Geophysical inversion in an integrated mineral exploration program: examples from the San Nicolás deposit

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Summary

The ability to produce three-dimensional physical property models of the subsurface from surface geophysical data, coupled with an increasing need to explore for minerals in concealed terranes, results in geophysical inversions providing more significant information to the exploration team. We examine the role that geophysical inversion can play in an integrated mineral exploration program, and the impact it can have on the results. As an example, geophysical data from the San Nicolás copper-zinc massive sulfide deposit in Mexico are inverted.

Density and magnetic susceptibility distribution models, inverted from regional gravity and magnetic data respectively, define large-scale structures that reflect the tectonic setting of the region. Several distinct anomalies that exhibit high density and magnetic susceptibility values are identified. A correlation method that determines volumes of high density and magnetic susceptibility isolates five anomalies, two of which are associated with mineralization.

At a more detailed scale, the deposit is well defined by gravity, magnetic, CSAMT, and IP methods individually. Each of these data sets has been inverted to generate a 3D physical property model. A drill-hole that is targeted on the intersection of these favorable physical property distributions would have intersected the heart of the deposit. This demonstrates the advantages of using these methods in concert.

Lastly core physical property measurements are used to improve inversion results. The inclusion of data from a single drill-hole is shown to significantly enhance the detailed magnetic susceptibility distribution and produces models that correlate better with known mineralization.

Introduction

Mineral exploration programs commonly employ a staged approach when assessing large amounts of land or data. The aim of this approach is to systematically discern the most prospective targets from a large amount of land without allowing any economic mineralization to be overlooked. These targets can then be evaluated with a local exploration program and drill-testing. Figure 1 is a simplified flowchart that shows the role geophysics plays at any stage of a mineral exploration program. Several iterations of this process might occur as a program advances and homes in on an economic resource.

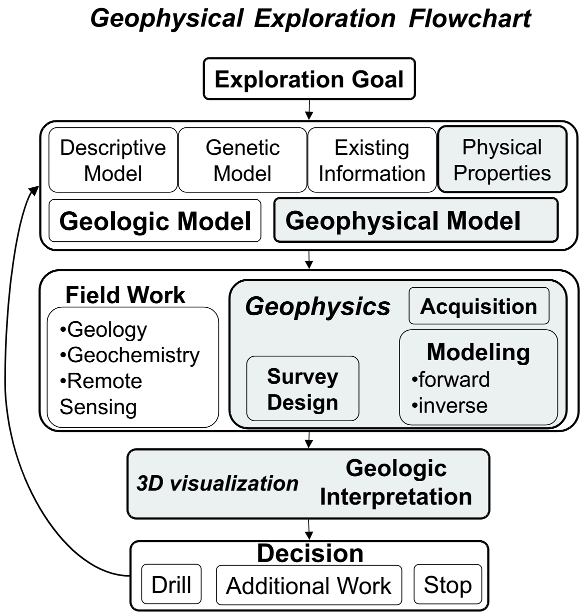

Fig. 1: Exploration flowchart with the geophysical components that are addressed in this study being highlighted

San Nicolás, owned by Teck Cominco Limited and Western Copper Holdings Ltd., is an unmined, volcanic-hosted, massive sulphide deposit containing ore-grade copper and zinc with associated gold and silver. It is located in Zacatecas State, Mexico. The deposit is hosted in marine volcanic and sedimentary rocks with mineralization predominately found stratigraphically after the formation of rhyolitic lava domes and before the deposition of mafic extrusives above. Throughout the region, the rock assemblages are intruded by granitic plutons, and are unconformably overlain by felsic volcanic flows and tuffs (Johnson et al., 2000). A section of rocks has been uplifted to form a horst, within which the San Nicolás deposit is found.

The massive sulphide ore at San Nicolás is primarily made up of pyrite, chalcopyrite, and sphalerite, with some magnetite and possibly pyrrhotite. From this mineralogy, the deposit is expected to have the following physical attributes: high density; high magnetic susceptibility (due to the presence of magnetite and pyrrhotite); high conductivity (this variable property often depends on the connectivity of the conducting paths); and high chargeability due to the presence of metallic minerals.

