MINE SITE EXPLORATION
AND ORE DELINEATION

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ORE DELINEATION IN THREE DIMENSIONS

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ABSTRACT

At the spatial resolution required for successful implementation of geophysical ore delineation, most ore bodies must be considered three-dimensional, meaning they cannot be adequately approximated by two-dimensional geometries. In recognition of this, our general approach to developing geophysical ore delineation technology relies on attempting to tightly integrate geophysical modelling and inversion with three-dimensional representations of geological data. When a program of ore delineation is undertaken, there is relatively abundant three-dimensional geological information already available. We are thus expected to use geophysics to cost-effectively add to an already substantially-understood geological picture. Our chances of success in accomplishing this are enhanced by building upon a three-dimensional model adequately representative of currently understood geology at the site in question.

The linkage between geophysics and geology is accomplished by constructing a three-dimensional physical property distribution, consistent with the best existing geological interpretation, and physical property data from wireline logs or core samples. The three-dimensional physical property distribution is used for both geophysical forward modelling, to compare to field data, and as a starting model in iterative inversions. We use advanced visualization techniques to simultaneously view the three-dimensional physical property model, the geological surfaces from which it is derived, and the geophysical results. A geophysical result may be either a simulated response from a forward model or the output from a numerical inversion, in the form of an updated physical property distribution. We propose the iterative refinement of the geological interpretation to ensure consistency with the geophysical data. The key to success with this approach is that the geological and geophysical data are viewed simultaneously. All relevant geological, geophysical, and rock property data reside in a common, visual model of the earth.

The high resolution demands of ore delineation geophysics result in a focus on seismic and high frequency electromagnetic methods. Borehole wireline logging is employed to develop an understanding of the relationship between physical properties and geological description. Examples from massive sulphide deposits illustrate the benefits obtained by the integration of geophysical and geological data.

INTRODUCTION

Geophysics in the mining industry has almost exclusively addressed the problem of detection of ore bodies up to the point of a successful discovery drillhole. The delineation or definition drilling program following a discovery hole is now often accompanied, in the early stages, by time-domain borehole electromagnetic surveys, presently the last general contribution of geophysics to the ongoing refinement of the geological interpretation. Refinement of the geological picture of an ore body is, however, an ongoing process from initial discovery to drilling of production blastholes, with the borehole spacings decreasing and the resolution requirements increasing at each step. Geophysics has yet to find a routine role in the detailed post-discovery geological work.

Aside from problems inherent in changing any long-established practice there are several technical reasons why geophysics is generally utilized in only the initial discovery stage of a mine. Exploration geophysics requires only that the presence of ore is indicated with some probability. Ore delineation applications presuppose not only the existence of an ore body but also some prior level of knowledge of the ore geometry. Ore delineation applications of geophysics thus demand, as their product, an increase in the level of detail at which ore geometries are currently known. This product is fundamentally different from that of exploration geophysics in two ways. Firstly, we require "high resolution." Secondly, we require an ability to frame the geophysical interpretation in terms of an existing geological model, in the process integrating geophysical and geological data. Each of the technology gaps in extending current geophysical practice to delineation rather than the detection of ore stems from either the resolution required of the geophysical survey or an inability to capture the existing geological knowledge in the interpretation of geophysical data. There are partial

In "Proceedings of Exploration 97: Fourth Decennial International Conference on Mineral Exploration" *edited by* A.G. Gubins, 1997, p. 639–650

technology shortfalls in three main areas: geophysical instrumentation, modelling and interpretation software, and tools and methods for the integration of geological and geophysical data.

An added complexity in ore delineation geophysics, at least at typical Canadian massive sulphide ore bodies, is that the geometrical complexity demands that modelling and interpretation consider a fully three-dimensional earth. This may be considered an aspect of the high required resolution. On a resolution scale of several metres to tens of metres, assumptions of two-dimensionality of the earth should be routinely questioned.

In this paper we explore the three-dimensional ore delineation problem by examining aspects of the technology gaps noted above, with a focus on application to massive sulphide ore deposits. We give an example of a typical geological ore delineation problem, discuss geophysical hardware and software technologies currently deployed on an experimental basis, and then focus on a methodology for the integration of geological and geophysical data.

THE GEOLOGICAL ORE DELINEATION PROBLEM

Aside from a few early attempts at establishing ore connectivity between distant points with mise-à-la-masse techniques (e.g., Parasnis, 1967), attempts to undertake high-resolution geophysical surveys at the ore delineation or definition stage have, until the last couple of years, been rarely reported. Recent experimentation with geophysical ore delineation, primarily in Canada, Australia, and South Africa, has been driven by mining economics and the emergence of hardware and software that is making the significant success of high resolution mining geophysics appear possible. One way mining companies are attempting to lower operating costs is through minimization of unplanned grade dilution resulting from the inadvertent mining of waste rock. Ore left in place at or near the boundaries of the mining excavation is even more costly than the mining of waste rock. One of several sources of both problems is error in the geological interpretation of ore boundaries, which in turn largely govern the mine excavation geometry. At most large mining companies the cost of each percent of dilution (measured by a ratio of tonnes of waste mined to total tonnes mined), and each percent of ore left in place, is measured in the millions of dollars, giving a strong economic impetus to developing technology which yields more accurate ore delineation.

The geological interpretation of an ore body is refined at a series of smaller spatial scales as the mine progresses from discovery to production. The objective of the geologist evolves from estimating the geological resource, to establishing the mineable reserve, to eventual reconciliation of the grade predicted to grade mined, ideally on a stope-by-stope basis. A contribution of geophysical data at any of the delineation scales could be useful, though the geophysical tools and techniques may change as the survey scale and resolution requirements get smaller.

An example, modified from a field study from a Canadian massive sulphide deposit, illustrating the typical complexity of massive-sulphide ore geometry, is given in Figure 1. This example is indicative of delineation at a scale midway between that of coarse resource estimates (drill-hole intervals in the 50–100 m range) and stope-scale estimates (blastholes separated by a few metres). The approximately vertical black lines in the longitudinal section are drillhole traces at a nominal spacing of 30 m, drilled down from the access drift shown at the top of the figure as two dashed lines. The interpreted ore geometry is indicated by cross-hatching for massive sulphide ore and an X-pattern for stringer sulphide ore. A relative grade scale is indicated as bar graphs along the borehole axes. The sulphides are indicated as occurring within a folded volcanic sequence; a tuff unit immediately hosting the ore with rhyodacites in turn surrounding the tuffs. The tuffs contain substantial amounts of disseminated sulphide, predominantly pyrite, while the rhyodacites are relatively free of sulphide mineralization. The massive sulphides themselves may or may not be ore depending on the mineralogy, with waste zones of massive pyrite commonly found adjacent to copper-zinc ore. The plan view shown at the bottom of Figure 1 represents a horizontal slice showing ore-waste boundaries at the same scale.

