Innovations in Cross-hole Borehole DCIP Visualization

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Summary

In recent years significant advancements have been made in the development of borehole technologies to image off-hole resistivity and chargeability. These technologies aim to improve the understanding of the off-hole extent or presence of disseminated mineralization, in much the same way as borehole electromagnetic methods have been used over the past few decades. Despite the technological advances in data acquisition, data processing methods that enable the geologist to easily visualize the spatial location of borehole profiling and cross-hole tomography results continue to remain a challenge within the industry.

This paper presents the results of an Occam-type 2D inversion innovations that has been applied to high resolution EarthProbe cross-hole DCIP tomography data. The inversion algorithm is based on complex algebra to invert the resistivity and chargeability simultaneously. In undertaking 2D tomographic inversion in a mining scenario, where borehole configurations are typically 3D, consideration is given to the applicability of the 2D inversion algorithm. Enhanced spatial visualization and correlation with geologic information is achieved by subsequently presenting inversion results using a 3D platform, thus providing a product that can be readily used by geologists to guide exploration activities.

Introduction

Borehole resistivity and chargeability (DCIP) imaging can provide valuable assistance to mining exploration programs. In-hole data can provide information on the DCIP signatures of key lithologies and mineralization, thus enabling improved understanding of which geophysical signatures reflect geologic features of interest. Off-hole data provides information on the spatial extent and orientation of in-hole features, as well as identifies off-hole targets.

Spatial resolution is most effectively achieved through electrical DCIP tomography between boreholes. Cross-hole tomography is achieved through quadrapole measurements using many combinations of current (AB) and potential (MN) electrode positions to provide a very high resolution image.

Multi-electrode data acquisition system and adequate 2D/3D inversion algorithms have been developed and increasingly applied in resistivity/IP surveys over the past two decades in the environmental and geo-engineering field. In contrast, 2D and 3D inversion applications for mineral exploration has been limited due to challenges posed by non-planar borehole geometries and necessarily large mesh sizes which significantly complicate the inversion process. The adaptation of an Occam-type 2D inversion algorithm is tested on high-resolution EarthProbe cross-hole data to assess its ability provide geologically representative information in the mining/exploration field.

EarthProbe Borehole DCIP Technology

The EarthProbe DCIP system has emerged from a resistivity technology developed by Geoserve in Germany for geotechnical and hydrogeologic applications. The University of Toronto, through CAMIRO funding, and Caracle Creek, with the assistance of IRAP funding, tested and adapted the system for mining applications (Qian et al, 2007; Palich and Qian, 2011). The resultant EarthProbe DCIP system is successfully enabling geophysicists to adjust their scale of surveying to the scale of geologic features applicable to modern exploration projects. EarthProbe's narrow electrode spacing and ability to operate in multiple surface and borehole configurations facilitates both improved target delineation and characterization of host rock and mineralization signatures.

EarthProbe uses borehole cables with up to 24 electrodes spaced at either 4 m or 16 m with the capacity to profile boreholes up to 250 m or 400 m, respectively. Data are collected with the electrode array in a single borehole in which the current and potential electrode setup is the same as for a surface Schlumberger survey (Figure 1).

Vertical profiles provide information regarding in-hole features and can detect off-hole features up to 100 m from the borehole. The resistivity and chargeability information collected at the borehole can also be used to provide realistic bulk rock properties of the host rock and mineralized zones for improved characterization.

The EarthProbe system can also be configured to collect tomographic images. Cross-hole tomography, in which both current electrodes and potential electrodes are placed in two boreholes, can provide detailed information about resistivity distribution between the boreholes and assist in determining the orientation and connectivity of in-hole features between boreholes (Daniels 1977; Daniels