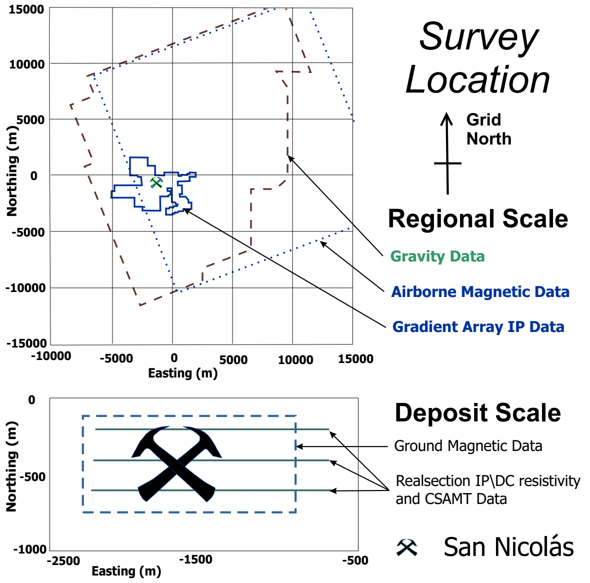

Fig. 2: Plan view of survey locations at San Nicolás.

Data

Data were collected at San Nicolás (figure 2) during the last five years, and provided to U.B.C. by Teck Corporation. For the regional-scale modeling we invert gravity and airborne magnetic data. Local-scale modeling involves the inversion of gravity, ground magnetic, CSAMT, and IP data. For detailed modeling of the deposit, we include magnetic susceptibility measurements that were made on core from one drill-hole.

Inversion

In a typical geophysical inverse problem we are supplied with data d^{obs}, some information about their errors, and an ability to carry out forward modelling that relates m, the physical property of interest, to the data. Our goal is to find the distribution of the physical property that produced the data. However, the inverse problem is nonunique and it is common to find a particular solution that is consistent with our *a priori* information about the model m and also adequately reproduces the data. The *a priori* information usually consists of generating a solution which is close to a reference model and is also smooth in the three spatial directions. The inversion algorithms used here all adopt that philosophy. The result is a model that hopefully exhibits the gross features of the earth and is geologically interpretable.

Regional inversion

Regional-scale inversion of gravity and magnetic data is performed in order to generate areas for detailed follow-up exploration. The survey areas for these data sets are shown in the upper portion of Figure 2. The inversion algorithms are those developed by Li and Oldenburg(1996, 1998). Regional inversion of gravity data produces a model that contains 707625 density-contrast cells of size 250m x 250m x 100m. The distribution of values within this model shows: a horst, within which the deposit is located; denser mafic rocks that have been intruded along regional faults; both large, deep and smaller, shallow intrusive bodies; and a coarse representation of the massive sulfide deposit. An isosurface plot of the density is shown in Figure 3*a*. Inversion of airborne magnetic data generates an equally large model that enables intrusive bodies, an outcropping magnetic rhyolite, and the deposit to be identified. An isosurface plot of susceptibility is shown in Figure 3*b*.

The individual inversions are informative, but for massive sulfide exploration we are looking for targets that have high density and high susceptibility. We therefore carry out a correlation procedure to find volumetric regions that are high in both of these properties. This produces the image in Figure 3*c*. We note, that with the cutoff levels used, there are 5 locations that are characterized by high values of correlation. One was immediately identified as a deep intrusive. Of the others, one is the San Nicolás deposit, and the volume at the bottom has also been explored and found to be mineralized. This illustrates that the joint interpretation of gravity and magnetic inversion can be very beneficial at the regional scale.

Local inversion

Having localized likely areas on the regional scale, the next step is to explore these areas using more detailed surface geophysical surveys. The enhanced resolution means that the inversions can be carried out with smaller meshes and more detail about the physical property characterization should be available. This stage of the work builds on the regional knowledge already obtained. Along with the gravity data, which was used for the regional modeling, more localized data sets are considered from ground magnetic, CSAMT, and IP methods. The inversion of these data is discussed in more detail in Phillips et al. (2001). The CSAMT data were inverted using a 1D inversion algorithm (Routh and Oldenburg, 2000) and then stitched together to make a 3D image. The IP data were inverted using the algorithm by Li and Oldenburg (2000). The 3D models of density-contrast, magnetic susceptibility, resistivity, and chargeability models all define the deposit very well. Figure 4 shows north-facing cross-sections through the physical property sections with geology overlain. It is apparent that inversion of any of these data types would have resulted in a successful drill-hole. In combination, the inversion results provide even more information, especially when the images are jointly interpreted with geologic understanding about the deposit.

