methods include radio-imaging (RIM) surveys between holes to map ore continuity and structure. The use of these methods is designed to improve the knowledge and reliability of the ore boundaries at an earlier stage of evaluation, which in turn should reduce the time and cost of the evaluation process;
- geophysical logging of blast holes to define ore-waste contacts to a resolution of a few centimetres, and in some cases to directly estimate ore grade. Applying this approach routinely to production blast holes is designed to yield substantial cost benefits through improved timeliness and accuracy of resource information, less dilution, and improved mill performance.

Much of CRA's investigation of the use of geophysics for mining and mine evaluation has to date been carried out at the site of the Century zinc deposit in northern Australia, discovered by CRA Exploration in 1990. The discussion and examples presented below will focus on the work at Century, and the role that geophysics has played through the various phases of evaluation of the deposit and proposed development of a large open-pit mine.

RESOURCE DEFINITION GEOPHYSICS AT THE CENTURY ZINC DEPOSIT

Geology

The Century Zn-Pb-Ag deposit is located about 250 kilometres north-north-west of Mount Isa, Queensland. Substantial drilling (about 500 diamond core holes) from 1990 to 1995 has outlined a geological resource containing about 120 million tonnes of 10.5% zinc, 1.5% lead, and 35 g/t silver.

The Century deposit occurs within sediments of the Proterozoic Mount Isa Inlier, and is locally unconformably overlain by Cambrian rocks comprising dolomitic limestone, chert and chert breccia (Figure 1). The deposit is hosted by dolomitic siltstones and carbonaceous shales. The mineralised sequence is about 40 m thick, and consists of four laterally continuous subdivisions (Units 1 to 4). The bulk of the mineralisation occurs as stratabound, banded sphalerite, galena, and pyrite within black carbonaceous shales of Units 2 and 4. A barren dolomitic siltstone

