Cost effectiveness of geophysical inversions in mineral exploration: Applications at San Nicolas

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Effective mineral exploration programs maximize the benefit of appropriate technologies in order to increase cost effectiveness by optimizing the use of drilling, reducing risks, and increasing the speed of discovery. In other words, correct use of available tools can allow exploration programs to find more ore, faster, with less expense.

It is well documented that geophysical data can be extremely useful in mineral exploration programs. This has become more evident in recent years due to the increased ability to invert geophysical data to produce 3-D subsurface models of physical properties. These models, along with physical property values of local rock types, are used to interpret geology and structure, and ultimately help the geologist spot drill holes. Often the most effective use of geophysics comes when it is employed in an iterative manner. It can build on geologic information already obtained and help guide further exploration as the project proceeds from reconnaissance, to anomaly follow-up, to the delineation of known occurrences and mine development.

The purpose of this paper is to illustrate potential cost effectiveness by showing how much information can be obtained about a deposit by inverting surface geophysical data alone. The only other information needed is estimates of the physical properties of the various rock types in the area. Geologic information is only used as a measure of success of the inversions performed. As an example we present the results of the inversion of different geophysical data sets over the San Nicolas copper and zinc deposit. The high quality 3-D images delineate the major aspects of the deposit and thus, in addition to finding the deposit, they have the potential for substantially reducing costs in any drilling program.

San Nicolas, owned by Teck Corporation and Western Copper Holdings, is an unmined, volcanic hosted, massive sulphide deposit in Zacatecas State, Mexico. In 1997, a gradient array induced polarization survey indicated a chargeability anomaly which, when drill tested, proved to be caused by a significant volcanogenic massive sulfide deposit. That deposit is now known as San Nicolas.

The huge volume of sulphides, and resulting large reserve estimates (72 million tons grading 1.35% copper and 2.27% zinc), has prompted the acquisition of many different geophysical data sets at San Nicolas. Data were collected to help in the exploration process and to test the effectiveness of different methods over such a deposit. While answers were also sought to more specific geologic questions, such as detecting high-grade zones at depth and finding new exploration targets, this paper focuses on the success of geophysical inversion in detecting the deposit itself. We show the results from inversion of gravity, ground magnetic, controlled source audio magnetotelluric (CSAMT), and induced polarization (IP) data.

Geology and physical properties. The San Nicolas deposit is a volcanogenic massive sulphide deposit containing ore-grade copper and zinc with associated gold and silver. The deposit is hosted in a series of interwoven mafic and felsic volcanic rocks which lie unconformably over graphitic mudstones (Figure 1). The deposit is almost entirely bounded to the east by a southwest-dipping fault, which could have been a feeder structure. Mineralization continues to follow the fault at depth in an unconstrained part of the deposit referred to as the "keel." The deposit is flanked by a thick succession of rhyolites to the west. The volcanic succession that envelops the deposit is overlain by a Tertiary-aged breccia overburden, which varies in thickness from 50 to 150 m. The breccia includes tuffs and clasts derived from the underlying volcanics. Outcrops of the breccia have been mapped to the northwest, but an overlying thin veneer of Quaternary alluvium is present in the vicinity of the deposit. Hydrothermal alteration, which may cause a change in physical property values, is prevalent throughout the deposit and surrounding geology.

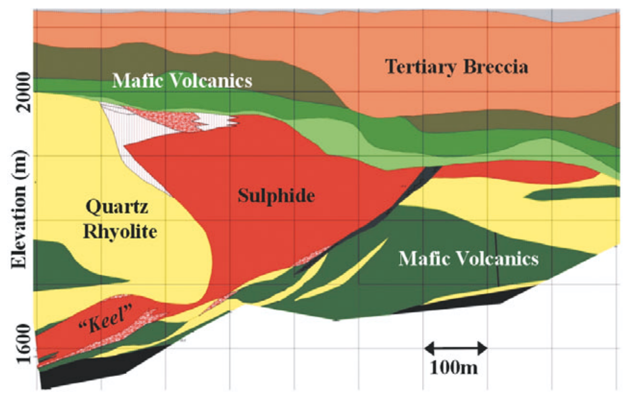

Figure 1. North-facing simplified geologic cross-section of the San Nicolas deposit (line 400 South) as interpreted from drill holes.

Table 1. Estimated physical properties for the five major rock units shown in Figure 1

Rock Type	Density (g/cm^3)	Magnetic susceptibility (S.I. x10^{-3})	Resistivity (Ohm-m)	Chargeability (msec)
Tertiary breccia	2.3	0-5	20	10-30
Mafic volcanics	2.7	5	80	30-50
Sulphide	3.5	10	20-30	200
Quartz rhyolite	2.4	0-10	100	10-20
Graphitic mudstone	2.4	0	100+	30-70

Laboratory measurements on core samples, inferences from simple modeling, and published data are used to assign appropriate estimates of physical property values to the rock types found at San Nicolas. Table 1 shows that the massive