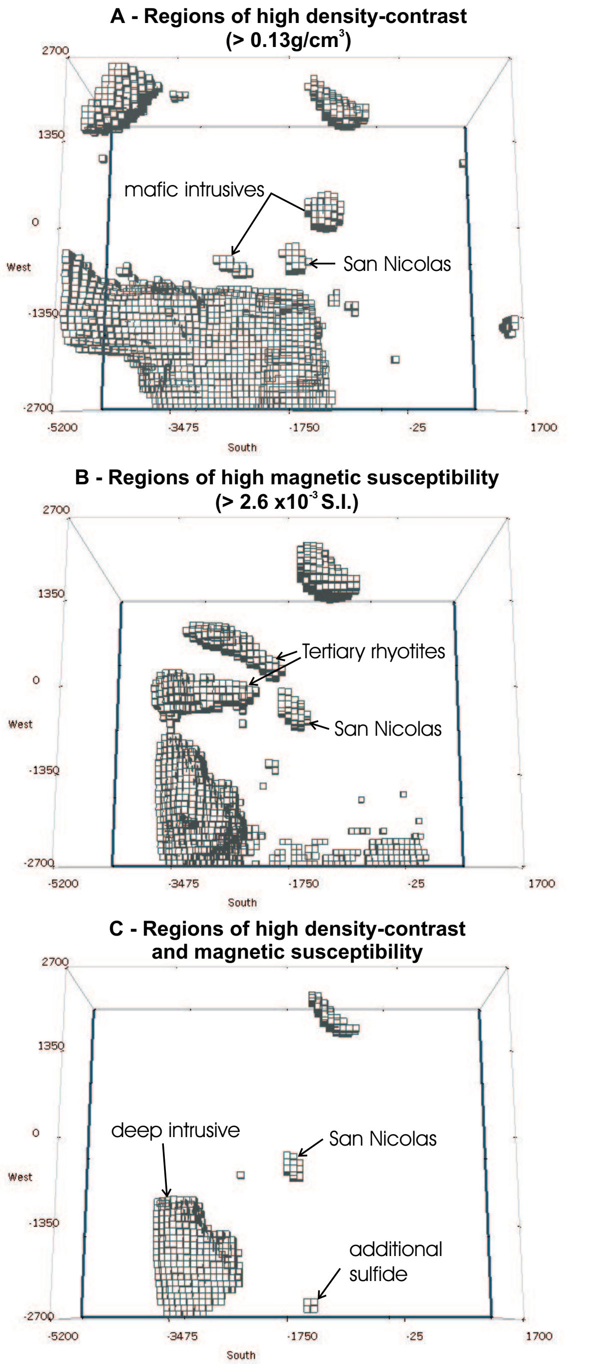

Fig. 3: Top: regions of the density-contrast model greater than 0.13 g/cm^3, Middle: regions of magnetic susceptibility model that are greater than 2.6×10^{-3} S.I., Bottom: regions where both density contrast and magnetic susceptibility are high.