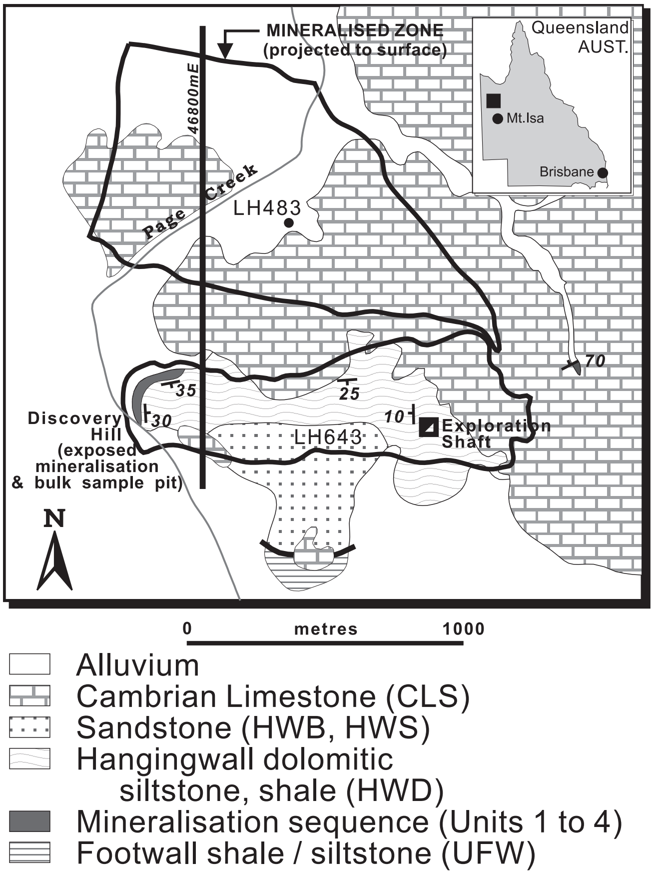


Figure 1: *Century deposit location and geology.*

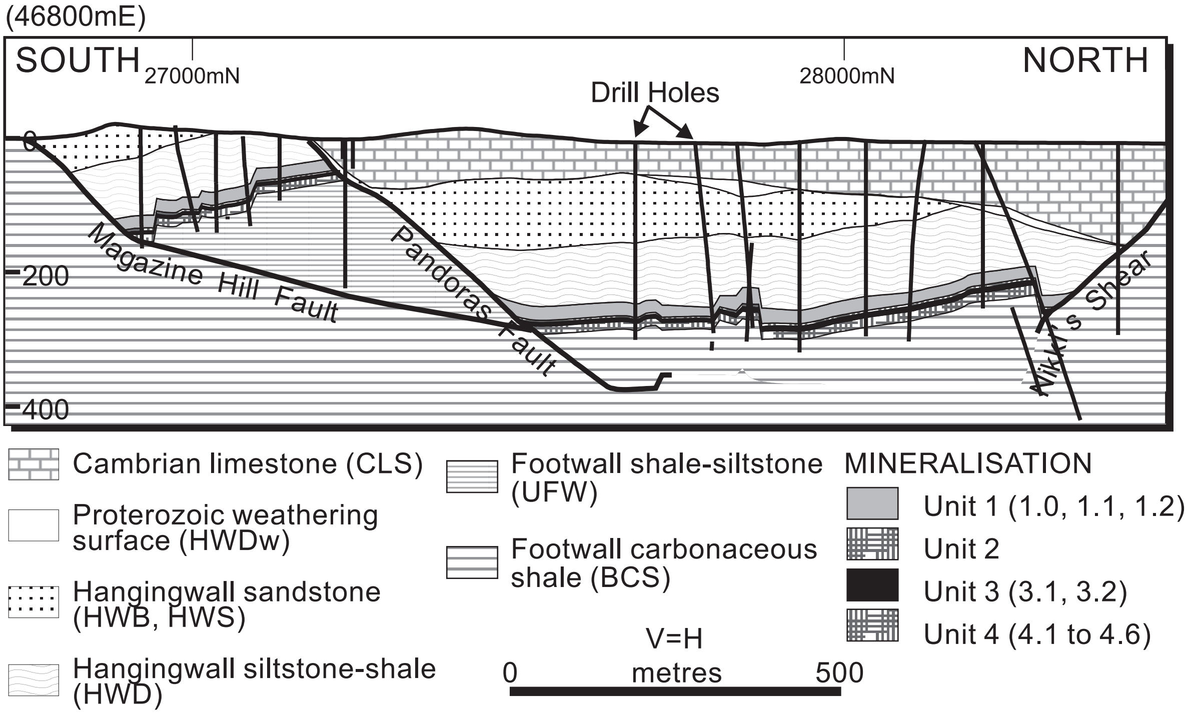


Figure 2: *Century deposit cross-section 46800E.*

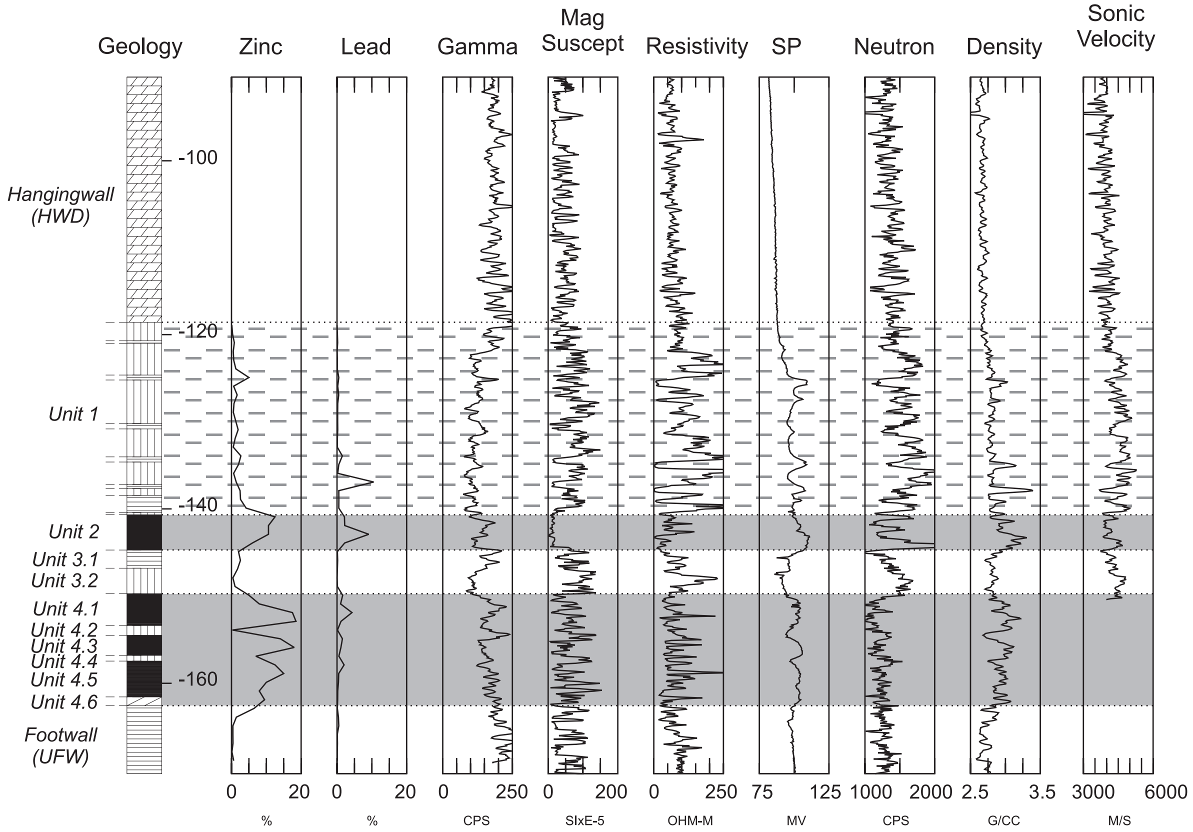


Figure 3: *Century deposit composite geophysical log.*

bed within Unit 3 represents a semi-continuous marker bed throughout much of the deposit. The mineralised sequence has excellent grade continuity but is disrupted by late faulting. A detailed description of the geology and mineralogy of the deposit is included in Waltho *et al.*, 1993.

Figure 2 shows a schematic north-south crosssection through the deposit. The deposit consists of a smaller, shallow southern block which subcrops in the southwestern margin of the ore body, and a larger, deeper northern block completely concealed beneath Cambrian limestone and recent alluvium. Bounding surfaces to the deposit comprise either post mineralisation faults or Cambrian and younger erosional surfaces.

Physical characteristics of the ore and host

Comprehensive laboratory petrophysical measurements on Century core have been made on several samples by CRA Exploration, and as part of an AMIRA research project (P436) investigating the application of geophysics in mine planning and mining (Fullagar *et al.*, 1996a). These have been evaluated in conjunction with extensive geophysical log data collected from a large proportion of the holes drilled. A typical composite geophysical log through the Century ore sequence and host rocks is presented in Figure 3.

These results show that the Century ore body is typical of many shale-hosted sulphide base metal deposits throughout the world. In particular, the ore is characterised by distinctive physical properties, including high density, low natural radioactivity, and low magnetic susceptibility.

The main difference is that the Century ore, consisting mainly of sphalerite with relatively low iron sulphide, is not very conductive and in parts is more resistive than barren host shales. However, petrophysical measurements on core and downhole IP surveys showed the ore has high electrical chargeability. Figure 4 is a statistical summary of the IP and resistivity response recorded in drillholes, clearly indicating how chargeable the ore units are compared with other lithologies.

The physical properties analysis also indicated diagnostic contrasts between some of the host lithologies. While not specifically useful for ore evaluation, this knowledge has helped address other problems arising during the project development. For example, the high resistivity of the Cambrian limestone has been exploited to assist with a hydrological problem associated with development of a large pit (see below).

Role of geophysics

The discovery of Century was based largely on testing of a zinc soil geochemical anomaly which was delineated on regional gravity, ground magnetic and soil sample traverses (Thomas *et al.*, 1992; Broadbent, 1996). No anomalous response was detected on the gravity or magnetic data, or on other geophysical surveys attempted prior to the discovery.

Despite the lack of success of geophysical techniques in the initial detection of ore, the recognition after the discovery of contrasts in the physical properties of the ore and host sediments provided some confidence that geophysical methods could have a role in further exploration and evaluation of the deposit. Geophysical surveys carried out over and within the Century deposit since its discovery have included:

- detailed ground and airborne surveys (gravity, magnetics, electromagnetics (EM), IP/resistivity, reflection seismic);
- borehole geophysical logging;
- inter-borehole geophysical imaging.

The work has resulted in some successes, in particular relating to:

- defining the overall lateral and vertical extent of mineralisation;
- mapping lithologic boundaries and structure within the deposit;
- provide data for ore reserve estimates and mine planning;
- support geotechnical studies for pit design, and;
- to aid ongoing exploration in the area.

Detailed surface surveys

Lateral and vertical extent of mineralisation

Following the initial discovery of zinc-rich, low sulphide mineralisation, and the knowledge that EM methods did not detect the mineralisation, it was believed by some that the IP method could provide a suitable means for mapping the extent of the mineralisation beneath the Cambrian cover. A limited number of IP/resistivity traverses were subsequently completed over the Century deposit and immediate environs, indicating the presence of a good IP anomaly approximately coincident with the mineralisation as known at that time (Thomas *et al.*, 1992). The source of the surface IP anomalies was subsequently confirmed by IP/resistivity logging of selected drillholes (Figure 4).

The downhole IP/resistivity surveys provided reassurance that IP anomalies represented good exploration targets. In fact, initial drilling into the deeper northern ore zone (Figure 2), which is completely masked by hundreds of metres of barren limestone and sediments, was essentially guided by the presence of the IP anomaly in this area. Although only a limited number of IP lines have been completed over the deposit, the information obtained has enhanced early exploration and confirmation by drilling of the lateral limits of mineralisation far sooner in the evaluation process than if IP surveying had not been attempted.

As well as mapping the lateral extent of the ore body, more recent work by CRA Exploration (Aravanis *et al.*, 1996) has demonstrated that it is now possible to transform the IP/resistivity data into an approximate depth "image" of the mineralisation (representing the vertical distribution of chargeable material). This work has utilised inversion algorithms developed by the Geophysical Inversion Facility group at the University of British Colombia (Oldenburg *et al.*, 1996). Figure 5 shows the image derived from unconstrained inversion of surface IP/resistivity

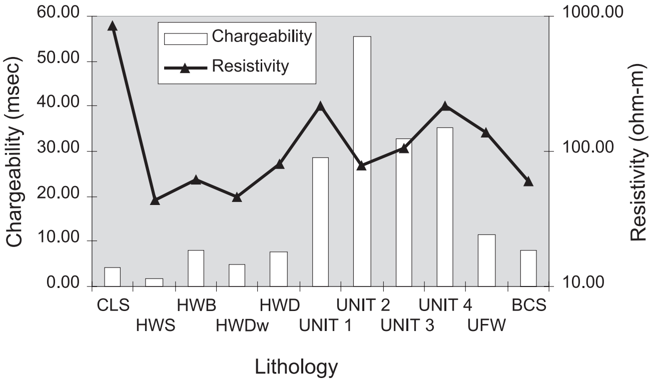


Figure 4: *Century downhole IP/resistivity statistical summary.*

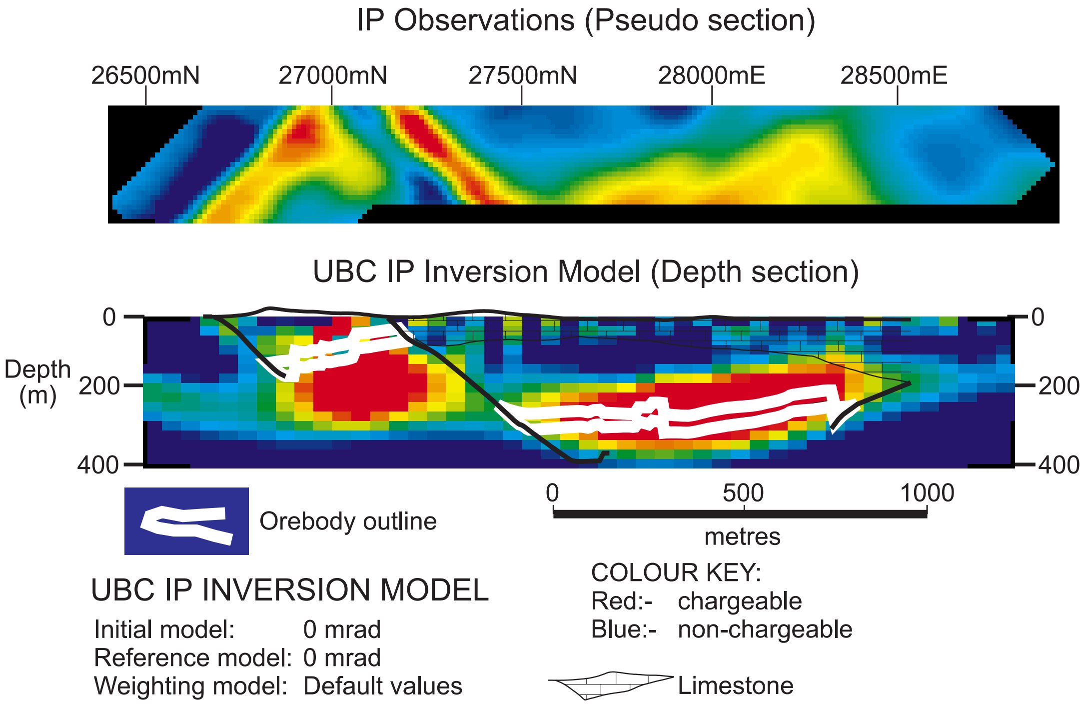


Figure 5: *Century deposit Line 46800E IP pseudo-section and inversion model compared with ore body location from drilling. IP data are from 100 m dipole-dipole frequency domain survey.*

data adjacent to the cross-section presented in Figure 2. The outline of the ore body derived from subsequent drilling is superimposed.