Taken together, the longitudinal and plan sections demonstrate the highly variable geometry of the ore boundaries in all three dimensions. The three-dimensional geometrical variability, combined with challenging resolution requirements at the delineation stage of geological interpretation, place severe demands on the geophysical surveys considered.

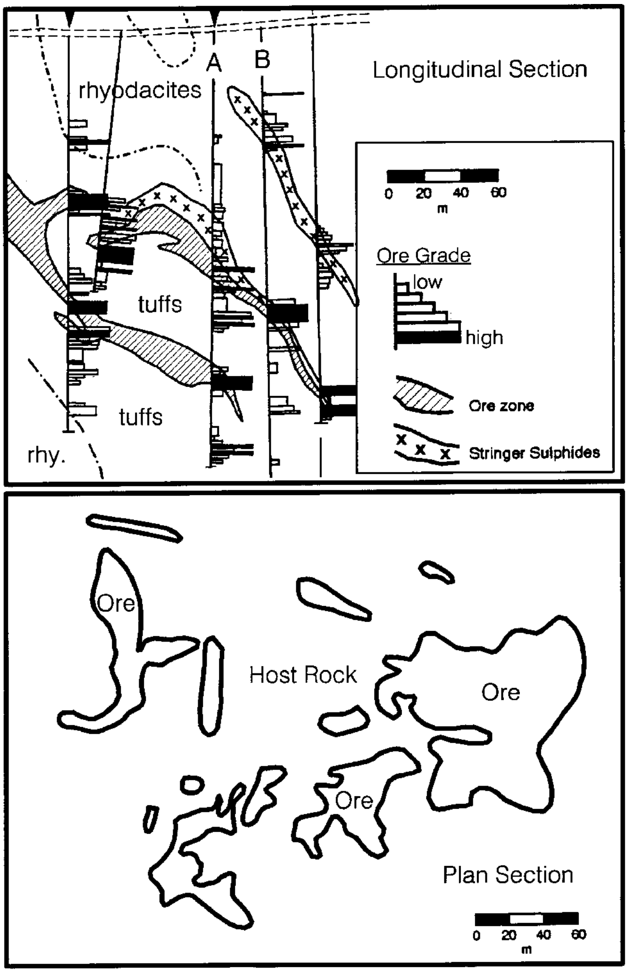

Figure 1: *Longitudinal and plan sectional views of a geological interpretation in a base metal, massive sulphide mine. The vertical or sub-vertical heavy black lines in the longitudinal section are delineation boreholes, drilled at a nominal spacing of 30 m.*

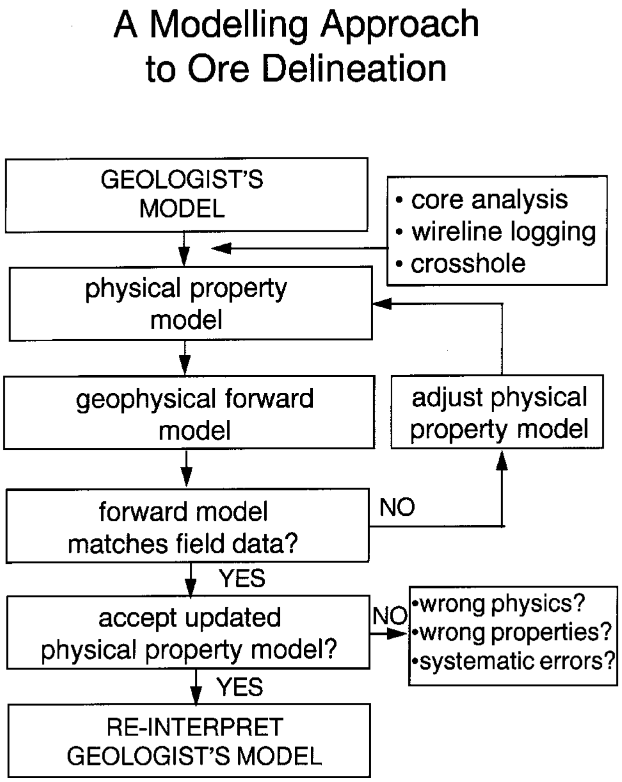

Figure 2: *Flowchart outlining the essential steps in integrating geological and geophysical data into a "common earth model," shared by the geologist and geophysicist, and consistent with both the geological and geophysical data.*

The success or failure of our ability to use geophysics for ore delineation rests ultimately on the answer to the following question: Given plans and sections such as those of Figure 1, constructed from geological interpretation of the drill core, can geophysical surveys be used to confirm or modify this interpretation in a significant way? And if the answer is yes, the technological challenge can be met, then can the results make enough of a difference for it to be cost effective to deploy geophysical surveys? The geologist making the interpretation from drillhole data will benefit more from successful geophysical surveys where the geology is difficult to otherwise interpret, meaning that the geophysics has to be successful in precisely those environments in which simplifying geometrical assumptions, such as local two-dimensionality, are unlikely to hold. Thus, to be useful, geophysical technologies at the ore delineation scale must treat the earth as fully three dimensional.

GEOPHYSICAL TECHNOLOGY FOR ORE DELINEATION

High resolution requirements and relatively small survey dimensions dictate that conventional mineral exploration instrumentation and data interpretation methods are unlikely to find success in ore delineation applications. In this section we briefly overview the geophysical survey instrumentation and data interpretation methods that are currently finding experimental use in ore delineation. At the sectional interpretation scale (a few tens of metres between boreholes), the high resolution requirement has resulted primarily in experimentation with borehole seismic and electromagnetic methods, in which the phenomena can be described largely by the physics of wave propagation. In spite of many reported field trials showing promising results, routine production success with either seismic or electromagnetic methods has yet to be reported. At the stope scale, borehole wireline logging has been used for ore delineation work for several years now with several reported successes. Each of these general geophysical areas are reviewed briefly below.

Seismic methods

Seismic methods for underground ore delineation rely on either a crosshole geometry or a similar geometry adapted to the mining excavations. Success with the seismic method depends on a physical contrast between ore and waste in seismic velocity, for tomography surveys, or acoustic impedance, for reflection surveys. Massive sulphides may or may not have a velocity contrast with their host, depending on the detailed mineralogy, yet will virtually always have a strong acoustic impedance contrast by virtue of the typically great difference in density between sulphides and non-sulphide bearing host rock (Salisbury *et al.*, 1996).

The potential success of seismic velocity tomography for massive sulphide ore delineation must therefore be treated on a case-by-case basis. When contrasts in velocity exist the ore velocity may be higher or lower than the host velocity. Examples are the Sudbury nickel sulphides, which are of lower velocity than their host (Pflug *et al.*, 1995), and the pyrite-rich zones commonly encountered in the massive Cu-Pb-Zn sulphide ores of the Canadian Shield or northeastern New Brunswick, which are typically of higher velocity than their host.