Table 2. Survey and inversion parameters for each of the four data sets

Survey type	Gravity	Magnetics	CSAMT	IP
Inversion time (CPU time only)	Regional: 11.42 hr Local: 14.75 hr	1.3 hr	10 hr	Resistivity: 43.1 hr Chargeability: 4.6 hr
Configuration	East-West lines	East-West lines	T.M. mode East-West lines w/ Tx electrode 3.5 km north	Combined gradient array and *Realsection* array
Number of observations	813	614	5400 (30/station)	1182
Number of lines	15	7	3	9 + 3
Line spacing	100 m – 200 m	100 m	200 m	100 m and 200 m
Station spacing	25 m – 100 m	12.5 m	25 m	20-25 m
Preprocessing	Instrument/tidal drift Free-air Bouguer anomaly Regional removal	Diurnal corrections 44 000 base level removed Contaminated data discarded	Apparent resistivity and phase calculated from Ex and Hy field measurements.	Electrodes moved to fit nodes on 3-D mesh.
Other survey specifications	Location determined using GPS	Inc 50.638 Dec -13.43 (w/ ref. to local grid) Inducing field 44 000 nT	15 frequencies: (0.5 Hz–8192 Hz) Transmitter dipole length: 1.7 km Mean Tx-Rx separation: 3.7 km	5 transmitter spacings: 500 m to 2500 m
Recovered model	3-D density contrast	3-D magnetic susceptibility	1-D electrical resistivity	3-D chargeability
Noise estimation	0.05 mGal	2nT	Resistivity: 5% Phase: 35 mrads	5% + 1 msec
Number of cells	446 684	115 200	60 layers/station	117 600
Cell size	25 m x 25 m x 25 m	25 m x 50 m x 25 m	1 m to 28 km	25 m x 25 m x 25 m
Starting model	0.0 g/cm^3	0.001 S.I.	best fitting half space	0 msec
Reference model	0.0 g/cc	0.0 S.I.	100 Ohm-m	0 msec
Weighting	*Le*=*Ln*=*Lz*=50 (α_s= 0.001, α_x=α_y=α_z=2.5) and depth weighting: $(z+z_0)^{-2}$	α_s= 0.001, α_x=α_y=α_z=1, and depth weighting: $(z+z_0)^{-3}$	α_s= 0.01, α_z=1	Le=Ln=Lz=50 (α_s= 0.001, α_x=α_y=α_z=2.5) and distance from Tx electrode: $(1/r^2)$
Method of regularization	GCV	Chifactor=1	Chifactor = 1	Chifactor = 0.25
Achieved misfit	106	662	Mean of 31	293
Other inversion parameters	Topography included	Positivity enforced Topography not included		

sulphide deposit has been assigned high density, magnetic susceptibility, chargeability, and low resistivity. Based on the above information, the deposit can be delineated by using gravity, magnetic, electric/electromagnetic, and IP methods. It is noted that the low resistivity values assigned to both the sulphide and overlying Tertiary breccia can make it difficult to distinguish the deposit from the Tertiary overburden.

Inversion. The goal of an inversion process is to find the distribution of a physical property (which we generically refer to as the model) that produced the observations. The primary difficulty is nonuniqueness. The data supply only a finite number of constraints upon the model and thus there are infinitely many solutions. To find a specific answer that is geologically interpretable we proceed in the following manner. We first define a model objective function that measures the amount of horizontal or vertical roughness of the model or distance from a reference model. Then, from all the models that acceptably fit the data, we choose the one that minimizes this objective function. If the objective function is suitably chosen, then at least the larger scale features of the constructed model should reflect the major features of the earth.

In addition to designing the model objective function, it is also necessary to be specific about what it means to "fit" the data. Unfortunately, we usually don't know what the data errors are so we assume that they have a Gaussian distribution and we supply an initial guess regarding their standard deviation. We hope our initial guess is good enough that it provides the correct relative errors between the data.

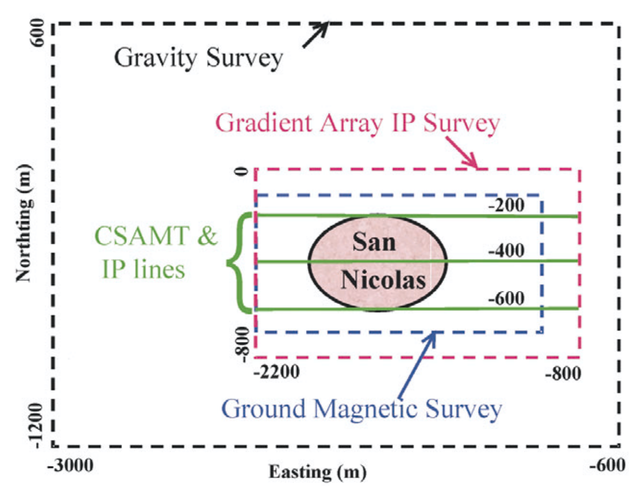

Figure 2. Survey layout. Lateral extents of the data sets used for the inversion are shown relative to the deposit.

If so, then the absolute noise level can be estimated through L-curve or Generalized Cross-Validation techniques, or by carrying out a couple of inversions using different tolerances for the misfit. The inverse problem is therefore stated as the following optimization problem: Find a model that minimizes the model objective function subject to fitting the data to a specified tolerance. It is important to understand that the generated computer model depends upon the model objective function, the assigned errors, and the achieved misfit tolerance. The latter is important. If we reproduce the data too well, then we are fitting the noise in the observations and the model will have artificial and erroneous structure. If we fit the data too poorly, then we are not extracting all the information that the data contain about the earth.