This work clearly demonstrates the potential mapping capabilities—both laterally and vertically—of a surface geophysical method for which the physical property contrasts have a close association with the mineralisation, defining the approximate extent of ore prior to extensive drilling. The image of the ore body, provides the explorer with improved capability for successful drill targeting, but also has the potential, by the application of constraints from initial drilling, to substantially define the ore boundaries and estimate reserves at a far earlier stage of the evaluation process than hitherto possible.

Geotechnical applications

Although the predominantly sphaleritic Century ore has little electrical conductivity contrast with the host sediments, surface electromagnetic methods have been successfully applied, based on the conductivity contrast between the Proterozoic sediments and overlying limestone (Figure 4), to assist geotechnical work associated with pit design. Two phases of Controlled Source Audio-Frequency Magnetotelluric (CSAMT) surveys were completed over the deposit in order to:

- locate large blocks of detached Proterozoic shale within the limestone, the shale presenting a geotechnical hazard for pit slope stability during initial excavation of the limestone portion of the proposed pit;
- determine the thickness of the surrounding water-saturated limestone in order to estimate the likely water flow into the open pit as it is excavated.

The CSAMT method was chosen in preference to conventional TEM methods due to logistical considerations associated with the limestone topography, and the belief that CSAMT is more sensitive than TEM methods to delineating contrasts in the more resistive lithologies present in the Century area.

The first work was only partially successful in that only very large blocks of shale—typically greater than 50 m cubed—could be delineated. The survey results did not offer sufficient resolution to confidently locate smaller blocks, but improved survey design may have provided better resolution.

The second phase of work proved useful in mapping the base of the limestone, and hence assisting with the hydrological study for the pit design. Figure 6 (after Mayers and Bourne, 1994) shows a plan of the resistivity model obtained from inversion of the CSAMT data, and collated at a vertical depth of 100 m. The intense blue represents the presence of resistive limestone at this depth, while the warmer colours indicate the presence of less resistive shale and siltstone.

The depth to the base of the limestone is shown in selected drillholes. In general, there is a good correlation between the intersected thickness of limestone and depths predicted from the CSAMT resistivity model. The results show that post-depositional faulting has led to large variations in the limestone thickness in the vicinity of Century, and importantly the limestone is "necked" to the north and east of the deposit. The CSAMT result thus gives some confidence that the total volume of water flow into a proposed pit will be significantly less due to the thinning of the water-saturated limestone than if the limestone had been uniformly thick to the north and east of Century.

Table 1: *Summary of qualitative log responses.*

	Cambrian limestone		Prot. sandstone (h/wall)		Prot. shale and siltstone (h/wall)		Ore zone		Prot. shale and siltstone (footwall)	
Natural Gamma (API cps)	very low	25	high	160	moderate	125	low–mod	70–150	high	200
Magnetic Susceptibility (SI x 10^{-5})	very low	<10	low	0–50	low-moderate	0 –100	v. low (ore)–mod (waste)	0–150	low–mod	50–150
Resistivity (ohm-m)	high	>1000	low	60	low	75	variable	50–200	low	80
Density (g/cc)	moderate	2.7	low	2.6	moderate	2.7	mod–high	2.8–3.0	moderate	2.6–2.7
Neutron (API cps)	high	1500	high	1600	moderate	1200	low	700–variable	moderate	1200
Sonic Velocity (m/s)	very high	5000–6000	moderate	4500	moderate	4000	mod–high	4000–5000	moderate	4000

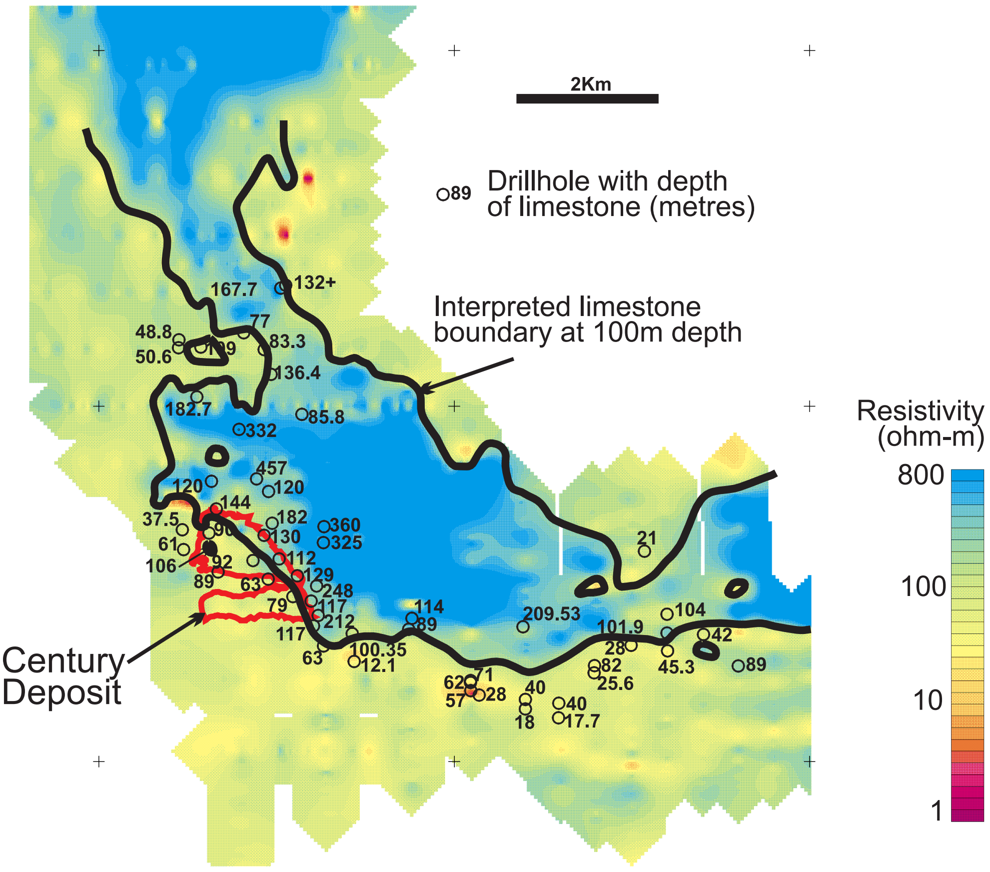


Figure 6: *Century deposit region showing smooth-model inversion of CSAMT resistivity at 100 m depth, compared with limestone depth from drilling. The more resistive areas (blue) represent limestone greater than 100 m thick.*

Geophysical logging

Although geophysics did not feature strongly in the initial discovery of ore, downhole geophysical "characterisation" logging was carried out at Century in several campaigns commencing soon after the initial drillholes were completed. The work was commissioned for several reasons:

- to assist geologists and geophysicists to gain a better understanding of the in situ physical properties of the deposit and its host rocks as an aid to interpretation of exploration and geotechnical data;
- to provide data to assist with the correlation of lithologies, and definition of the structure of the ore zones between drillholes;
- to provide quantitative in situ density information to assist with estimation of the ore reserves;
- to provide rock strength information to assist in the geotechnical assessment of the deposit by mining engineers.

The logging programs utilised standard suites of electrical and nuclear tools (resistivity, resistance, self potential (SP), natural gamma, density and neutron), as well as tools such as dipmeter, magnetic susceptibility, and sonic velocity which were not commonly used in base metal geophysical logging prior to that time.

Lithological correlations

Interpretation of the downhole logs indicate that the major lithologic units and the mineralised zones can be readily distinguished by their density, natural gamma, neutron, resistivity, sonic and magnetic susceptibility properties. Figure 3 shows a composite log of a typical drillhole through the Century deposit. Table 1 summarises the responses that characterise the main lithological units for each of the main log types.