The practical resolution limit of crosshole seismic velocity tomography in a massive sulphide environment, with a detectable velocity contrast, appears to be on the order of ten percent of the crosshole spacing (McGaughey, 1990). The metal zonation in many deposits may yield a velocity zonation, making seismic velocity tomography difficult to interpret, particularly as the part of the deposit making the greatest contrast with the host may be massive pyrite, which is not ore. Furthermore, low velocity targets such as the Sudbury ores have the intrinsic difficulty of first-arrival raypaths skirting the target, resulting in the ray coverage within the target being necessarily lower than in the host, creating potential shadow zones of low coverage, and thereby downgraded resolution (Dyer and Worthington, 1988; Bregman *et al.*, 1989). A further complication of seismic velocity tomography is the near-pervasive velocity anisotropy of several percent detected in underground mines, largely attributable to the ubiquitous, preferentially oriented joint sets (Pratt *et al.*, 1993; McGaughey *et al.*, 1994). In spite of the known difficulties, massive sulphide ore in Canada has nevertheless been successfully imaged by velocity tomography both in Sudbury with its relatively low-velocity ore (King *et al.*, 1996) and New Brunswick with its relatively high velocity ore (McGaughey *et al.*, 1994).

Seismic reflection for ore delineation applications has been attempted rarely in the underground environment, yet holds promise. The advantages of reflection surveys, particularly in a crosshole geometry, are the high potential resolution and the virtually guaranteed, necessary contrast in the physical property of acoustic impedance for massive sulphide targets. The disadvantage of seismic reflection surveying is expense, both in data acquisition and processing. Proper interpretation of a reflection survey requires data that are not spatially aliased; in an ore delineation application this will typically mean source and receiver spacing intervals of not more than 0.5 m. A survey over a crosshole spacing of 50 m, and over one hundred metres or so of hole length, will therefore demand the acquisition of waveforms corresponding to raypaths numbering in the low tens of thousands. Data processing demands are also high, requiring first-arrival picking, bandpass filtering, separation of up-going and down-going waves, tube wave and direct wave removal, and crosshole migration. Crosshole processing flows are discussed in detail for oil and gas applications in Rector *et al.* (1995) and Lazaratos *et al.* (1995). The same general principles and methods apply to crosshole data gathered in a hard rock environment. The ability of seismic reflection methods to image massive sulphide ore boundaries has been documented in case studies in the Canadian Shield using both VSP (Eaton *et al.*, 1996) and crosshole geometries (Meng and McGaughey, 1996).

Assuming the cost of crosshole reflection surveys can be routinely borne, an ideal geological situation would feature sharp contrasts in density between ore and waste and no contrast in velocity. Lack of velocity contrast will facilitate reflection processing, particularly as migration velocity will not be a serious issue. (The chances of successfully migrating high-frequency data is severely reduced by errors in the velocity structure.) In cases where there is a significant disseminated halo around the ore, resulting in a gradual density increase towards the ore boundary, and perhaps the boundary itself being an economically defined cut-off in a continuously varying grade distribution, seismic reflection methods will probably not work.

The largest current practical issue in seismic methods for ore delineation is the lack of a good, slim-hole, commercially available downhole source that can operate repeatably, with a short cycle time, in fluid-filled holes. Operation at depths of up to at least several hundred metres is necessary; a depth capability to 2000 m would permit more general field application. An ideal source would also be required to be useful at crosshole distances in excess of 200 m in granitic rocks. The other necessary elements for successfully employing seismic technology in ore delineation appear to be in place: borehole receivers, high frequency, high dynamic range, multi-channel seismographs, and the processing software and methodology are all to some extent commercially available.

Electromagnetic methods

Time-domain borehole electromagnetic methods utilizing large loop sources have been used successfully for years in exploring the vicinity of existing mine workings. The recent advent of three-component borehole receivers is further increasing the application of this method. In this section, however, we focus on electromagnetic methods for ore delineation that may be used on a smaller scale, to image or delineate an already discovered ore zone. The requirement for higher resolution in delineation applications leads us to electromagnetic methods where the underlying physics can be at least partially framed, as in seismic methods, by the concepts of wave propagation. This has led to recent experimentation with radar and radio imaging techniques.

Radar methods use frequencies high enough that the simplifications of wave propagation physics hold accurately for the electrical properties of the host rocks in which they are employed. The high frequency of radar surveys (commercially available tools operate in the tens of megahertz to about one gigahertz), which permit resolution and data processing analogies to seismic methods are, also, unfortunately, the downfall of radar for the majority of potential ore delineation applications. Absorption per unit distance of propagating electromagnetic energy increases sharply with frequency up to the true propagation frequencies, at which survey distances can become quite limited. Field experiments in highly resistive hosts, such as in the Sudbury basin, have, however, yielded useful crosshole radar ranges of up to 100 m (at an estimated host rock absorption of 0.5 dB/m at 22 MHz) at the low frequency end of the radar spectrum (Livelybrooks *et al.*, 1996). Livelybrooks *et al.*, however, report on the other major problem associated with operating at radar frequencies in either a crosshole or single-hole mode: geological noise. Geological noise comes in the form of strongly reflective fluid-filled fractures, changes in the host lithology, and scattering from minor sulphide concentrations. An additional noise source, in single-hole surveys, is the critically refracted waves travelling near the borehole wall generating the first arrivals. In summary, getting into a frequency range with electromagnetics in which wave propagation concepts are as useful as they are in seismology also gets us into a frequency range in which largely irrelevant elements of the geology have an unfortunately large effect on the data. This tends not to be the case with seismic methods.

A sensible alternative to radar would appear to be the radio imaging method ("RIM"), in principle similar to radar, but operating in the hundreds of kilohertz to low megahertz band, where range will be higher and geological noise lower. Radio imaging instruments operate in the frequency domain by transmitting continuous monochromatic waves, usually stepped over a series of frequencies (only one of which is typically used in data interpretation). Application of the method conventionally employs a crosshole or between-gallery geometry in which data are collected to facilitate tomographic processing (a dense network of overlapping "rays" joining source and receiver positions). Radio imaging surveys have been attempted experimentally in several applications for many years with varying degrees of reported success. Examples include tunnel detection (Lytle *et al.*, 1979), detection and mapping of coal, salt, or potash seam disturbances (for example Nickel, 1978; Hill, 1984; Shope, 1987; Liu *et al.*, 1991; McGaughey and Stolarczyk, 1991), and ore delineation (for example Rao and Rao, 1983; Thomson *et al.*, 1992; Fullagar *et al.*, 1996).