Because the information that we are able to recover about the physical property depends on the degree to which we are able to fit the data, it follows that field data should be as accurate as possible. This involves two aspects:

1) The datum should be measured as accurately as possible. This generally requires repeat observations. Estimates of uncertainty, perhaps obtained from the repetitive observations, should also be provided, because a datum supplied without an uncertainty estimate is incomplete.
2) In order to work with the datum it is required to know precisely what the datum is. Thus, locations of transmitter and receiver electrodes or coils, orientations of instruments, data normalizations or changes in units, and detailed knowledge of any processing that is applied to the data, are crucial elements in defining what the datum is and how it is connected to the physical property distribution.

These "details" quantify the datum, and without their knowledge the inversion cannot proceed! This is a major difference compared with older-style use of geophysical information where anomaly detection, generally in the form of "bump-finding," was needed. There, field data undergoing numerous normalizations and smoothing could be plotted to reveal interesting areas. Although those procedures remain valid today, such data cannot be rigorously inverted.

From the above, where we showed that the inversion depends on choice of model objective function, defining a misfit criterion, and deciding how well the data should be fit, it follows that the inversion of any geophysical data is not a turn-key operation. Most data require a couple of inversion runs to provide insight about the data errors and how well the data can, or should, be fit. Additional inversions, using different model objective functions, may also be run to provide insight about the nonuniqueness or to generate a model that has different geologic structure. As a consequence, any geophysical data set is likely to be inverted at least a few times. This requires time on the part of a skilled processor. It also requires computational resources.

The inverse problem is solved computationally, first by dividing the earth into cells whose physical property values are constant. The size of the cells should be small enough so that they don't act as an additional regularization for the inverse problem. In other words, the cells should be smaller than the resolving power of the experiment at any depth. Forward modeling consists of solving a system of equations to predict the responses at each observation location. For 1-D problems, the cells are layers, and the size of the problem is small. However, for 3-D models (as used in the gravity, magnetic, and IP studies), the number of cells is large (100 000 or greater). Thus large matrix systems need to be solved. In addition, when the problem is nonlinear, the inverse problem is iterative and the large matrix systems need to be solved many times.

To put this into perspective, a typical 3-D inversion of gravity or magnetic data may require a few hours or a day to complete, and a 3-D dc resistivity and IP inversion may take a couple of days. Inversion times for a Pentium III, 600-MHz processor with 1Gbyte of RAM are given in Table 2 for the results presented here. Man-hours to prepare and invert the data are variable but if computing resources and background information about physical property values were available, the following work is estimated to require three

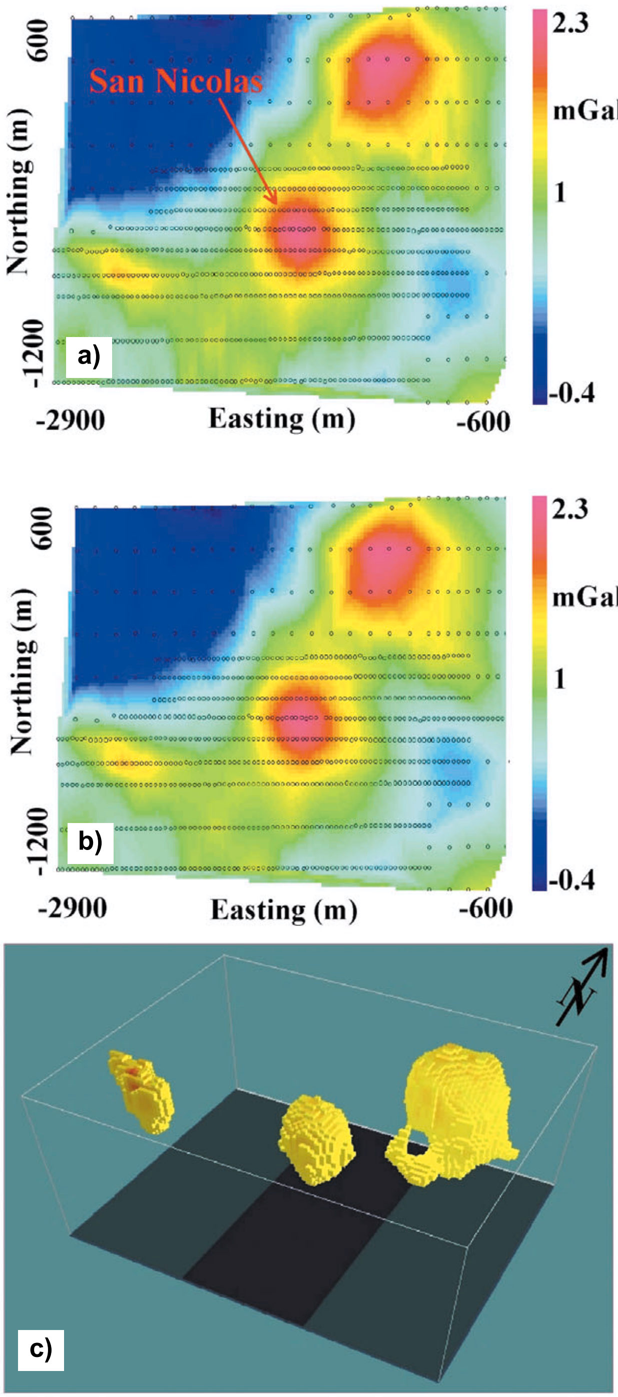

Figure 3. Inversion of gravity data. (a) Observed gravity data with regional trend removed. (b) Predicted gravity data. (c) Perspective view of density contrast model, volume-rendered with a cutoff at 0.17 g/cm^3. The San Nicolas deposit is represented by the center anomaly.