The mineralised sequence (Units 1 to 4) is well differentiated by the density, natural gamma and magnetic susceptibility logs. The density contrast is attributed to the presence of sulphides and an increase in iron carbonate (siderite) content. The internal waste unit within the ore zone (Unit 3.2) is characterised by lower density and generally higher gamma, magnetic susceptibility and resistivity compared with the mineralised intervals.

Quantitative analysis

The quantitative analysis of the log data, which attempts to transform such data into useable physical or chemical quantities such as density, grade, rock strength, etc., is dependent on the equivalence of data from the different logging tools used at various times and by various contractors. Variations arise from differences in tool specifications, but also from "environmental" factors including borehole diameter, fluid content and properties, temperature, weathering, smoothness of the hole wall, etc.

Comparisons to a calibration standard, such as the API standard, are used by most logging contractors, but do not account for most of the environmental factors. For example, an inspection of different API standard calibrated natural gamma logs can show some marked offsets in absolute values recorded.

The most successful form of calibration achieved at Century has been the use of a "calibration" drillhole which was resurveyed at regular intervals during each logging program. Such action ensured that the repeatability of logs over a known interval could be compared and quantitatively adjusted by means of a correction factor if necessary.

Quantitative analyses which have been undertaken on the Century data have included automated lithological and grade prediction studies, but have primarily been aimed at determining in situ density and rock strength variations.

Automated lithological prediction

Experimental work designed to test the possibility of predicting lithology and grade directly from a combination of geophysical logs was carried out on selected geophysical logs from Century. Three approaches were attempted:

- artificial neural networks (ANN);
- linear regression and discriminant analysis;
- cluster analysis (lithology prediction only).

Some encouragement was obtained from the initial prediction tests, but it was clear that factors such as measurement uncertainty (calibration differences, depth discrepancies in the training sets, etc.) or the level of data "conditioning" (such as filtering) can have a large influence on the predictions. The results produced from the ANN tests were not sufficiently encouraging in either lithology or grade prediction to use this as a viable method at present.

On the other hand, reasonable predictions of lithology were obtained from the cluster analysis method using the LogTrans software developed as part of the AMIRA P436 project (Fullagar *et al.*, 1996a). Figure 7 shows an example of prediction of lithology at Century using this method. The prediction for the hole presented (LH643) is based on a statistical analysis of data from holes nearby. In effect, the prediction is unconstrained by the log results and geology from LH643. The results compare favourably with the mapped lithologies, even though part of the ore sequence in LH643 is missing due to faulting.

Improvements to and routine use of such software in the future could save considerably on the cost of manual logging of core, but the greatest savings would result from the use of percussion rather than core drilling for a large proportion of the drillholes. This approach would be applicable to a deposit such as Century in which the need for closely spaced drilling is more related to structural interpretation rather than grade control.

Density

The most extensive quantitative analysis of the Century log data has been done for the purpose of density determination for ore reserve estimation. Several independent methods were considered and tested in order to determine a suitable approach. The methods used included:

- Archimedes'-type measurements on whole core at site, or by a laboratory on core fragments submitted for geochemical analyses;
- laboratory measurement of density of pulverised and homogenised drill core samples by acetone titration;
- physical measurement (dimensions and weight) of whole drill core at site;
- stoichiometry, based on base metal and sulphur assay data;
- geophysical (gamma-gamma) logging of drillholes.

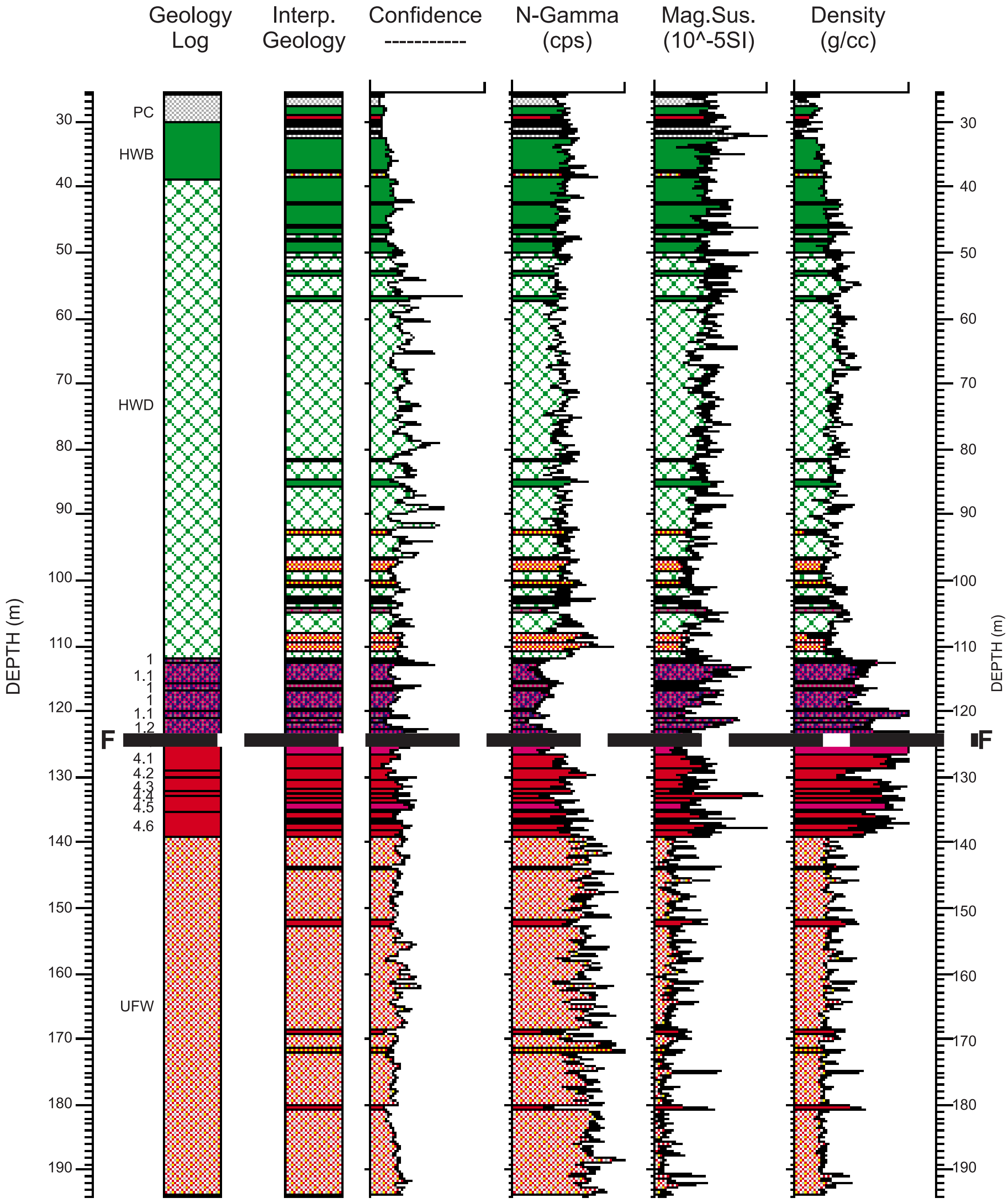


Figure 7: *Lithology-based LogTrans geologic interpretation of Century drillhole LH643 derived using statistics from nearby control drillholes. The interpretation has successfully predicted a normal fault across which part of the ore body is missing.*

Of these methods, geophysical logging is considered to provide the most consistent measure of bulk density, although physical measurement and stoichiometric calculations based on zinc, lead, iron, manganese and sulphur assay data also proved useful. The titration method proved to be the most unreliable, yielding many spurious values probably due to small variations in the measurement method.