Although the radio imaging method appears to operate in a desirable frequency band, successfully balancing the requirements of relatively high resolution and relative insensitivity to geological noise, it is currently plagued by a series of problems which have resulted in it not yet being currently applied anywhere on a routine basis in ore delineation applications. The frequencies typically used in radio imaging, on the order of 1 MHz, are too high for application of the quasi-static approximation on which conventional mineral exploration electromagnetic interpretation is based. On the other hand, radio imaging frequencies are too low to properly apply the assumptions of wave propagation, as is done in radar interpretation. Radio imaging data has resisted successful interpretation because it fits into neither the well-understood quasi-static model nor the wave propagation model of the physics of electromagnetic methods. In special cases, such as resistive coal or potash seams bounded by conductive rock layers, the physics is adequately described with a waveguide model, and interpretation has proved routinely successful. In the general case, in particular the challenging case of attempting to image essentially arbitrarily complex three-dimensional targets at very high conductivity contrasts, interpretation of radio imaging data has been unsatisfactory. Virtually all reported uses of the method employ a crude two-dimensional tomographic reconstruction of an absorption-coefficient image based on a straight ray inversion of total field amplitude. The resulting images have tended to exhibit spurious artifacts and other inexplicable features almost to the extent that they exhibit conformance to the known or assumed geology. This state of affairs is to be expected when we know we are applying unreasonable assumptions in the processing and interpretation of data.

Not only is the proper interpretation of radio imaging data not currently understood, there is also presently a deficiency with available instrumentation. Currently available radio imaging systems measure total field amplitude only, with no phase information. This situation would be workable if one could reliably assume that amplitudes are controlled only by absorption coefficient along a raypath connecting source and receiver—an assumption appropriate in medical x-ray tomography, to which analogies with radio imaging are often drawn. If the data are influenced by scattering, as they must be in the high conductivity contrast massive sulphide environment, the likelihood of successful interpretation is severely limited without phase information.

Although radio imaging data are acquired at frequencies beyond applicability of the quasi-static approximation, the wavelengths employed are nevertheless much longer than those used in either seismic or radar, with consequently lower anticipated resolution. Wavelengths on the same order as the survey dimension itself are typical. In the seismic tomography literature the "Fresnel thickness," or effective earth-sampling width of a ray is assumed to be given by the Fresnel zone radius $(\lambda h / 4)^{1/2}$ for wavelength λ and raypath length h (Nolet, 1987). If the analogy to the seismic raypath concept is useful in radio imaging (data are now almost universally processed with software written for seismic tomography) a radio imaging wavelength of $\lambda = h$ would indicate that an ostensibly two-dimensional image plane has a thickness on the order of half the crosshole spacing. This indicates strongly that interpretation of radio imaging data must, if it is to be successful, consider the three-dimensional variability of the earth. It is likely that radio imaging interpretation methods will mature in the next few years, and such surveys may become commonplace in ore delineation. It is nearly certain that to be practically useful in the field, in high resolution ore delineation applications, the data interpretation will have to be considered a three-dimensional problem.

Borehole wireline logging methods

The discussion of seismic and electromagnetic methods focused on the crosshole geometry because it is most closely aligned with the conventional method of geological interpretation: connecting geological units and structural features from hole to hole in a planar section. The data on which geological interpretation is based are the diamond drill core logs, with typical mining projects involving the systematic drilling of tens of thousands of metres of delineation holes. Slimhole wireline logging technology, appropriate for the hard rock mining industry, has recently reached a state of maturity where one can also contemplate routine geophysical logging of boreholes either from surface or in the underground environment. These geophysical tools can potentially find several productive uses in ore delineation applications, in support of either geological logging of core or crosshole geophysical technologies. In this brief discussion we consider only those tools that estimate the value of a physical or chemical property of the geological formation close to the borehole. (There also exist single-hole tools whose purpose is the off-hole detection of ore, such as borehole gravity and magnetic sensors. For a description of the latter in a mining application, see Kowalczyk *et al.*, 1996.) The role of physical-property wireline logging in ore delineation applications is discussed in detail in Wänstedt (1992, 1993) and McCreary and Wänstedt (1995).

McCreary and Wänstedt (1995) examine three areas in which borehole wireline logging may make a contribution in ore delineation: increasing ore body sampling at the delineation stage, controlling geological dilution at the production stage, and as an aid in the interpretation of crosshole geophysics. In the first two application areas, the technical challenge is the identification of ore boundaries and ore grade in non-cored holes. In the third, the challenge is calibrated, in situ measurement of the physical properties to which the crosshole geophysical methods are sensitive.

The potential for increasing ore body sampling could be realized if a certain percentage of a delineation drilling budget were devoted to percussion drilling followed by wireline logging. The percussion-drilled holes would replace much more expensive diamond-drilled holes. The wireline logging is an in situ surrogate for the expensive process of core handling, logging, and assaying. In the study by McCreary and Wänstedt (1995) of Noranda mines, the economics were such that devoting thirty percent of a delineation drill program budget to percussion drilling, followed by wireline logging, yielded a fifty to ninety percent increase in the number of drillhole intersections with the ore body, depending on the minesite. The study included the costs of the geophysicist's labour and the logging instruments. The economic benefit can, of course, only be realized if the interpretation of physical property logs, alone or in combination, is successful in estimating ore boundaries in percussion holes. Recent experience has shown the chances of success to be highly site-dependent. If the ore-waste boundary represents a sharp boundary in an easily measurable physical property, such as conductivity or density, it can be identified easily and precisely. This, fortunately, is often the case as many ore-waste boundaries are massive sulphide to non-sulphide boundaries, presenting the required physical property contrasts. The nickel ores of Sudbury fall into this group. The problem is much more difficult in the many polymetallic, massive sulphide deposits in which economically important details of the sulphide mineralogy are difficult to establish from physical property logs. An example is the discrimination between pyrite and chalcopyrite, which are difficult to distinguish in practice with easily-run conductivity and density logs, but may be distinguished with operationally more difficult and expensive spectral gamma-gamma or acoustic velocity logs. Nevertheless, significant progress has been reported in the more difficult problem of sulphide mineralogy discrimination through the use of multivariate statistical and neural network analysis (McCreary and Wänstedt, 1995).

The second application of wireline logging in ore delineation is the control of dilution at the production stage of mining. Thousands of metres of percussion blastholes are drilled in the large blasthole stope operations that are common in the underground mining of massive sulphide ore bodies. These holes provide no core and the drill cuttings are not conventionally sampled. If these holes could be geophysically logged for identification of the ore-waste boundary, the blasting of the stope could be adjusted before the explosives are loaded. Inco has reported (Balch *et al.*, 1995) large cost savings in blasthole nickel sulphide operations through last-minute blast alterations on the basis of simple conductivity logging.

The third application of borehole wireline logging in ore delineation is the calibrated measurement of rock physical properties in support of interpreting crosshole or other larger scale geophysical surveys. Forward modelling of seismic and electromagnetic surveys requires velocity, density, conductivity, and sometimes dielectric constant and magnetic susceptibility distributions as input. Numerical inversion codes require an initial estimate of the physical property distribution in the earth, even if it is only an average background value. Borehole wireline logs provide the most sensible measure of the earth's physical properties, if they can be accurately calibrated, because they are in situ measurements and can provide a statistically large data population. A database containing continuous geophysical and geological logs for a site would provide an excellent resource for establishing statistical correlations between the data of primary interest — the geological description — and the physical properties to which the geophysical techniques are sensitive.