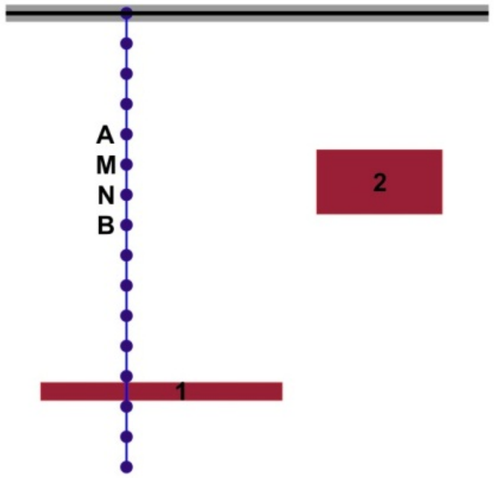

Figure 2: Electrode configuration for the single borehole vertical profiling surveys.

and Dyck 1984; Shima 1992). The configuration EarthProbe employs for cross-hole resistivity tomography was successfully proposed and demonstrated by Zhou and Greenhalgh (2000). In this configuration, the current electrodes and potential electrodes straddle the two boreholes (Figure 2).

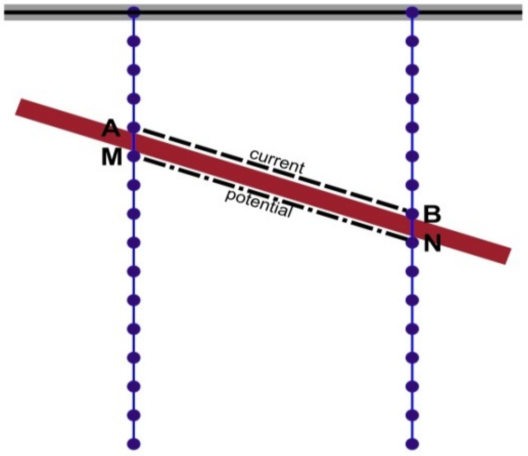

Figure 1: Electrode confirguration for cross-hole tomography surveys.

Challenges in Off-hole Visualization

Figure 3 presents "pseudosections" of the vertical profiling and cross-hole tomographic imaging results collected from two boreholes with a surface separation of 123 m. The two boreholes are non-planar with Borehole 1 oriented at an azimuth of 104^{o} and a dip of 67^{o} and Borehole 2 oriented at an azimuth of 95^{o} and dip of 71^{o}.

Vertical profiling identifies a low resistivity, high chargeability in-hole response in Borehole 1 associated with known gold mineralization and a predominantly off-hole response in association with narrow, low grade mineralization in Borehole 2. A second off-hole response is partially imaged below the in-hole anomaly in Borehole 1 and above the aforementioned feature in Borehole 2. The "bullseye" response in the tomography suggests a weak electrical and chargeable connectivity between the mineralized zones.

While pseduosection presentation provides some indication of the features present in association with the boreholes, two inherent challenges exist in visualising their spatial orientation:

- Single borehole vertical profiling does not confine the location of an anomaly within 3D space and therefore may represent the electrical response at that depth and distance from anywhere within a 360^{o} radius of the bore.
- Cross-hole tomographic data is necessarily presented as the AM-midpoint (X-axis) and BN-midpoint (Y-axis) effectively causing one borehole to be plotted against the other, which is spatially counterintuitive.

While the simple solution to these issues may be to conduct a 3D inversion of the data, several limitations often exist that prohibit 3D inversion from representing a viable processing option in many situations:

- In the absence of a 3D representative distribution of boreholes (nominally five or more) inversion artifacts are commonly generated;
- The narrow electrode spacing used to achieve rock property characterization combined with wide borehole spacings necessitates very large mesh generation because vertical and lateral mesh proportions must be maintained for inversion stability. This results in long inversion run-times that may not be practical for the delivery of useful results to support exploration programs;
- Typical non-vertical, non-parallel borehole orientations further add complexity to mesh generation and size.