All methods have limitations. For example, the chemical assay-based methods yield data restricted to the assay intervals only, while the physical measurement methods are more subject to measurement error arising from slight variations in the procedure. Geophysical logging yields very consistent results, but the conversion of the measured count-rate to a density value is subject to error due to differences of material contained

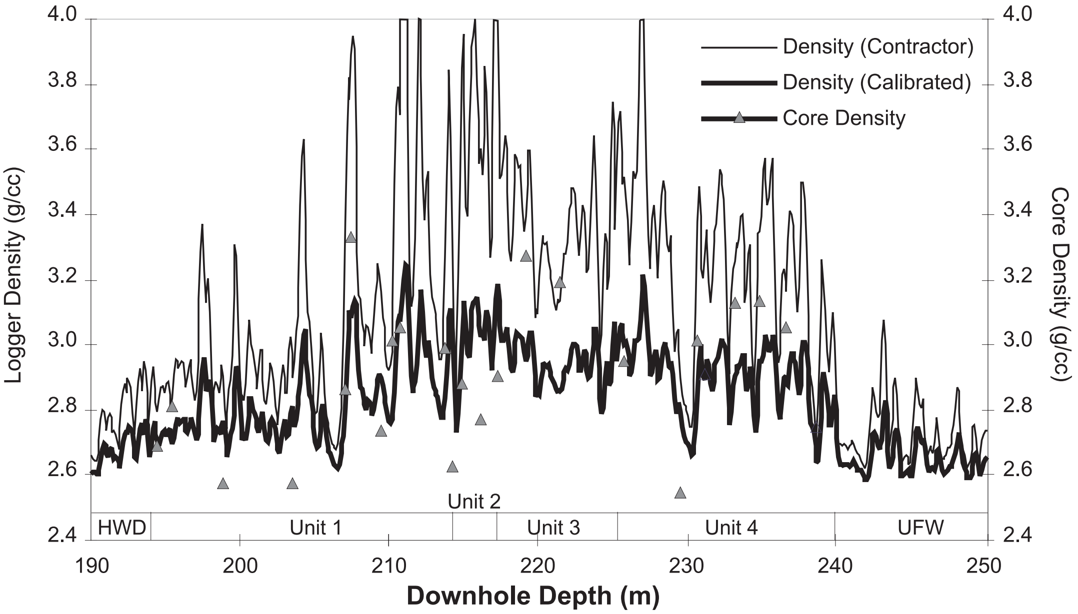


Figure 8: *Comparison of gamma-gamma log derived density (showing differences in calibration standards) and density measurements on core for Century drillhole LH483.*

within the volume of rock sampled by the logging tool compared with the smaller volume of rock in the core used as the reference value.

Calibration factors supplied by the logging contractor should be used with caution in hard-rock mining environments, as most of the calibration standards are devised for logging in lower density sedimentary environments hosting petroleum or coal deposits. Figure 8 shows the comparison between the contractor's derived density, and the recalculated density log using the calibration derived from the physical measurement of core. The result of using the former is a large overestimation of the ore density and therefore contained tonnes of ore.

The major advantages of using geophysical logging for density determination are:

- the data are available and consistent through the length of the drillhole rather than just over an assayed interval;
- data can be obtained for non-cored holes, reducing the requirement for cored holes. However, the non-cored holes must be well drilled so that the hole walls are reasonably smooth—caving and irregularities in the wall are the main sources of error with this method. Calliper data collected in conjunction with the density logs can be used to correct or exclude data affected in this manner.

The main limitation of density logging is the use of a strong radioactive source, and the possibility that such a source could become stuck in a drillhole, thus requiring some effort and expense to recover the source. For the work at Century, a procedure was implemented to only use the density tool after one or more successful runs with other non-radioactive tools. In this way the safety risk was considered manageable, and a high proportion of density logs from the available holes was achieved.

Rock strength

Measurement of the strength and fracturing characteristics of both the ore and the host rock (including the overlying shale, sandstone and carbonate) is essential for mine planning at Century, and has implications for pit design, blasting requirements, and milling of the ore. Initially a traditional approach to prediction and modelling of the rock strength variations within the deposit was taken, utilising standard procedures such as measurement of RQD (rock quality descriptor) on all core. These data were then compared with a number of test measurements of UCS and other strength parameters on selected pieces of core.

To assist with this problem, sonic velocity data acquired from a standard slimline sonic tool was investigated to determine if this information could provide more uniform and extensive information than reliance on RQD and limited core measurements. A study (Duplancic, 1996) was initiated as part of the AMIRA P436 research project to address this requirement. The focus of this specific study was to determine what is the relationship between rock strength (measured as UCS) and sonic velocity, measured both on core samples in the laboratory and in situ in the borehole.

Figure 9 shows a portion of a sonic velocity log from Century, with the laboratory velocity (P-wave measured at 1 MHz) and UCS measurements superimposed. The velocity data shows a reasonable correlation, but the correlation with UCS is poor. The analysis found that the relationship between velocity and rock strength is a function of the lithology and the rock porosity, more than the intrinsic variation in strength. Figure 10 demonstrates this relationship schematically, suggesting that it would not be feasible to predict UCS from the borehole velocity data without first accounting for the porosity and lithological variation.

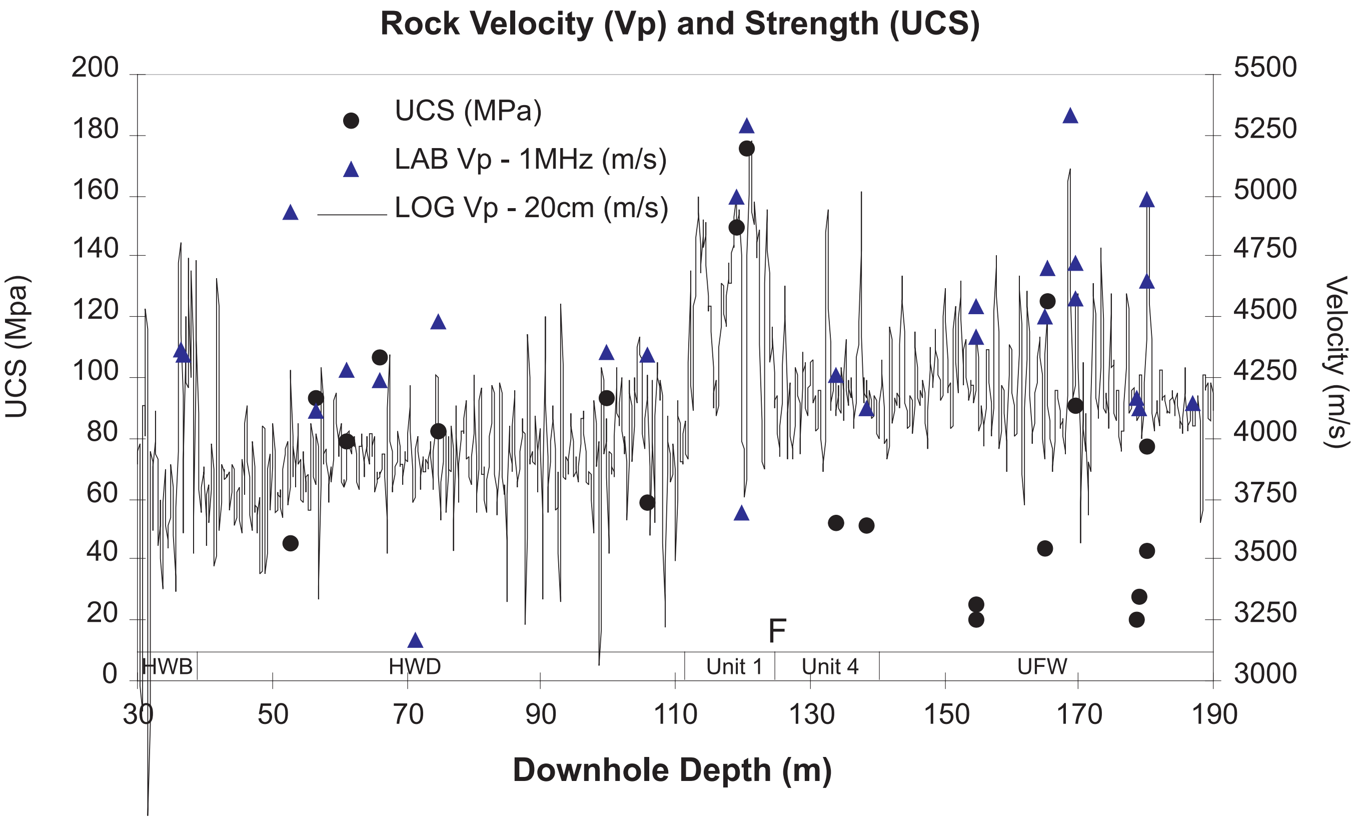


Figure 9: *Comparison of geotechnical data derived from laboratory measurements and sonic logs for Century drillhole LH643.*

The study also noted that these results could be adversely affected by sample quality and laboratory measurement problems, and lack of enough samples to gauge statistical reliability. However, it must be concluded from this work that at best the prediction of UCS from velocity can only be regarded as indicative only.