THE INTEGRATION OF GEOLOGICAL AND GEOPHYSICAL DATA: THE COMMON EARTH MODEL

As the delineation of an ore body progresses, a three-dimensional geological model is constructed. Traditionally the geological model is represented by a series of two-dimensional sectional interpretations, together constituting a three-dimensional model, even if it is never explicitly constructed as such. The central challenge of applying geophysics to ore delineation is to confirm, deny, or modify an existing three-dimensional geological model.

Geophysics in exploration is used to detect ore, not define its geometry in anything but the crudest of terms. Because the objective of exploration is detection only, the interpretation of geophysical data can generally be done with only a background knowledge of geological context, and an understanding of typical responses to geophysical surveys in the area. Modelling of ore bodies with abstract geometries such as plates or spheres in half-spaces or layered earths is still useful. The exploration approach will not be as successful when the existence of a deposit is already known, and its extent and geometry already partially understood. The geophysicist must fully utilize the existing geological interpretation in an attempt to add value to it. Our approach in ore delineation is to attempt a tight integration of geological and geophysical interpretation through the point at which they overlap: the physical properties of rocks.

The flowchart of Figure 2 shows the steps in an integration of geological and geophysical data. The input is a geological model representing the deposit and local host geology, as it is currently understood. The output is the geological model adjusted to ensure consistency with the geophysical data. The output model is shared by the geologist and geophysicist. Using a term from the petroleum industry, where a similar data integration effort has been in progress for several years (see, for example, Wyatt *et al.*, 1992), we call the shared model the "common earth model." It belongs to all the geoscientists who contribute to it and draw from it. The common earth model is known to be quantitatively consistent with both the geological and geophysical field data. As new data become available the flowchart is re-entered and the common earth model further refined. Thus the procedure is iterative.

The first step in the process of building the model is conversion of the geologist's initial interpretation into a three-dimensional physical property model. The physical property model must be appropriate to the geophysical data acquired at the site. This may initially involve conversion of two-dimensional plans and sections on paper or in a CAD system into a three-dimensional model of all pertinent geological surfaces and volumes. The three-dimensional physical model can take several forms: examples are acoustic impedance contrast on a meshed surface, and seismic velocity or electrical conductivity on a two- or three-dimensional grid. A prerequisite to the mapping of physical properties to geological surfaces or volumes is an understanding of the relationship between physical properties (for example, acoustic impedance, seismic velocity, electrical conductivity) and geological description (for example, rock type, ore versus waste, metal grade, alteration, rock quality indices). The data for studying such relationships are derived from core analysis, wireline logging, and perhaps crosshole surveys themselves to ensure consistent physical property calibration between wireline and crosshole data. A recent example of a study seeking to identify the relationships between physical properties and geological description in a complex, polymetallic, massive sulphide deposit may be found in Laflèche (1996).

Geophysical forward modelling can be carried out once a physical property model is constructed from the existing geological interpretation. There are historical reasons why forward modelling has quite rarely been done, using earth models that would appear plausible to a project geologist. One reason is lack of urgent need, until recently, for forward modelling software capable of simulating the earth other than in fairly simple forms. Many useful results have been returned by highly abstract models of the earth (for example, a plate in a whole space). A related reason is lack of available numerical modelling codes that accept realistic parameterizations of the earth, and the expense of computers powerful enough to run them. This has changed over the last few years, particularly with the availability of finite-difference seismic and electromagnetic codes that accept fairly general three-dimensional earth parameterizations. Examples of such codes are described in Olsen (1993) and Newman (1995). (The seismic simulation codes are currently more reliable than the electromagnetic codes, which still cannot provide generally acceptable solutions over the range of frequencies, physical properties, and geological geometries we expect to encounter in ore delineation applications.) Another problem in undertaking geologically realistic simulations of geophysical surveys is the great practical difficulty in converting geological interpretations, drawn either by hand or electronically, into the numerical parameterizations demanded by the forward modelling code. This problem is being solved as the tools for computer-aided interpretation of geology become more sophisticated. Several commercially available products for mine planning, ore reserve estimation, or general geological modelling now provide the capability for building and manipulating three-dimensional models with physical property parameterizations suitable for linking to geophysical forward modelling codes.

If the physical property model is trusted to be reliably representative of the geologist's model, and the forward modelling codes are accurate, then reliable simulation of geophysical field surveys are possible. A simple comparison of the forward solution to the field data will reveal whether or not the geological model is consistent with the geophysical data. The geological model is confirmed, for practical purposes, if the geophysical field data and the forward-modelled solution are in agreement. (Strictly speaking, for most geophysical techniques, there will be other physical property models that would result in the same geophysical data — but if the physical property model originated with a geological interpretation, and the geophysical field surveys are well designed, this problem of non-uniqueness should be rendered academic.) If, on the other hand, the forward model disagrees with the geophysical field data, the physical property model must be adjusted until agreement is reached. The relationship between physical properties and geological description may have to be revisited or, more importantly, the geometry of the geological units may require adjustment. This could be done, for example, by adding a previously unknown ore lens, changing the continuity of various units between holes, or thinning or thickening of geological units. The adjustment may be done purely on the basis of geological intuition or it may be guided by numerical inversion of the differences between forward data and field data (the residuals) to solve for a quantitative perturbation of the physical property model. The process just described is not currently reported to be carried out in a routine, production mode anywhere.

Figures 3 through 10 illustrate some of the steps portrayed in the flowchart of Figure 2 and discussed above. A critical element in the effective integration of minesite geological and geophysical data is powerful three-dimensional visualization of the data. Appropriate visualization software appears to be the only effective method of sharing and understanding complex geometrical data. Figures 3 through 10 are example screen images from a particular geological modelling and visualization system called Gocad, but other commercial systems could be used for the same general purpose.

Figures 3 through 6 are from a field study at the McConnell Test Site near Sudbury. The nickel sulphide ore body is shown in light orange in Figure 3, with five boreholes from one drill section shown in red. The topographic surface and base of overburden surface are shown in yellow and blue-green, respectively. This is a view of the geologist's model. A crosshole seismic survey was carried out between the central borehole and its up-dip neighbour. The raypaths are shown in Figure 4, colour-coded by total travel time along the ray. The white grid forms a two-dimensional plane, best-fit by least squares to the two relevant boreholes, which can serve as a finite-difference grid for forward modelling seismic data. Seismic velocities can be mapped from the geological model onto the grid and a link made to the forward modelling software. Figure 5 shows the result of tomographic velocity inversion, visually embedded in the geological model. The low velocity nickel sulphides are indicated by the red anomaly within the ore body, which has been rendered semi-transparent. The geometry of the ore surface could be manually shifted to more closely match the geophysical anomaly, if required. Figure 6 shows a two-dimensional migrated crosshole reflection section, also embedded in the geological model, and again the interpretation of the ore surface position could be modified on the basis of this result. Wireline log data is shown in one of the boreholes; the radius of the log display is proportional to density, the colour scale reflects the natural gamma log response.

