BOREHOLE RESISTIVITY TOMOGRAPHY FOR MINERAL EXPLORATION

W. Qian[1,2], B. Milkereit[1] and M. Gräber[3]

[1]Dept. of Physics, University of Toronto, Canada
[2]Geoserve Logging & Tomography, 42 Oakford Dr., Markham, Ontario, L6C 2Y8, Canada,
e-mail: wei.geoserve@gmail.com
[3]GeoServe Angewandte Geophysik, Kiel, Germany

SUMMARY

This paper focuses on the use of cross-borehole electric methods in ore body delineation. A BRT (Borehole Resistivity Tomography) test survey has been conducted to map massive and semi-massive sulfide zones between boreholes up to 180 m apart. The boreholes need to be water filled, so as the electrode array couples to the rock formation. We have established a multi-step procedure for data acquisition, processing and interpretation. Between boreholes, we have successfully imaged the massive sulfide mineralization in a moderately conductive host.

INTRODUCTION

Electric resistivity surveying along the earth's surface is a well-known geophysical exploration technique. Due to its conceptual simplicity, low equipment cost and ease of use, the method is routinely used in mineral exploration. Borehole resistivity tomography, in which both current electrodes and potential electrodes are placed in two boreholes, can provide detailed information about resistivity distribution between the boreholes (Daniels 1977; Daniels and Dyck 1984; Shima 1992). Daniels and Dyck (1984) demonstrated a variety of applications of borehole resistivity measurements to mineral exploration. Unfortunately these early case histories didn't include an inversion of the data. Conventional mise-a-la-masse types of measurements are carried out by placing a current electrode in a conductive zone and measuring the potential field distribution in one or more boreholes (Mwenifumbo, 1997). Recently, with enhanced computing resources, there has been increasing interest to construct tomographic images through geophysical inversions (Loke and Barker, 1995, 1996). However, smoothness constraint OCCAM type of inversion often yield unsatisfactory results, particularly when there are large contrasts in the resistivity model, a situation often encountered in mineral exploration.

During the summer of 2006, we collected several single borehole Vertical Resistivity Profiling (VRP), borehole-to-borehole, and borehole-to-surface resistivity tomography (BRT) data sets across three different massive sulfide deposits. Here we report results from the Nash Creek Zn-Pb-Ag deposit, New Brunswick, Canada. The Nash Creek Zn-Pb-Ag deposit is located along the western margin of the Jacquet River Graben in northeastern New Brunswick (Canada). Ordovician to Devonian age strata form part of the Tobique Volcanic Belt (Dostal et al., 1989) and comprise a succession of intra-cratonic, rift-related bimodal mafic to felsic volcanic rocks with interstratified sedimentary strata. Sulfide mineralization occurs as stratabound and laterally continuous zones of matrix filling or replacement style mineralization, as fracture filling within flow or pyroclastic units, and as discrete breccia zones. The mineralized environments are charcterized by strong clay alterations, silification and carbonitization. At Nash Creek, wide spread brecciation and alteration zones (often associated with a pyrite-rich matrix) pose a problem for conventional electromagentic exploration methods: high-grade sulfides (good conductors) are imbedded in laterally extensive alteration envelopes (moderate conductors).

The boreholes were water filled and borehole to borehole separation varied from 40 m to 180 m. The data acquisition system was developed by Geoserve in Germany for near surface archaeological and hydrological applications. What is unique about the borehole resistivity system is its electrode and borehole cable design, which allow seamless integration of borehole and surface measurements. The use of borehole cables with up to 24 electrodes each allows the system to acquire more than one thousand resistance readings per hour. The data acquisition geometries are shown in Figure 1. The configuration for cross borehole resistivity tomography was proposed by Zhou and Greenhalgh (2000). In this configuration, the current electrodes and potential electrodes straddle the two boreholes. Very clean waveform data has been acquired for both configurations (Figure 1 d-e). In this paper, we follow the popular convention and use “A” to denote the positive current electrode, “B” the negative current electrode, “M” the positive potential electrode and “N” the negative potential electrode.