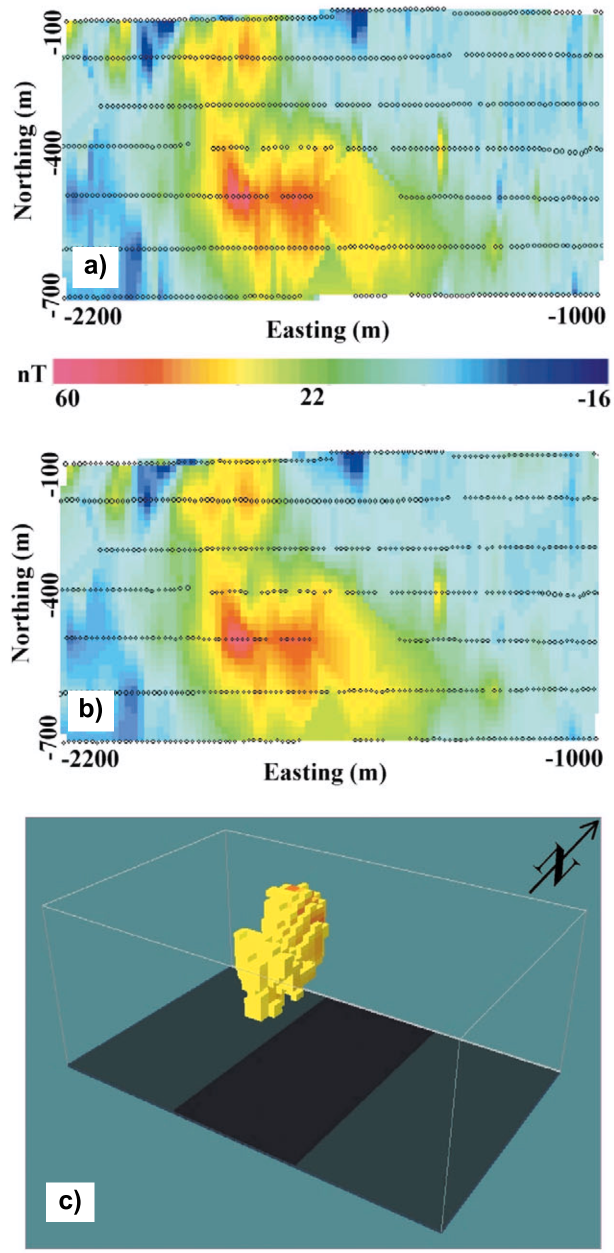

Figure 4. Inversion of ground magnetic data. (a) Observed total field magnetic data. (b) Predicted magnetic data. (c) Perspective view of magnetic susceptibility model, volume-rendered with a cutoff at 5 × 10^{-3} SI.

to four weeks to complete.

Despite the computational time and manpower costs, the expenditures to invert the data can be worthwhile. This is illustrated by the following inversions. Gravity, ground magnetic, CSAMT, and IP data are inverted to produce density contrast, magnetic susceptibility, resistivity, and chargeability models respectively. Figure 2 shows a plan view of the locations for each survey along with the approximate extents of the deposit projected to surface. All inversions were three-dimensional except for the CSAMT. Those data were inverted to recover a vertical 1-D resistivity distribution beneath each station and the results were concatenated or "stitched" together to produce a 3-D resistivity model.

Inversion of gravity observations. Gravity surveys involve measuring local irregularities in the earth's gravitational field with the aim of using these measurements to determine subsurface density variations. Quantec Geofisica de Mexico and Geociencias Consultores collected gravity data at San Nicolas in 1998. Traditional corrections were applied to the data; however, no terrain corrections were applied because of low topographic relief. Table 2 summarizes survey specifications and inversion parameters.

Inverting the gravity data required a two-pass procedure. First, 3934 data, over an area of 7 × 7 km centered on the deposit, were inverted to produce a regional density model. This large-scale density model was used to generate a