Figures 7 through 10 are adapted from a field study in a massive sulphide, base metal mine in the Canadian Shield. The study area is the same as that pictured in Figure 1. The two boreholes, shown in red in Figure 7, correspond to the holes labelled “A” and “B” in Figure 1 (A on the left and B on the right in Figure 7). The holes are nominally 30 m apart. The yellow surface is the rhyolite-tuff contact. This formational boundary appears geometrically uncomplicated in the two-dimensional section of Figure 1, but is revealed to be a surface of substantial complexity when rendered in three dimensions. The horizontal and vertical planar, coloured slices indicate relative seismic P-wave velocity. The seismic velocity grid was derived from a geostatistical block model (regular three-dimensional grid) of metal grades, and a physical property study which explored the statistical relationship between metal grade and seismic velocity. The colour scale indicates the relative velocity scale from blue (low) to red (high). Figure 8 is similar to Figure 7, with the host formational contact replaced in the view by its line of intersection (shown in white) with the central, horizontal slice through the three-dimensional velocity grid.

If the geological interpretation (block grade model) and the physical property relationships are both correct, a seismic velocity survey should reflect the highs and lows of the three-dimensional velocity grid. Figure 9 shows the contact from the other side, hole A now on the right, and hole B on the left of a gridded rectangle. The rectangular, planar grid has been automatically best-fit in a least squares sense to the geometry of boreholes A and B, and represents the area of coverage of a crosshole seismic field survey carried out between the two boreholes. The colour field on the gridded plane represents seismic velocity, at the vertices of the rectangular, triangulated grid, extracted from the three-dimensional velocity grid. We thus have an estimate of the seismic velocity variation within a two-dimensional crosshole image plane, extracted from a three-dimensional geological model. The objective of the crosshole survey is to confirm, deny, or modify the expected velocity variation within that plane. The result is shown in Figure 10, which shows a view similar to that of Figure 9, with the addition of a couple of slices through the three-dimensional velocity grid, and with contact rendered partially transparent. The two-dimensional crosshole grid shows relative seismic velocity, with the central velocity high occurring in the position predicted by the metal-grade block model via its statistical transformation to a velocity model. Although the crosshole image is a blurred representation of the expected response, we know to expect this kind of fuzziness from crosshole tomography, and we accept the result essentially as a confirmation of the geological grade model in that area.

The sequence of steps illustrated by the examples in Figures 3 through 10 correspond to steps in the flowchart of Figure 2. They represent a concrete example of how geology and geophysics can be directly integrated into a common model of the earth. The second field study demonstrated how a connection between geology and geophysics can be built through analysis of rock physical properties. Although the details of the physical property study are beyond the scope of this paper, it should be clear that we have constructed a block model, or three-dimensional grid, consisting of both geological (metal grade) and geophysical (seismic velocity) properties. The relationship between the geology and the geophysics is held entirely in the statistical correlation between these elements of the three-dimensional grid. We expect that the procedures outlined here will soon come into practical use in ore delineation.

DISCUSSION AND CONCLUSION

Geophysics has not found wide use in mining geology following the initial exploration and detection of ore. Costs associated with errors in geological interpretation at the delineation stage of a project, however, are such that use of geophysics may often prove cost-effective. Unlike exploration geophysics, the delineation problem requires that geophysical technologies add to an already substantially well-understood geological model. We have demonstrated that widespread success in accomplishing this is likely to occur only through the use of seismic and high-frequency electromagnetic techniques, particularly in crosshole geometries.

More importantly, once the technologies of acquiring and processing seismic and high-frequency electromagnetic data in the mining environment are understood, success in their deployment is only likely to come when their interpretation is tightly integrated with three-dimensional geological interpretation. The methodology we propose for carrying this out is not innovative in theory. Implementing it

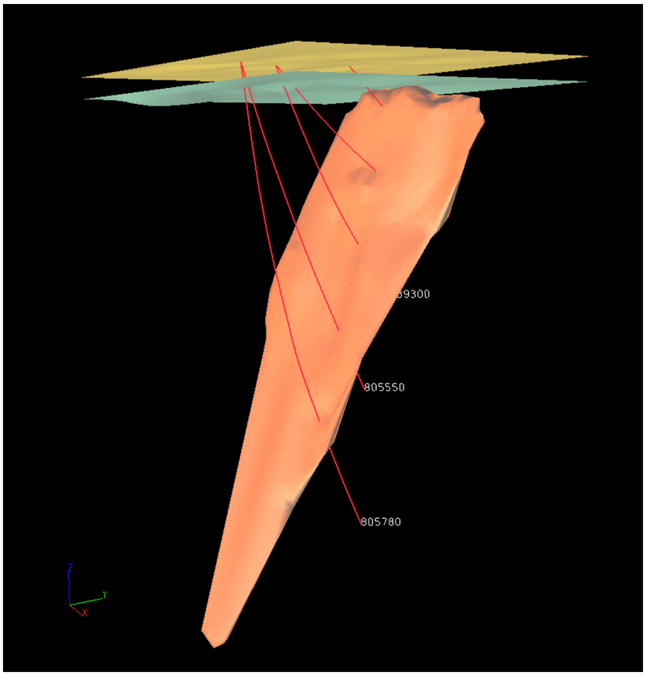

Figure 3: *Three-dimensional rendering of the massive nickel sulphide deposit at the McConnell test site, near Sudbury. The yellow and blue-green surfaces are topography and base-of-overburden surfaces, respectively. The red lines are delineation drillholes.*