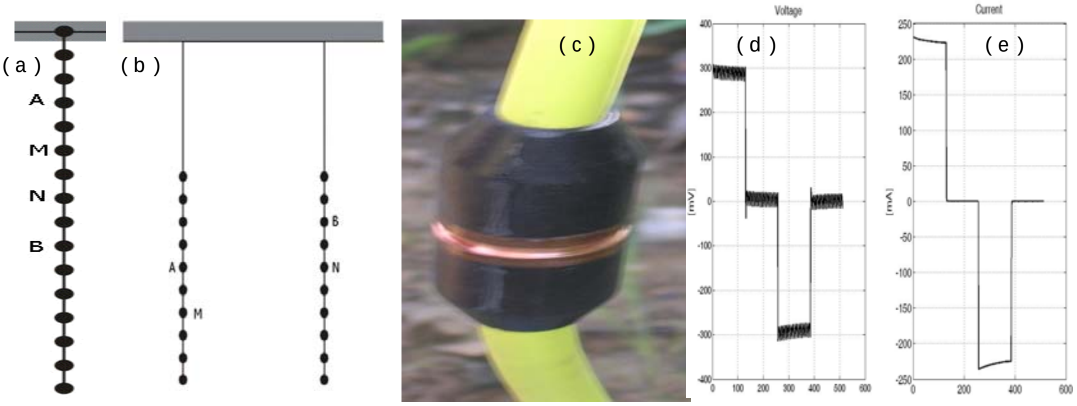

Figure 1: (a) borehole electrode cable deployment for vertical resistivity profiling; (b) cross borehole tomography; (c) copper-ring electrode; (d) measured voltage waveform; and (e) injected current waveform for 180 m electrode separation between boreholes.

VERTICAL RESISTIVITY PROFILING

From the electrode array in a single borehole, we perform Vertical Resistivity Profiling (VRP), in which the current and potential electrode setup is the same as surface Schlumberger survey. The measured voltages are converted into apparent resistivity through a geometry factor, which takes into account the earth-air surface. The apparent resistivity pseudo-section is created by assigning the apparent resistivity at AB/2 away from the borehole. An example of such a pseudo-section is shown in Figure 2, in which we can clearly identify that the sulfide zone has a resistivity of less than 15 ohm.m. This zone is located between the depths of 82 and 97 m and its lateral extension is more than 40 m. However, from the measurements in a single borehole, we can not determine the azimuth (direction) of this extension. Surface electrode lines must be deployed for the determination of the azimuth. VRP has another advantage in that it provides bulk resistivity measurements. Conventional resistivity logging provides resistivity readings on a scale of tens of centimeters, while VRP measures bulk resistivity on a scale of ~ 10 m. Although the borehole induction electromagnetic methods are sensing bulk resistivities, they have no resolution for resistive and moderately resistive formations. VRP resistivity data can be used for calibration / interpretation of other EM datasets.

CROSS BOREHOLE ELECTRIC CURRENT MAPPING

When a constant injection voltage is applied between electrodes A and B across the two boreholes as shown in Figure 3, the electric current flowing between A and B depends on the contact resistances of electrodes A and B, and the rock formation resistance from A to B. If the borehole is water filled, we can assume the contact resistance is uniform. Thus the electric current from A to B maps the rock formation resistance between points A and B. An example of the electric current between A and B is shown in Figure 3. Note the data shows characteristics of two conductive zones (marked I and II in Figure 3) between the two boreholes. The borehole separation is 65 m.

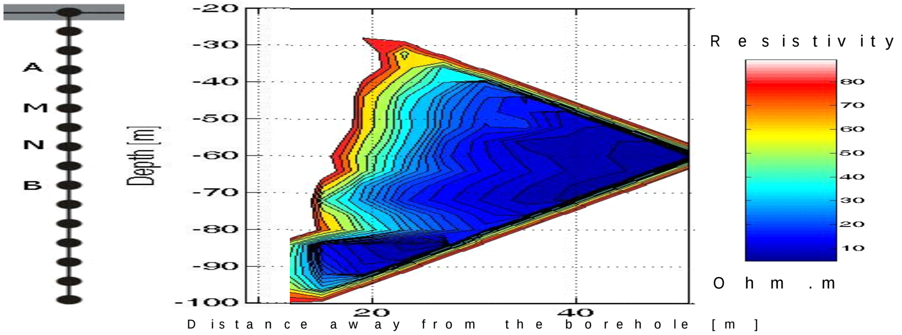

Figure 2: VRP apparent resistivity pseudo-section. Note the low resistivity (< 15 ohm.m) mineralization encountered between the depths of 82 and 97 m, extending more than 40 m away from the borehole.

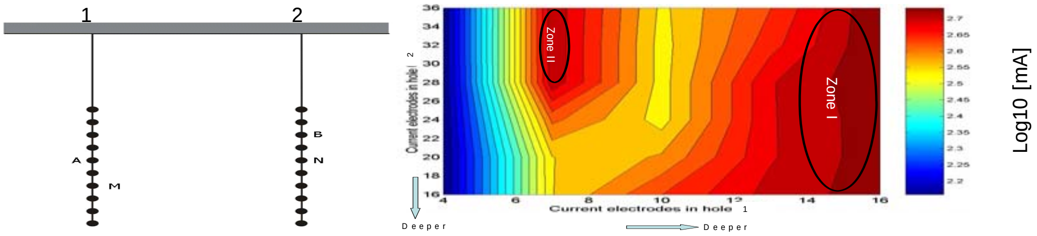

Figure 3: Quality control of electric current flowing between electrodes in two boreholes with constant voltage excitation.