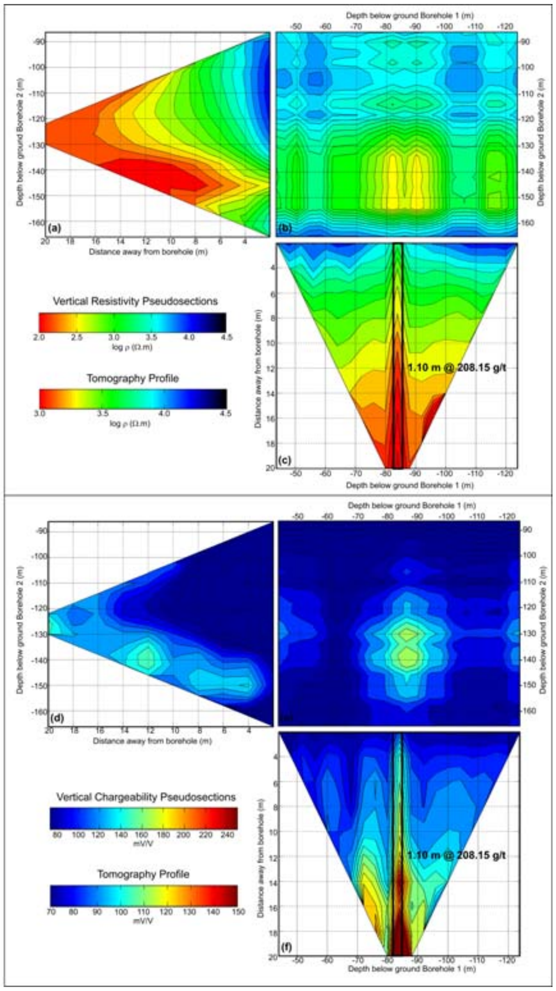

Figure 3: "Pseudosection" presentation of vertical profiling and tomographic results between two boreholes for a) vertical resistivity profile of Borehole 2, b) resistivity tomography between Borehole 1 and Borehole 2, c) vertical resistivity profile of Borehole 1, d) vertical chargeability profile of Borehole 2, b) chargeability tomography between Borehole 1 and Borehole 2, and c) vertical chargeability profile of Borehole 1.

2D Tomographic Inversion

Rapid 2D inversion of the cross-hole tomography data was undertaken on the example data to test its ability to resolve some of the spatial visualization issues previously identified.

2D tomography inversion results were obtained using a complex resistivity inversion algorithm originally proposed by Kemna and Binley (1996) and discussed in detail in Kemna (2000). The algorithm directly solves for conductivity magnitude and phase by consequent adoption of complex calculus. Although the approach is analogously applicable to 3D imaging (Shi et al., 1998; Yang et al., 2000), we assume that the region of interest may be represented as a 2D distribution. This is considered a fair approximation for the data presented because it exhibits a layered sequence of sediments with predominantly vertical rather than lateral conductivity variations. Accordingly, 3D effects in impedance data collected in a vertical image plane at the site are expected to be insignificant.

The tomography algorithm was developed for geotechnical and environmental applications where boreholes are almost always vertical and therefore all electrodes between boreholes can be defined on a single plane. This assumption does not hold true for most mining scenarios, including our example data. To undertake the 2D inversion for our data, a vertical plan was specified and then all electrode positions were projected onto this plane. Ideally, the boreholes should be onor closely aligned to this plane for the inversion results to accurately honour the data.

Results of the 2D inversion are presented in Figure 4 for resistivity. The accuracy of the model can be evaluated from the data presented in Figure 5 where the value of the measured data is plotted on the X- axis and the value of the predicted data is plotted on the Y- axis. Here we can see that the data is fitted reasonably well and there is no statistical bias in the data fit. If all the data are fitted perfectly, the data point should all be on the 45^0 slope red line.

In support of the strong statistical correlation, the inversion results honour the features identifed in both the single borehole vertical profiling and cross-hole tomography pseudosections. An in-hole feature is modelled in Borehole 1 at 80 m and a weaker in-hole feature is modelled at 140 m in Borehole 2. Additionally, an off-hole feature is imaged below the mineralized zone in Borehole 1 and above the mineralized zone in Borehole 2, consistent with the single borehole profiling results. This off-hole feature between the two mineralized zones appears to provide the source of electrical continuity between the boreholes that was identified by the cross-hole tomography.