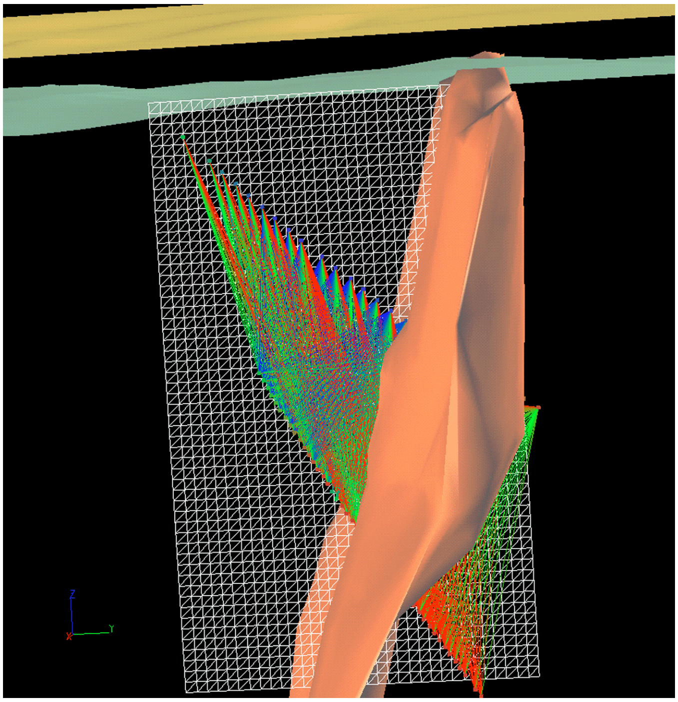

Figure 4: *Two-dimensional, finite-difference grid (in white) best-fit to seismic source and receiver positions from a crosshole survey at the McConnell test site. Seismic (straight-ray) raypaths from the field survey are shown coloured proportionally to their total travel time.*

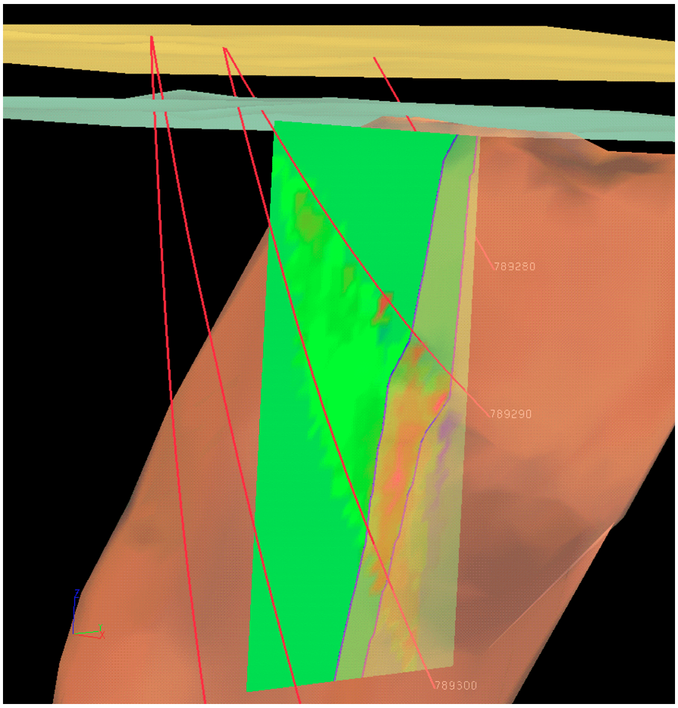

Figure 5: *Two-dimensional seismic velocity tomogram shown embedded in the McConnell ore body. The red velocities, visible primarily inside the ore surface (which has been rendered partially transparent), correspond to the known velocity low of the ore body.*

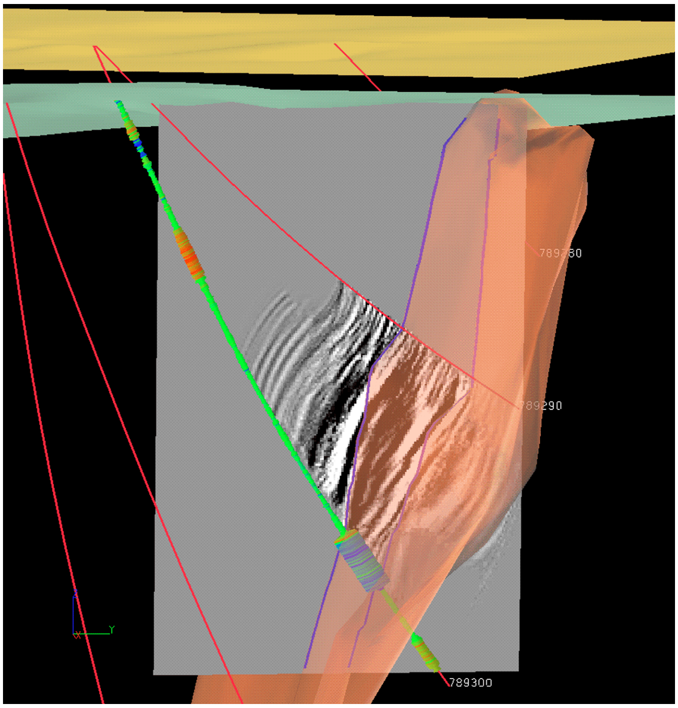

Figure 6: *Migrated, crosshole seismic reflection image from the crosshole seismic survey at the McConnell test site. Strong reflectivity can be seen near to, but not exactly coincident with, the top and base of the ore. One of the boreholes shows wireline log data: radius is proportional to density, and colour scale reflects the values of a natural gamma log.*

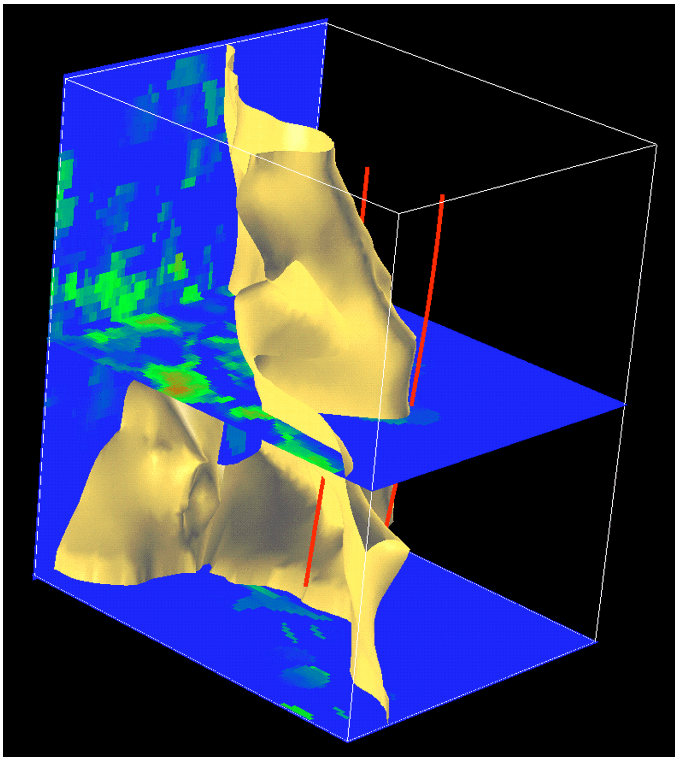

Figure 7: *Three-dimensional view of a host formational contact (in yellow), with slices from a three-dimensional seismic velocity grid derived from a, and two delineation boreholes (in red), at a Canadian massive sulphide, base metal deposit. The two boreholes are the same as those labelled A and B in Figure 1.*