CROSS BOREHOLE RESISTIVITY TOMOGRAPHY (BRT)

We construct the BRT model by applying the following steps: (1) use VRP pseudo section to build a starting model at the two borehole locations; (2) perform inversion on VRP data only (use the starting model to constrain the inversion, no smoothness stabilizations applied); (3) build a starting model between two boreholes using the two resistivity inversion models derived from VRP data; (4) constrain the near borehole resistivities and let the tomography inversion adjust the resistivities in the central region; and finally (5) fine tune the tomography inversion model with geological / petrophysical constraints (where available). The BRT shown in Figure 4 indicates continuity (zone I) of the conductive massive sulfide (< 15 ohm.m) between the two boreholes. Conductive zone II is restricted to the immediate vicinity of borehole 2.

CONCLUSIONS AND OUTLOOK

Single borehole VRP data can detect conductive zones within a 30 m range around the borehole and it also provides an independent estimate of bulk (4 - 100 m) resistivity for calibration / interpretation of other EM datasets. The cross-borehole tomography data can map conductive zones between boreholes up to 180 m apart. In the future, we plan to: (a) refine our 2D inversion procedures; (b) optimize the data acquisition and QC procedures; (c) study the 3D effects and develop 3D tomography methodologies; (d) utilize the IP information in the waveform data; and (e) build electrode cables for deployment in boreholes deeper than 200 m.

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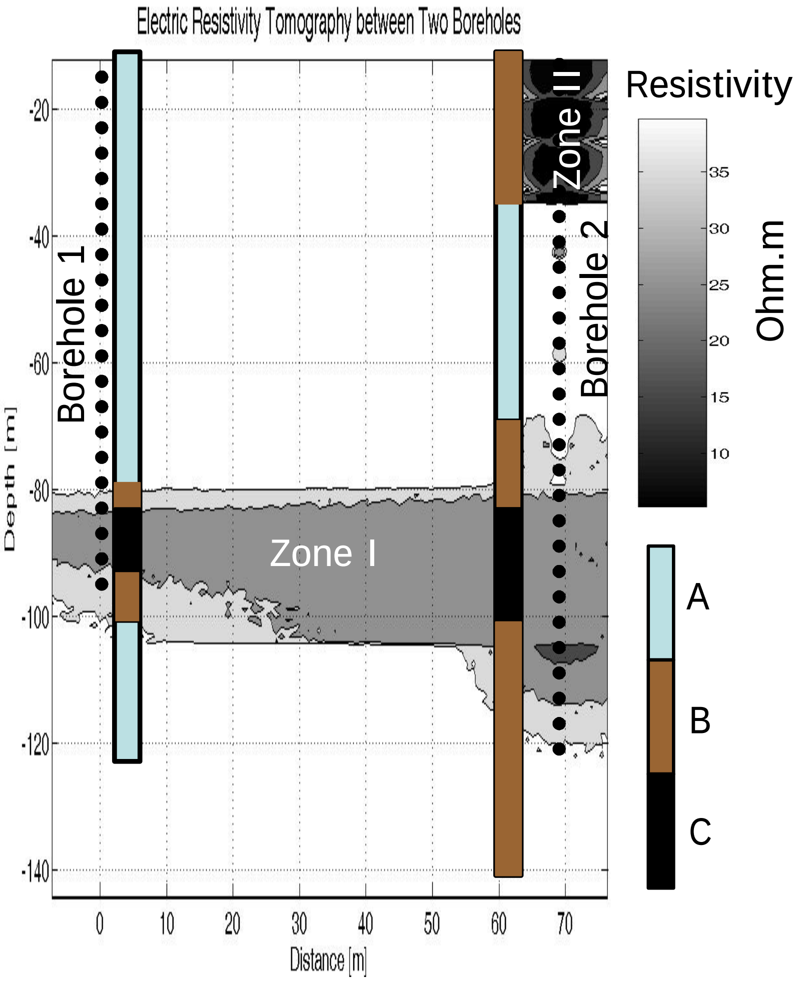

Figure 4: BRT between two boreholes with overly of key lithological units; A: alteration bleached, no significant Zn mineralization or Pyrite-content, resistivity larger than 40 ohm.m; B: brecciation, matrix Pyrite rich (5 – 10 % Pyrite), less than 1% Zn content, resistivity between 15 and 40 oh.m; C: strong brecciation, often more than 5% Zn content, resistivity less than 15 ohm.m. Black dots represent the electrode positions in the two boreholes.