Structural prediction from geophysical logs

One of the earliest problems recognised at Century was the presence of small-scale faulting within the deposit (Waltho *et al.*, 1993). These faults are mostly steeply dipping, and trend in several preferred directions. As surface exposures of these features are masked by the irregular structure of the Cambrian limestone cover, drillhole intersections provided the only indication of the presence of these faults initially. However, because most of the drillholes are vertical, only limited information about the structures is available from the drilling.

Some thought was put into methods which may assist with the prediction of the presence and geometry of such faults between drillholes. Seismic and electromagnetic imaging were postulated and are discussed below. Due to the lack of confidence and uncertainty of the availability of these techniques at the time, an alternate method was sought that utilised individual boreholes, and making predictions from the information in the borehole.

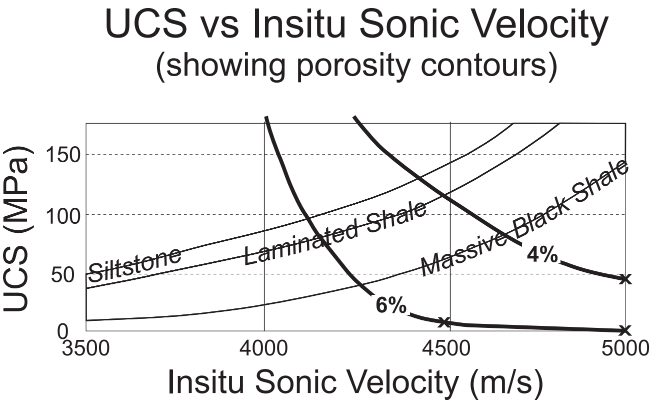


Figure 10: *Approximate relationships between sonic velocity, rock strength (UCS), and porosity, Century deposit (after Duplancic, 1995).*

Measurement of the core orientation and the dip of the strata in the core is the traditional approach to interpreting structure between drillholes in stratiform deposits. However, the problem at Century was that, due to most of the holes being vertical, the reliability of the available core orientation data was questionable. To address this issue, tests using a combined dipmeter/hole deviation tool developed by BPB Instruments were carried out at Century. The results demonstrated that good quality

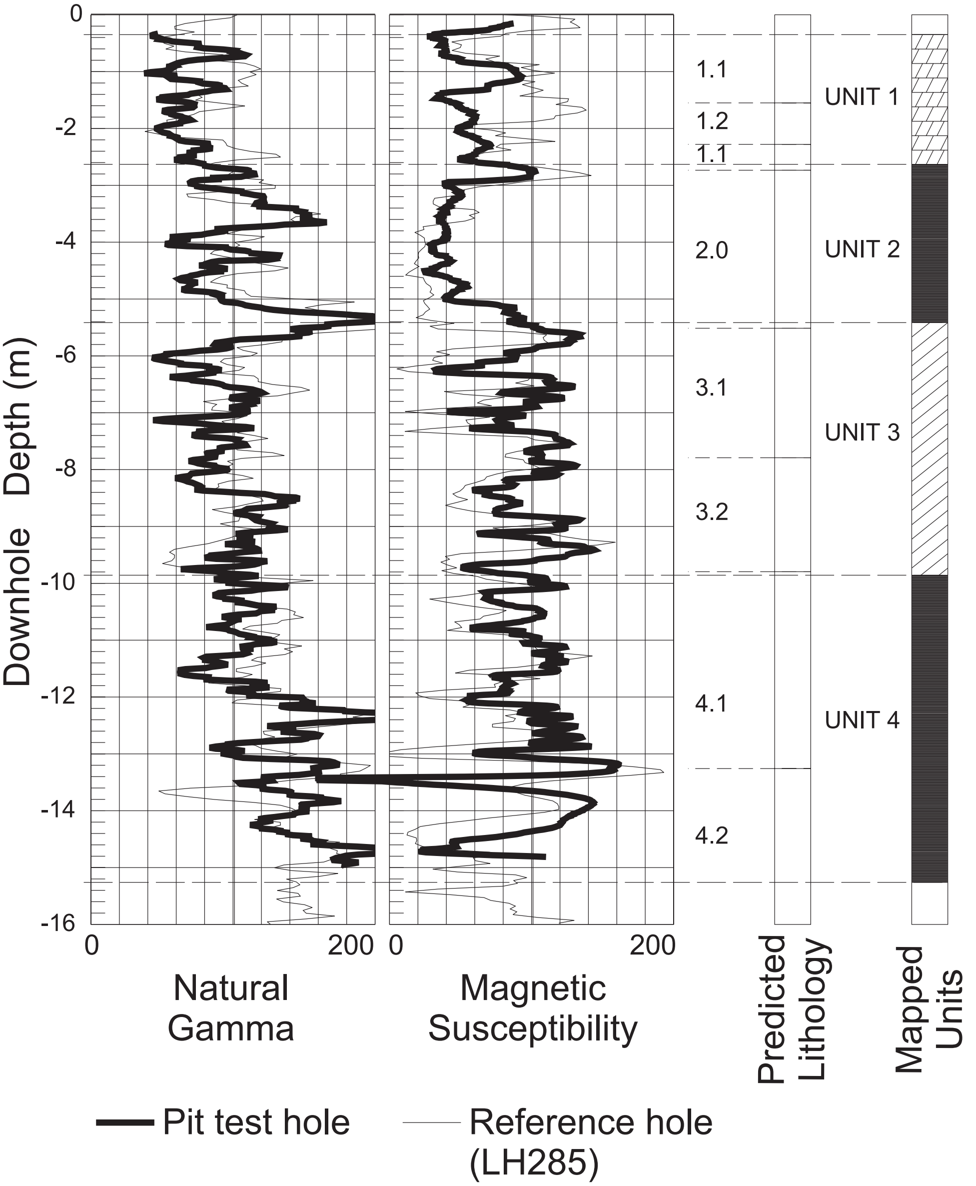


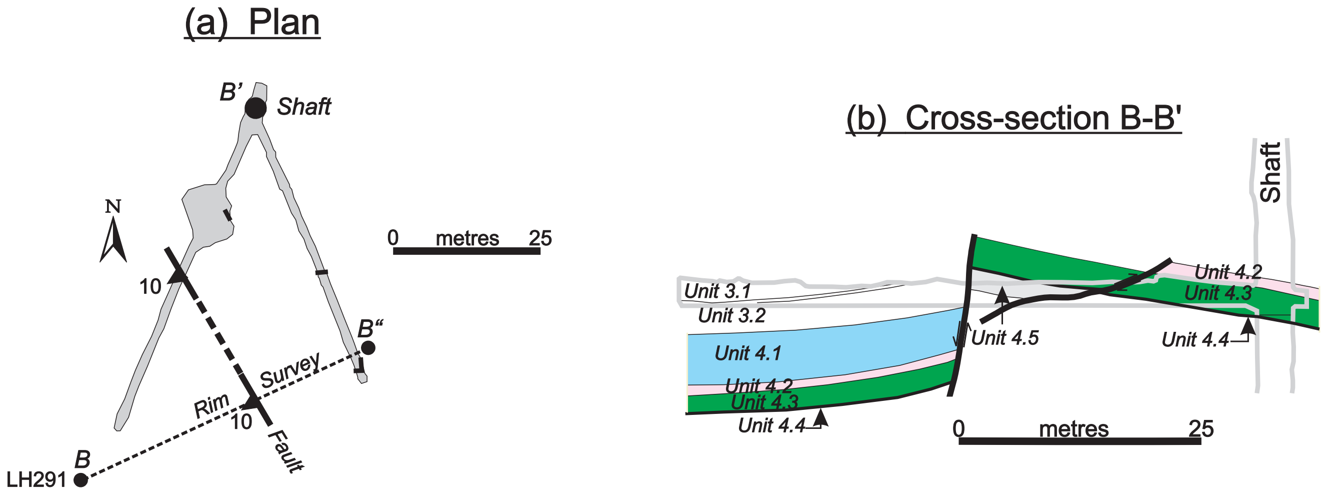
Figure 11: *Lithological prediction from geophysical log in blasthole, based on curve matching from nearby reference hole, Century bulk sample pit.*

oriented dip information could be obtained on the more laminated units (shales and siltstones) including the ore sequence. The amount and quality of the data obtained enabled the estimation of structural offsets between drillholes.

Blasthole logging

The recognition that lithological contacts could be readily delineated from borehole geophysical logs lead to the possibility that the blastholes planned for the bench mining of the deposit could be geophysically logged to provide more accurate information about ore-waste contacts than conventional geological logging from blast cuttings. Such information could provide a substantial benefit to the mining economics, by optimising the blast design and the mining of ore and waste. Most of the benefit would come in the form of reduced dilution of ore for grade control purposes.