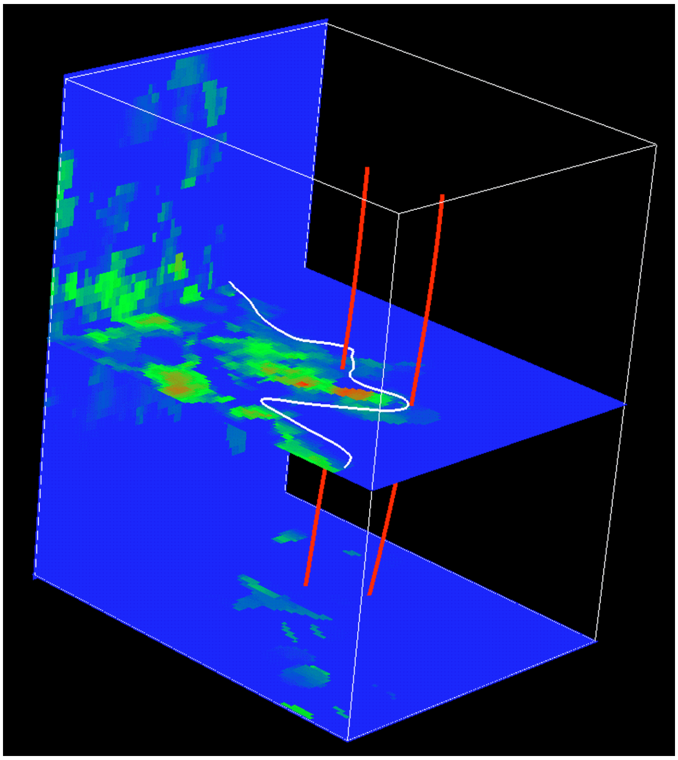

Figure 8: *The same view as Figure 7, with the contact replaced by its line of intersection with one of the slices through the velocity grid, to illustrate the relationship between the contact geometry, the velocity distribution, and the boreholes.*

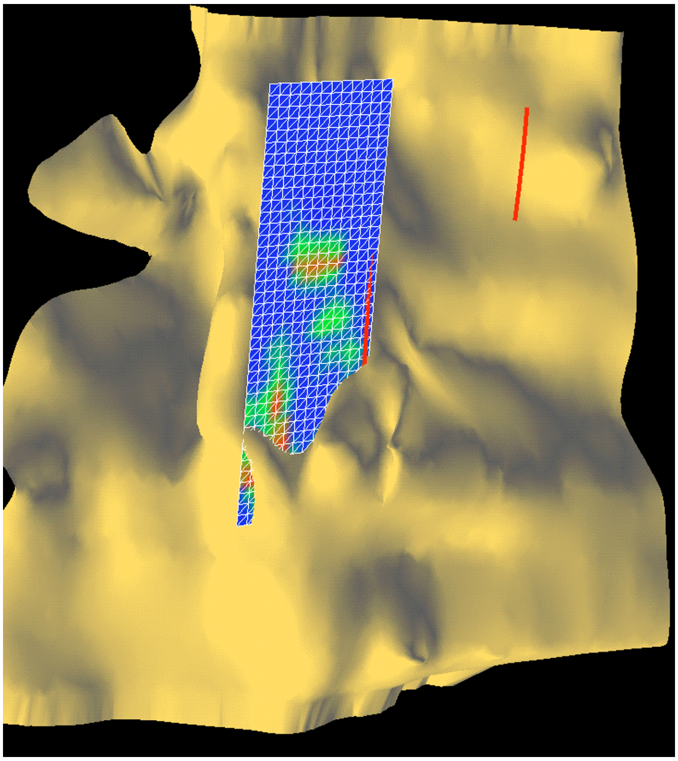

Figure 9: *Reverse view of the contact pictured in Figure 7, with a two-dimensional crosshole grid showing seismic velocity mapped from the three-dimensional velocity grid.*

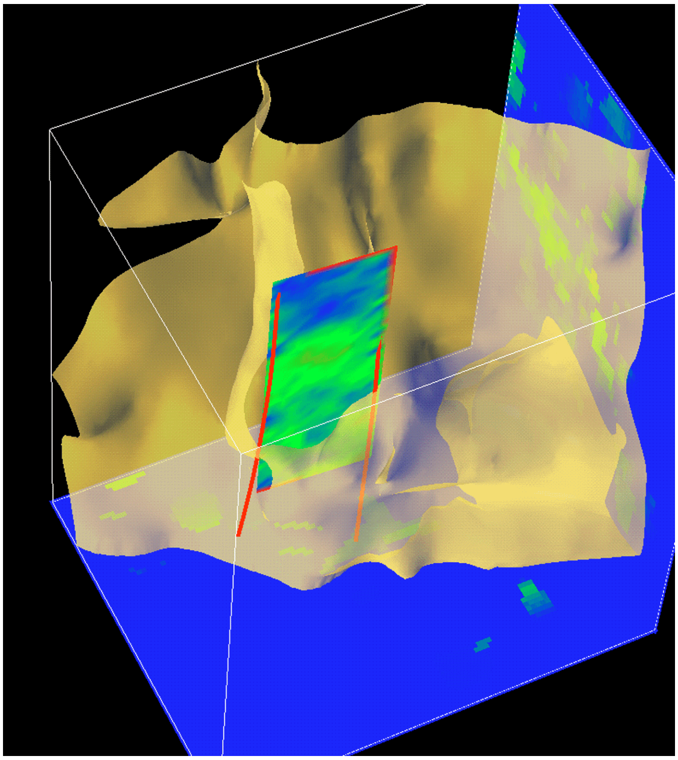

Figure 10: *Similar view of the contact and velocity grid pictured in Figure 9, with slices from the three-dimensional velocity grid for reference. The two-dimensional crosshole grid now shows the seismic velocity tomogram from field data. This essentially confirms the geological interpretation by finding a relative high in a location on the image plane coincident with that predicted by the three-dimensional velocity grid derived from the metal-grade block model.*

successfully in practice would, however, be an important innovation in the development of applied, mining geoscience, in which the worlds of the geologist and geophysicist still overlap far too little. We propose building the integration of geological and geophysical data around a common earth model, shared by the geologist and geophysicist, and containing both the geological and geophysical data. Our hope is that the distinction between the two types of data will become blurred if they reside in a common database and visual framework. Physical rock properties form the basis of the statistical relationship between the geological and geophysical data. If this vision is to find success, rock property data must be routinely acquired through core analysis and borehole wireline logging. Neither is routinely done at present in the mining industry.

Software for data integration, for creating the "common earth model," is widely available in 1997. Seismic technology is mature, requiring only an effective downhole source for routine use. Once the interpretation of radio-imaging data is better understood, and rock physical property databases become commonplace, the pieces can be brought together to greatly improve the effectiveness of modern ore delineation practice. The lessons learned, and the practices developed, should also improve the effectiveness of mineral exploration in general over the next decade.

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