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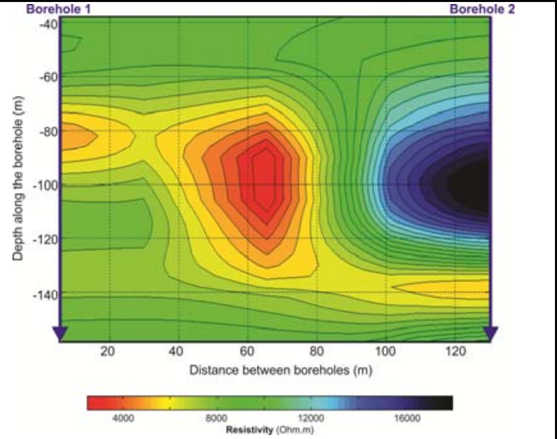

Figure 4: Results of the 2D cross-hole tomography inversion for resistivity.

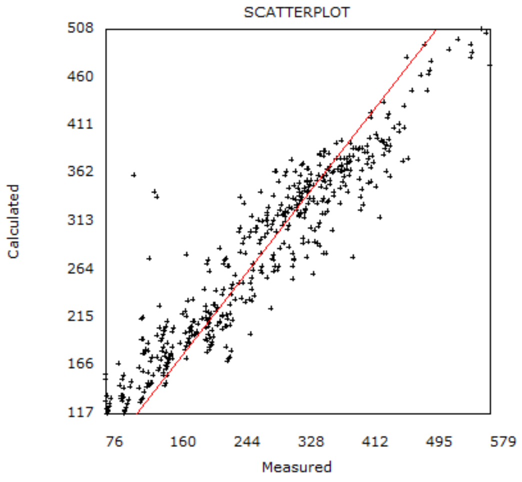

Figure 5: Scatterplot depicting the error between the measured and calculated data from the 2D resistivity inversion. The 45^0 sloped red line represents perfect agreement between the measured and calculated data.

3D Reconstruction

The final stage of the interpretation involves reconstructing the 3D orientation of the data to reflect the non-vertical plane from which the data were collected. The GoCAD platform was used for this purpose. Figure 6 presents the results of this process, with the 2D chargeability inversion results draped between the boreholes. The GoCAD platform futher enables the geophysical inversion to be presented along with geologic information including lithology and gold assay concentration. The result is an enhanced ability to spatially visualise the relationships between the DCIP data and key geologic exploration parameters, thus facilitating improved targeting using the borehole data.

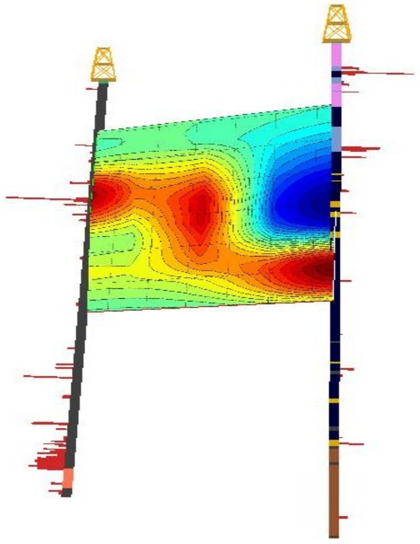

Figure 6: 3D representation of the 2D cross-hole tomography chargeability inversion, presented with comparison lithology (along the boreholes), and gold concentration (projected outwards from the boreholes).

Conclusions

The EarthProbe high resolution DCIP system has been demonstrated to be able to collect and meaningfully invert cross-hole tomography data. Despite the necessity to extrapolate cross-hole data off-plane using 2D inversion algorithms, tomographic inversion results are demonstrated to provide accurate spatial reconciliation of the information gathered by both single borehole profiling and cross-hole tomography. The ability to subsequently project the inversion results in true 3D space facilitates the geologic interpretation and spatial visualization process necessary to make cross-hole tomography a valuable exploration tool for the exploration and mining industry.

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