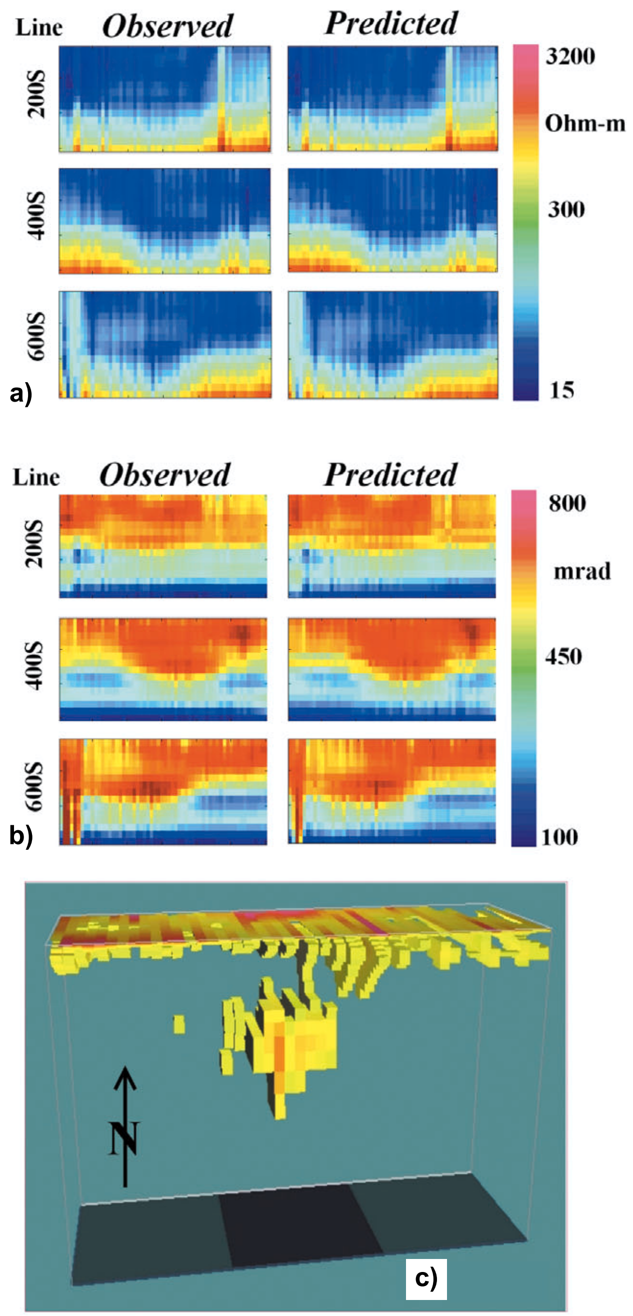

Figure 5. Inversion of CSAMT data. (a) Apparent resistivity data. Each data panel is displayed with increasing frequency in the vertical direction (from 0.5 Hz at the bottom to 8192 Hz at the top) and increasing station location in the horizontal direction (-2200 east at the left to –800 east to the right). Observed data are in the left panels and predicted data in the right panels. (b) Phase data (viewed in the same manner as apparent resistivity data). (c) Perspective view of resistivity model, volume-rendered with a cutoff at 30 Ohm-m. The 3-D resistivity model was constructed by "stitching" together the 1-D models created at each data station and interpolating to fill in volumes between the survey lines.

"regional" field over an area of 1.8 × 2.4 km centered on the deposit. The regional response was subtracted from the original data to produce a local data set to be inverted (Figure 3a). The local data clearly show the gravitational anomaly due to the San Nicolas deposit (labeled), as well as a similar sized anomaly to the northeast and a smaller anomaly to the west.

The model domain was divided into cells and the 3-D inversion carried out with the parameters in Table 2. Surface gravity data contain relatively strong information about horizontal variations in density but they don't have any inherent depth resolution. The depth distribution comes from incorporating an additional weighting into the inversion. The weighting procedure has been developed through the use of synthetic modeling and inversion. Figure 3b shows the predicted gravity data generated from inversion of the local data. The observed data have been reproduced very well.

The computed density contrast model is shown as a volume-rendered, isosurface plot in Figure 3c using a cutoff of 0.17 g/cm^3. Cells with density contrasts less than this value are invisible. Three bodies exhibiting high-density contrasts are well defined by the model. The center density contrast anomaly is coincident with the San Nicolas deposit and corresponds well with the dense massive sulphides. Figure 7a shows a north-facing cross-section of the density model overlaid with geologic boundaries.

Inversion of magnetic observations. In a similar manner to gravity surveys, variations in the earth's magnetic field are measured at the surface in order to gain information about subsurface magnetic susceptibility distributions.

Airborne and ground magnetic data were acquired at San Nicolas; here we consider inversion of total field ground data collected by Quantec in 1998. A base level of 44 000 nT was removed from the 614 diurnally corrected data as a processing step prior to inverting. In addition, several data in the center of the survey that were contaminated with cultural noise, such as a fence or steel-cased drill hole, were discarded.

The plot of observed total-field ground magnetic data (Figure 4a) shows a large response from the deposit and a small magnetic anomaly to the north. The observation locations are also displayed and the gaps where data have been discarded are clearly visible. The 3-D inversion was carried out with the parameters listed in Table 2. Magnetic data also have no inherent depth resolution and so, as with the gravity inversion, depth weighting is needed. The predicted data, shown in Figure 4b, are in good agreement with the observations.

Figure 4c is an isosurface representation of the 3-D susceptibility structure. The cutoff value is 5×10^{-3} SI. A distinct body of higher susceptibility is modeled. The majority of the susceptibility is coincident with the deposit, however, high values continue to the north. The correlation between magnetic susceptibility values and geology in the vicinity of the deposit can be seen in the north-facing cross-section (Figure 7b). The high magnetic susceptibilities associated with the deposit align well with the boundaries of the sulphide body.