Figure 11 shows the result of logging a test blasthole within a small pit excavated to obtain a bulk sample of the ore (Figure 1). Only natural gamma and magnetic susceptibility logs were obtained for this test. The prediction of the ore unit contacts was based on a comparison with curve shapes, using a template overlay, from nearby reference core holes. The main ore units as mapped from the pit face and extrapolated to the blasthole are also shown. The comparison with the interpreted lithologies suggests that the ore contacts can be predicted to a vertical precision of about 10 cm. This result was confirmed from the subsequent geophysical logging of about 50 blast holes drilled in the trial pit.



(a) Plan

(b) Cross-section B-B'

(c) Rim Section B-B"

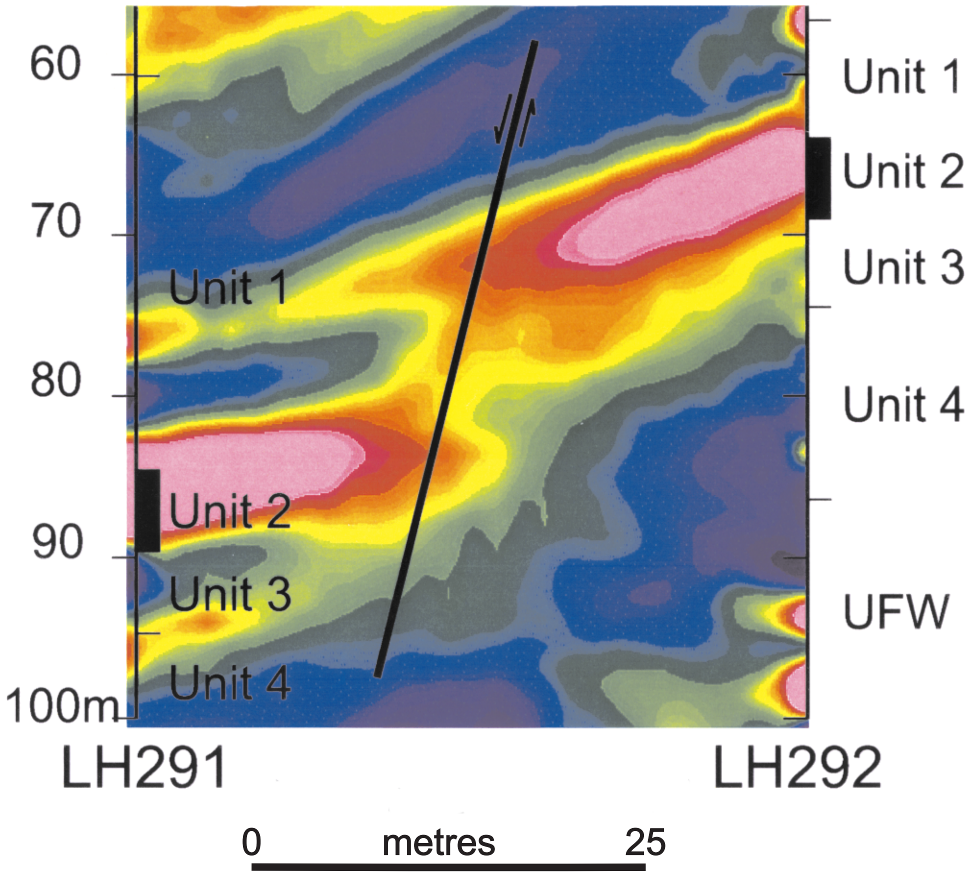


Figure 12: *Comparison between mapped geology in underground drive and Radio-Imaging Method (RIM) survey results, Century exploration shaft area:* ***(a)*** *location plan;* ***(b)*** *geological section through drive;* ***(c)*** *re-processed RIM tomogram (frequency 520 kHz) from drillhole section oblique to drive.*

The possibility of measuring ore grade in blastholes has also been considered and some testing conducted. The key to grade estimation is the measurement of density, but the use of a highly radioactive source in an active mining area was strongly discouraged. A test program was conducted by CSIRO Australia to trial a low-activity spectrometric probe developed by CSIRO (Charbucinski, 1993; Borsaru *et al.*, 1995) in order to measure zinc grade directly in blastholes. Such a probe would be an alternative to laboratory chemical analysis for grade control. Information available from such a probe would be available in a much shorter time frame than chemical analyses, and potentially should provide more accurate information on vertical grade variations than would be possible from analysis of samples taken from drill cuttings.

Initial results of such tests are promising. The tests suggest that such a tool could achieve better than ±2.5% Zn determination, with substantial opportunity for improvement (to a calculated limit of about ±1.5% Zn). Ore boundaries can be located to a vertical resolution of 10 cm. While the precision of this grade prediction is not as good as a chemical assay, it is unlikely that the result obtained from a bulk assay of drill cuttings will reflect the actual grade of the material to any better accuracy than indicated by the probe. Further work on the assessment and development of this technology has been recommended by CRA.

Inter-borehole imaging

Because the Century deposit is locally faulted, the delineation of faults within the deposit and the impact these would have on mine design and extraction of the ore have been subject to much investigation. To determine possible options to address this problem, some analysis of the potential application of seismic tomography, radio-frequency electromagnetic (RFEM) imaging, and borehole radar was undertaken to determine if either of these methods has the capability to define the structure of the ore zone between drillholes at Century.

Seismic tomography

Although surface seismic has little application at Century due to the rugged limestone topography and weathering (Thomas *et al.*, 1992), analysis of some test data suggested that reflectors are associated with lithologies within the ore zone. It was therefore postulated that borehole seismic tomography could map these units and provide a basis for structural interpretation between drillholes. However, seismic tomography was not undertaken at Century mainly because of the limited support to service such work in Australia.

Radio imaging

As an alternative to seismic, RFEM imaging has been assessed by CRA as having potential application at a number of its operations, including:

- delineation of the structure, including offsets caused by faulting, of coal seams or ore units between drillholes or mine development access ways;
- detection and location of geological or operational hazard zones between drillholes;
- detection of unknown ore not intersected by drillholes;
- assessment of quality of coal or ore between drillholes;
- detection and location of large voids (cavities, old workings, etc.) between drillholes.

Unlike seismic tomography, there are several potentially suitable EM tomography systems available, such as the RIM system (Stolarczyk, 1992), the Russian FARA system, the South African RT system and the Chinese JW-4 system (Fullagar *et al.*, 1996b). The RIM system has advantages in Australian conditions due to its lower frequency capability (down to 12.5 kHz). It was also the only commercially available system in Australia when the work at Century was being considered.

A trial of the RIM system was undertaken at Century in 1992 to determine its suitability in delineating the structure of the ore zone between drillholes. A test was carried out in the vicinity of an exploration shaft which had been sunk into the ore body to obtain a bulk sample of ore, and to provide access for geotechnical investigations and mapping of structure from drives within the ore body (Figure 12a, b). This mapping provided direct evidence of a previously unknown fault with throw about 10–15 m adjacent to holes in which a RIM survey was carried out.

Initial processed results from this survey did not provide much encouragement that the method could offer any information on the structure between holes to the resolution required for mine development and as a result, no further surveys have been undertaken. However, alternative data processing options were subsequently investigated, resulting in the image shown in Figure 12c. This result was obtained using exactly the same data as the initial processing, but in this case the tomographic inversion utilised the RWS software developed by VIRG-Rudgeofizika for their FARA system. The main difference with this software is that it utilises both the amplitude and phase information. The reprocessed image clearly indicates the presence of the fault very close to its predicted position. It is interesting to note that no specific a priori geological information available from the drillholes or the subsequent underground development were used to constrain the resulting image.

The use of RIM or equivalent radio-imaging systems could therefore play an important part in evaluation of the structure of an ore body such as Century in advance of infill drilling and mine development. This has not happened at Century to date probably due to the unfavourable impressions gained by the mine evaluation staff from the initial processing of the data and the passage of time before better results were obtained. However, it is estimated that, had the radio-imaging technology and processing been sufficiently developed, proven and accepted at the time of the Century discovery, the structural evaluation of the deposit may have been achieved at a significantly lower cost ($5–$10 million less), and in a shorter timeframe. The basis for this substantial cost benefit is in the reduction of the number and type (i.e., non-core) of boreholes required, but the main benefit comes from increased confidence in the reserves and the subsequent mine design and mining plan.

Borehole radar

A trial borehole radar survey was carried out at Century as part of the AMIRA P436 research project. The objectives of this work were to:

- map faults within the Proterozoic sediments, and determine their geometry;

- detect cavities, representing a future mining hazard, within the limestone.