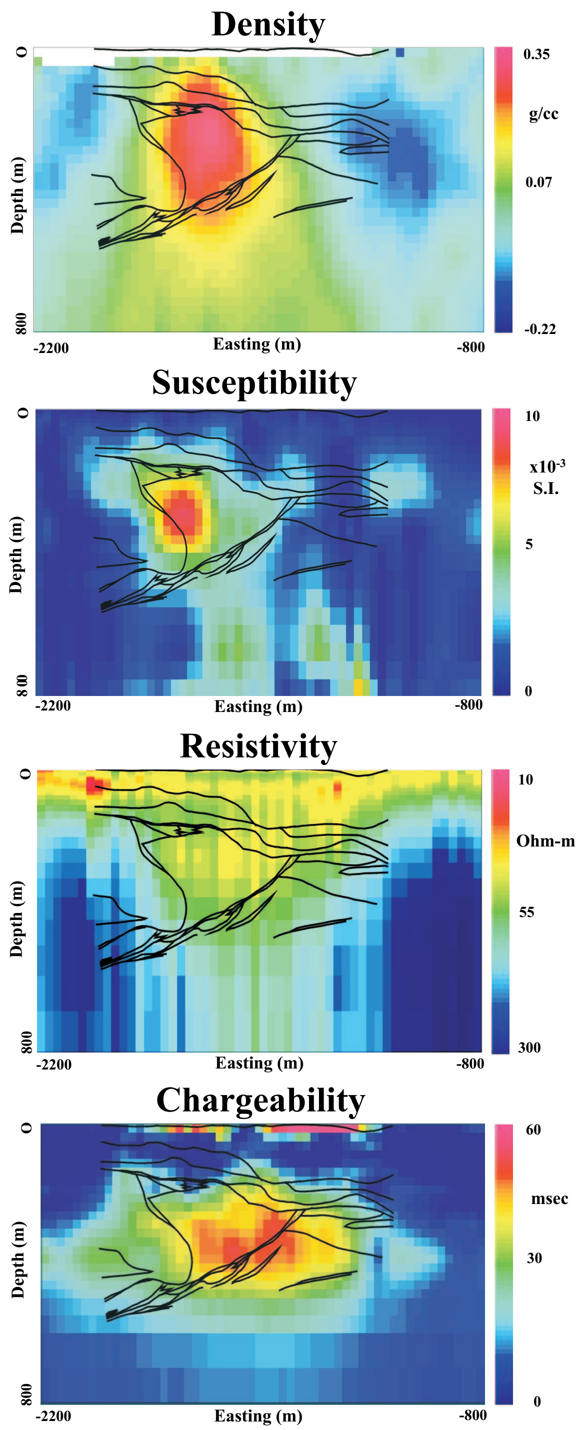

Fig. 4: North-facing cross-sections of local physical property inversion models with geology overlain.

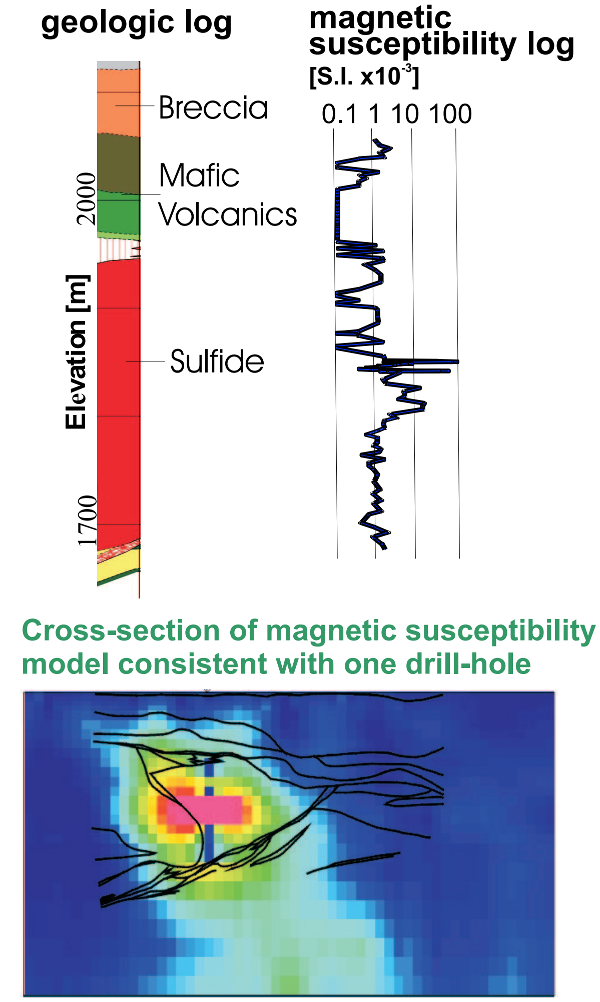

Fig. 5: Top: geologic and magnetic susceptibility log from a single drill-hole. Bottom: north-facing cross-section of magnetic susceptibility model that was generated by inverting ground magnetic data while honoring drill-hole measurements.

Detailed inversion

The next stage in the exploration process is to further delineate the mineralization that may have been found. Geophysical inversion can play a role at this delineation scale. If a target is drill tested, and whether or not mineralization is intersected, each drill-hole can provide additional information that can be used to further refine the inversion models. The inclusion of this data-independent information will help eliminate models that are inconsistent with known geology.

We use magnetic susceptibility measurements that were made on core from one drill-hole to constrain the inversion of ground magnetic data. The resulting model (Figure 5) shows a dramatic improvement in magnetic susceptibility distribution, and corresponds well with a known magnetic region in the deposit.

Conclusions

The effectiveness of geophysical inversion has been demonstrated by inverting various geophysical data sets at different stages of the exploration process. At the reconnaissance stage, the joint interpretation of gravity and magnetics was effective in localizing possible exploration targets. Integrated interpretations of ground-based inversions provided an unmistakeable target for the San Nicolás deposit and the incorporation of drill-hole information into the inversion generated enhanced detailed knowledge about the deposit. These results verify that high quality geophysical data and analysis can greatly increase the efficiency of finding and delineating mineral resources and expedite a drill program.

Acknowledgments

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