Inversion of CSAMT observations. The controlled source audio magnetotelluric method is an electromagnetic technique that uses a grounded dipole source and measures components of the electric and magnetic field at a number of frequencies in the audio range (0.1 Hz-10 kHz). Perpendicular, horizontal electric and magnetic field values are used to calculate apparent resistivity and phase at different frequencies. It is assumed that the fields are measured far from the source. At San Nicolas, data were collected with receiver lines perpendicular to perceived geologic strike. It is not obvious from the observed apparent resistivity or phase data (on the left in Figures 5a and 5b) that a conductive ore deposit is present.

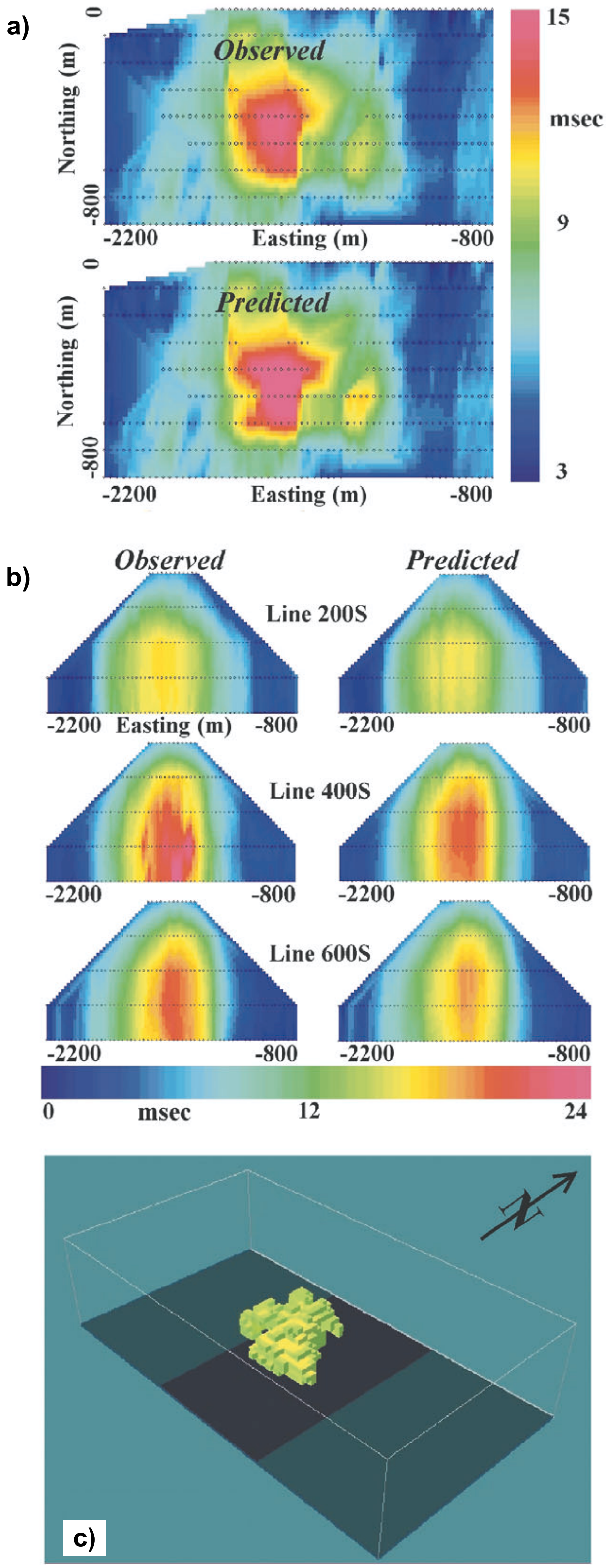

Figure 6. Inversion of IP data. (a) Observed (top panel) and predicted (bottom panel) gradient array data in plan view. (b) Observed (left panels) and predicted (right panels) Realsection array data for each line. The data panels are plotted with each row of data corresponding to a different transmitter electrode separation. The transmitter separation for the top row is 500 m and uniformly increases to a separation of 2500 m for the bottom row. (c) Perspective view of the chargeability model, volume-rendered with a cutoff at 45 ms.

The apparent resistivity and phase data are inverted to recover a one-dimensional, resistivity model beneath each station. The predicted apparent resistivity and phase data (on the right in Figures 5a and 5b) match the observed data quite well. The 180 1-D models were stitched together to form a 2-D model along each of the three lines of data. These were interpolated to fill in the volumes between the lines and produce a 3-D resistivity model. A volume-rendered image of the model, with an isosurface cutoff of 30 Ohm-m, is shown in Figure 5c. The large conductive feature at depth is the deposit. It is separated from a conductive overburden by an intervening layer of higher resistivity. The cross-section of the resistivity model (Figure 7c) shows that the deposit boundaries inferred from the inversion agree reasonably well with those inferred from drilling.

In order to test the validity of the 1-D models, the "stitched" 3-D model was forward modeled and apparent resistivity and phase data were calculated from the electric and magnetic field measurements. The forward-modeled data replicated the original data quite well at higher frequencies. Because the high-frequency data are sensitive to shallow features, this suggests that structure in the upper region of the stitched 1-D models is valid.

Inversion of IP observations. Induced polarization occurs when a current is applied to the earth and there is an accumulation of positive or negative ions in the pore fluid due to either the presence of metallic minerals, clay minerals, or graphite, or restrictions in the pore itself. The ability for a material to accumulate these charges is summarized by its chargeability. Voltages associated with induced charges can be measured in dc resistivity surveys.