The use of borehole radar to map faults was as a possible alternate to radio imaging, on the basis that the higher frequencies would give higher resolution of the structures, and that the radar could be carried out in a single hole reflection mode requiring less logistical effort. The results of this work were disappointing, due to the fact that the penetration distance of the radar signal using a 60 MHz source frequency through the weakly conductive sediments was very small (less than 5 m) effectively rendering the technique of little value for this problem.

The detection of cavities in the limestone with borehole radar was more promising. A reflection range of about 25 m at 60 MHz frequency was obtained, and features which may be related to cavities were noted. No testing or proving of such features has been possible to date, but the results are considered sufficiently encouraging to suggest that a radar method (including surface radar) may have application to the location of potentially hazardous voids during waste removal activities for an open-pit development .

DISCUSSION

The use of geophysics in the evaluation of the Century deposit was an attempt to influence, change and improve the process of resource definition in CRA, and eventually integrate such technology into routine mining practice. In parallel with the work at Century, CRA Exploration also implemented similar work at other diverse projects in Australia, in support of the evaluation of nickel sulphide, base metals, industrial minerals and coal deposits. CRA operating mines have also been active in assessing the use of geophysics, either on a trial basis or in a production mode, in the evaluation of iron ore, bauxite and coal. Some success has been achieved in each of these areas, but the use of geophysics in the mines is by no means routine as yet.

The work by CRA has demonstrated some of the potential benefits that could flow from the routine use of geophysics during resource evaluation, or integrated with mining. With regard to evaluation of a potentially mineable resource, areas where successful utilisation of geophysics could have a significant positive benefit to project development include:

- locating the lateral and vertical extent of ore at a much earlier stage of drill evaluation: the influence this would have on the time frame and accuracy of initial reserve estimations could have a major impact on development criteria;
- correlation of mineralised intercepts and prediction of structural offsets between drillholes: the information obtained on the structure and volume of ore should be of great benefit to mine planning and reserve estimation;
- substitution of cored with non-cored holes: if grade variation is relatively uniform, the use of geophysically logged non-cored holes as a substitute for more expensive and time-consuming cored holes could represent substantial cost benefits at an early stage of the project;
- direct measurement of physical parameters such as density or rock strength: geophysical logging potentially should provide the most consistent and reliable information on the in situ rock properties;
- geotechnical evaluation of cavities, zones of weakness or incompetent rocks representing potential mining hazards: reliable remote detection of such hazards has enormous implications to mine design and safety management;
- evaluation of hydrological conditions, and foundations for mine infrastructure: high resolution surface geophysics integrated with information available from drilling and water-monitoring can potentially provide more definitive solutions to some of these problems.

Knowledge obtained during the resource definition phase of the project also provides the evidence and confidence for successful utilisation of the geophysical technology in the mining process. Areas where application of geophysics has demonstrated some potential for integration into CRA's mining operations include:

- ore boundary delineation: detailed information on ore-waste contacts from geophysical logging of production drillholes or high resolution surface surveys can influence the optimisation of the blast design or ore extraction, yielding a substantial benefit to the mining economics due largely to the reduction in dilution of ore;
- grade control: where a relationship between grade and one or more physical properties is present, direct grade prediction in production drillholes is possible, yielding substantial benefits due to improved grade control, more rapid availability of data, and reduced laboratory costs;
- hazard detection: the remote detection of cavities, broken ground or geological impediments in advance of mining can substantially reduce personal and economic risk.

Knowledge and understanding of contrasts in the physical properties of the materials being mined is the fundamental principal which determines if there is a role for geophysics in the definition, evaluation and mining of a mineral deposit. This knowledge can only be gained from physical measurements on core or geophysical logging of drillholes. Therefore as a prerequisite to any mine evaluation program, it is necessary to acquire a suite of information on a range of physical properties, and then utilise either previous experience or indicative modelling studies to determine what geophysical methods may achieve the required goals of the resource definition.

CONCLUSIONS

Experience gained by CRA during the evaluation of the Century deposit and at other Australian mining operations suggests that successful application of geophysics in mine evaluation or during mining is achievable in certain circumstances. These circumstances are controlled by the contrasts in the physical properties of the materials being mined. To successfully utilise geophysics in mining, it is therefore necessary to acquire information on a range of physical properties, and then use this information to determine what geophysical methods may assist the evaluation process or mining operation.

The overall economic benefit of successful implementation of geophysical technology into all phases of resource definition and mining at RTZ-CRA operations is estimated at tens of millions of dollars annually. This projected benefit alone should stimulate the need for investigating further technological improvements and evaluation of available technologies at existing operations.

Despite this positive assessment, some barriers inhibiting the routine testing and implementing of such technology exist, largely relating to 'cultural' or 'mindset' attitudes and acceptance by the mine operators rather than technological deficiencies. Established mining operations are reluctant to change traditional approaches to resource definition unless there is a major problem with production. Some effort by mine management will be required to address these issues and support further evaluation of the technology before the use of geophysics will be accepted as a routine component of resource definition and mining.

Further anticipated technological developments, cost pressures on production, and gradual change of cultural attitudes amongst mine operators will in time ensure the use of geophysics in mining. The reality may be that only those mining operations which successfully exploit such developments will be the most efficient and economically viable mines of the future.

ACKNOWLEDGEMENTS

The assistance of staff of CRA Exploration and Century Zinc Limited with the work undertaken at Century over the period 1990 to 1996 is gratefully acknowledged. In particular, I acknowledge the efforts of Barry Bourne and Theo Aravanis in initiating some of the innovative work presented here, and the encouragement of John Main, Andrew Waltho and CZL staff to undertake such work when it could easily have been ignored. I also thank Peter Fullagar and the AMIRA P436 team for their input, and David Splatt and staff at CRAE for the cartography. The paper is published with the kind permission of CRA Exploration and Century Zinc Limited.

REFERENCES

Aravanis, T.A., Lane, R.J.L, Mutton A.J., and Robertson, W.J., 1996, Century geophysical characterisation study: CRA Expl. Internal Report 21841 (unpubl.).

Broadbent, G.C., 1996, The Century discovery—is exploration ever complete?: *in* Proc. Pacrim 95 Congress, Aust. Inst. Min. Metall. Publ. 9/95, Mauk, J.L., and St George, J.D., eds., 81-86.

Borsaru, M., Ceravolo, C., and Tchen, T., 1995, The application of the low activity borehole logging tool to the iron ore mining industry: Nucl. Geophys, **9,** 55-62.

Charbucinski, J., 1993, The ZERO PROBE—low radioactivity borehole logging tool: in Proc. Int. IEEE Symp. on Nucl. Science, San Francisco, 1-5 Nov., 1993.

Duplancic, P., 1995, A comparison of mechanical properties of rock with insitu velocity measurements at the Century deposit: B.E. (Hons) Thesis, Dept. of Min. and Metall. Eng., Univ. of Queensland.

Fullagar, P.K., Fallon, G.N., Hatherly, P.J., and Emerson, D.W., 1996a, Implementation of geophysics at metalliferous mines—final report AMIRA Project P436: CRC for Mining Tech. and Equipment Report No MM1-96/11.

Fullagar, P.K., Zhang, P., Wu, Y., and Bertrand, M-J., 1996b, Application of radio frequency tomography to delineation of nickel sulphide deposits in the Sudbury Basin: 66th Ann. Int'l. Mtg, Soc. Expl. Geophys. Denver, Expanded Abstracts 2065-2068.

Mayers, P.J., and Bourne, B.T., 1995, Geological and geophysical study of the Lawn Hill limestone annulus: Century Zinc Ltd. Internal Report 94/002 (unpubl.).

Oldenburg, D.W., Li, Y., and Farquharson, C.G., 1996, Applications of geophysical inversions in mineral exploration: 66th Ann. Int'l. Mtg, Soc. Expl. Geophys. Denver, Expanded Abstracts, 611-614.

Stolarczyk, L.G., 1992, Definition imaging of an orebody with the Radio Imaging Method (RIM): IEEE Trans. on Industry Applications **28**,. 5, 1141-1147.

Thomas, G., Stolz, E.M., and Mutton A.J., 1992, Geophysics of the Century zinc-lead-silver deposit, northwest Queensland: Exploration Geophysics, **23**, 361-366.

Waltho, A.E., Allnutt, S.L., and Radojkovic, A.M., 1993, Geology of the Century zinc deposit, northwest Queensland: Proc. Int'l. Symposium—World Zinc '93, Aust. Inst. Mining & Metallurgy, Melbourne, 111-130.