At San Nicolas, gradient array and "Realsection" array configuration data were acquired by Quantec. In the gradient array configuration, current electrodes are outside a rectangular area to be surveyed. The dc/IP potential data are collected using a roving receiver dipole within the rectangular area. The data are generally used only as a mapping tool because detailed information about conductivity at depth cannot be obtained without having multiple transmitter locations. However, the gradient data do provide some constraints on the resistivity, and they can be inverted along with the Realsection data. The gradient array IP data for San Nicolas are in Figure 6a. The large chargeability anomaly is associated with the deposit. There is no doubt that this is extremely valuable information regarding possible existence of an ore body, but the data provide no information about what is happening at depth. That requires data from other locations of the current electrodes.

In a Realsection survey, the voltages from consecutive dipoles are measured and plotted in a pseudosection format. The current transmitter electrodes straddle the potential electrode array and the transmitter electrode spacing is continually reduced to change current flow in the subsurface. Data are recorded only at those potential electrodes lying interior to the transmitters. The calculated chargeability is plotted beneath the receiver dipole and each row of the resultant pseudosection-type plot corresponds to a different location of the current electrodes. The final plot has an inverted appearance compared to pseudosections obtained with more traditional pole-dipole or dipole-dipole plots. Figure 6b shows the Realsection plots for San Nicolas. It is apparent that a chargeable body is present, but these pseudosections provide no tangible information about the depth of the target. That can only be obtained through inversion.

The inversion procedure for chargeability is a three-step process. First we need to estimate the resistivity for the model

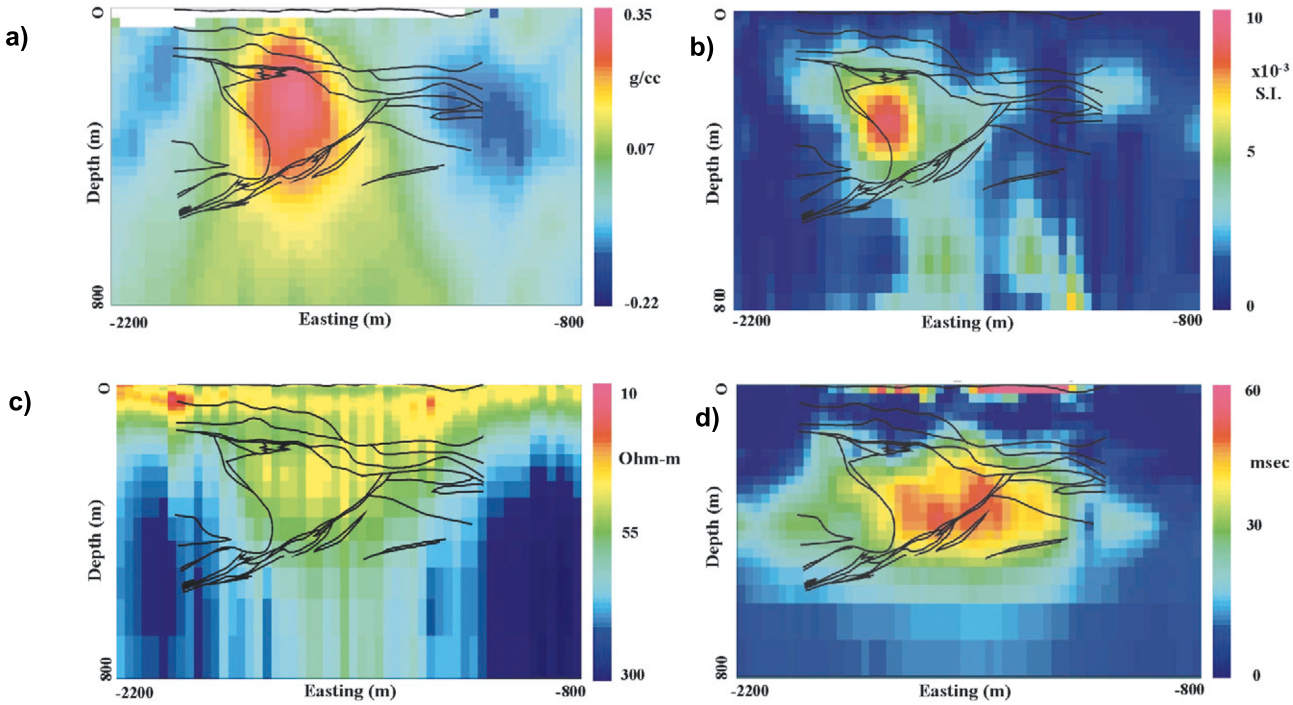

Figure 7. North-facing cross-section of physical property models at line 400 south with geology overlaid. (a) Density contrast model. (b) Magnetic susceptibility model. (c) Resistivity model. (d) Chargeability model.

volume; we do that by inverting the dc potentials. The sensitivities needed for the IP inversion are then calculated.

Lastly the IP data are inverted to recover a 3-D chargeability model. The details for the dc resistivity and IP inversion are in Table 2. Both the gradient data and Realsection data were inverted simultaneously. Figures 6a and 6b show the gradient and Realsection data predicted from the calculate model. These are in good agreement with the observations.

Figure 6c shows a northwest facing, perspective view of the volume-rendered chargeability model with a cutoff value of 40 ms. The spatial distribution of high chargeability values agrees quite well with the location of the deposit, as seen by viewing the cross-section in Figure 7d. That image also shows that areas of local, high chargeability, within the anomaly, are centered about the southwest-dipping fault.

Summary of inversion results. The physical property models recovered from the inversion are valuable in a number of ways. First, the volume-rendered images show a region at depth that has high density, high magnetic susceptibility, low resistivity, and high chargeability. From the physical property table this volume is thus a good candidate for being the sulfide. The volumetric images will change depending on the cutoff with which they are viewed but a drill hole spotted to intersect a zone of high density, susceptibility, chargeability, and low resistivity would have hit the ore zone. The massive size of San Nicolas perhaps makes this seem easy. However, the same procedure of carrying out the inversion and looking for co-locations of desired physical property contrasts can be used for finding smaller deposits whose data signatures are much more subtly encoded in the data.

On a more detailed level, the physical property models can be looked at in plan view or in cross-section. It is important to remember that the inversions are constructed to be smooth in the three spatial directions and that geophysical data acquired with surface sources and receivers have decreasing resolution with depth. Thus we do not expect to see fine scale structure in the recovered models, but structure that we do see is hopefully indicative of subsurface variation. Also, sharp boundaries will manifest themselves as smooth transition zones. These statements seem to be substantiated by Figure 7 where inversion results along an east-west section through the deposit are overlaid with geologic information obtained from the drilling program.

The density cross-section (Figure 7a) shows that the inversion has provided first order information about the sulfide location. The lateral dimensions are reasonably well defined and the centroid of the anomalous density coincides with the ore body. This is a useful result when one considers the lack of depth information contained in the data. The recovered density contrast is a smoothed version of the true density contrast, and it does not contain highly detailed structural information.

The highest concentration of magnetic susceptibility (Figure 7b) also coincides with the sulfide unit, although the centroid is displaced slightly to the left. Previous case histories have shown that the inversion is generally quite good at defining the horizontal limits of the body and also the depth to the top. This seems to be the case in Figure 7b. The explanation for the relatively high magnetic susceptibility extending downward from the sulfide unit is not known. It appears, however, that understanding the complete nature of magnetic susceptibility is not a straightforward exercise. We expect high susceptibilities to be associated with the sulfides. However, there can be magnetic minerals in host rocks and also magnetic minerals might be deposited by hydrothermal events that are not associated with San Nicolas deposit itself. This might explain the high susceptibility values that persist to the north of the deposit.

Figure 7c is a cross-section of the resistivity recovered from the CSAMT data. Electromagnetic data have depth resolution because data are acquired at different frequencies. The resistivity model locates San Nicolas and would have been very useful for exploration purposes prior to drilling. Identification of a resistive layer between the Tertiary overburden and the deposit suggests the survey has adequate resolution. This is confirmed by drill-hole information, which indicates only a thin (40 m) layer of mafic volcanics separating the two at a depth of about 150 m.

The chargeability cross-section (Figure 7d) identifies the San Nicolas deposit and allows interpretation of lateral and depth extents not apparent in the raw data. Along with the anomalous values that reflect the sulphide, the highest chargeability values are coincident with the southwest-dipping fault that is known to contain semimassive sulphides.

Summary. Thorough analysis of geophysical data by inversion provide the earth scientist with clear, practical information that can be used at different stages of the exploration process, either to increase the success of the first drill hole, or to aid in cost-effective delineation and in-fill drilling.

As a first stage, the models from individual surveys can be used in combination to select particular targets that have the physical property contrasts expected for the deposit. First pass inversions can generally be completed within one to a couple of days. The time depends on the survey type and the number of data. The next stage involves more analysis. Before the first hole is spotted, it is often prudent to carry out a few more inversions to look at the effects on the model of:

- fitting the data to a greater or lesser degree
- making changes to the model objective function (perhaps by altering the reference model)
- subtracting a different regional from gravity and magnetic data.

Ideally this is also a stage at which the model objective function is modified to incorporate a priori geologic information about the deposit, if such information is available.

The net result from a well-performed inversion is a model, or set of images, from which geologic information can be extracted and drill holes spotted. Good images can also impact on further acquisition of data needed to provide more information about possible targets. Finally, forward modeling and inversion can help design the most effective arrays needed to illuminate targets.

The increased information extracted from geophysical data must be traded off against manpower, computational, and time costs. What we have attempted to show here is that the superior information obtained by inverting data, compared to simply viewing the data themselves, is worth this cost. That is, the final product demonstrates a valuable return that even the fast-paced exploration program should find cost effective.

Suggested reading. Information on the 3-D inversion techniques used in this study can be found in "3-D inversion of gravity data" by Li and Oldenburg (GEOPHYSICS, 1998), "3-D inversion of magnetic data" by Li and Oldenburg (GEOPHYSICS, 1996), "Inversion of CSAMT data for a horizontally layered earth" by Routh and Oldenburg (GEOPHYSICS, 1999), and "3-D inversion of induced polarization data" by Li and Oldenburg (GEOPHYSICS, 2000). Oldenburg et al. overview inversion applied to mineral exploration in "Applications of geophysical inversions in mineral exploration" (*TLE*, 1998). TLE

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