3D inversion of SPECTREM and ZTEM data from the Pebble Cu-Au-Mo porphyry deposit, Alaska

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SUMMARY

This case study compares 3D inversion results from Spectrem Air's SPECTREM 2000 fixed-wing time-domain airborne electromagnetic (AEM) system, and Geotech's Z-axis Tipper Electromagnetic (ZTEM) airborne audio-frequency magnetics (AFMAG) system flown over the Pebble Cu-Au-Mo deposit in Alaska. Within the commonality of their physics, 3D inversions of both SPECTREM and ZTEM recover conductivity models consistent with each other and with the known geology. Both 3D inversions recover conductors coincident with alteration associated with both Pebble East and Pebble West. The 3D interpretation of both surveys has yielded improved the understanding of the geology, alteration and mineralization of the Pebble system. There are distinct practical advantages to the use of both SPECTREM and ZTEM, so we draw no recommendation on one system over the other. We do conclude however, that 3D inversions of AEM and ZTEM surveys add significant value to exploration.

Key words: 3D, inversion, AEM, AFMAG, SPECTREM, ZTEM, Pebble.

INTRODUCTION

Pebble is a calc-alkalic Cu-Au-Mo porphyry deposit located in the Bristol Bay region of southwest Alaska, approximately 320 km southwest of Anchorage and 27 km west-northwest of the village of Iliamna (Figure 1). Development of the Pebble deposit is managed by Pebble Limited Partnership (PLP), a joint venture between Northern Dynasty Mines Ltd (50%) and Anglo American plc (50%). Since discovery in 1988, over 886,177 feet of drilling in 1,085 holes have been completed, making Pebble one of the most intensively studied, undeveloped mineral systems in the world. At a 0.30% Cu equivalent cut-off, the latest Pebble resource estimate includes 5.942 billion tonnes in the measured and indicated category containing 25.0 million tonnes of copper, 66.9 million ounces of gold and 1.5 million tonnes molybdenum; and 4.835 billion tonnes in the inferred category, containing 11.6 million tonnes of copper, 40.4 million ounces of gold and 1.0 million tonnes of molybdenum. This resource base makes Pebble the largest gold and sixth largest copper deposit in the world.

Figure 1. Pebble location in southwest Alaska.

In 2009, a 3,840 line km SPECTREM AEM, magnetic and radiometric survey was flown over the Pebble district. The survey was done in two stages; a regional survey at 1500 m flight-line spacing, covering an area of approximately 30 km x 12 km, and a more detailed survey at 250 m flight-line spacing along strike of the Pebble deposit. Also in 2009, a 250 line km helicopter ZTEM AFMAG and magnetic survey was flown at 200 m line spacing over the Pebble deposit. Previous analyses (e.g., Pare and Legault, 2010) utilized 1D conductivity depth images, time constants and anomaly picking for interpretation of the SPECTREM data, and 2D inversion of one tipper component for interpretation of the ZTEM data. With the availability of 3D inversion for both SPECTREM and ZTEM, we have reinterpreted both surveys independently, and are now able to make a more quantitative assessment of the merits for both airborne electromagnetic methods for the exploration of porphyry systems such as Pebble.

EXPLORATION HISTORY

The Pebble deposit is underlain by Jura-Cretaceous to Eocene igneous and sedimentary rocks. The Pebble deposit is a calc-alkalic Cu-Au-Mo porphyry deposit which formed in association with granodiorite intrusions emplaced at roughly

90 Ma. The deposit comprises of the contiguous Pebble West and Pebble East Zones (Figure 2), discovered in 1986 and in 2005, respectively. Mineralization at Pebble West occurs around small granodioritic stocks that intrude the country rocks. The Pebble East mineralization occurs within a granodioritic stock and in sills that cut the country rocks. Pebble West extends to surface and Pebble East is entirely overlain by east-thickening, younger volcano-sedimentary cover, up to 600 m thick. Pebble is bounded to the southeast by the major ZG1 dip-slip fault, east of which the deeper Far East Zone has been discovered in 2006 with a deep hole (DDH6438), drilled east of ZG1 fault identified at > 1.5km depths (Figure 3).

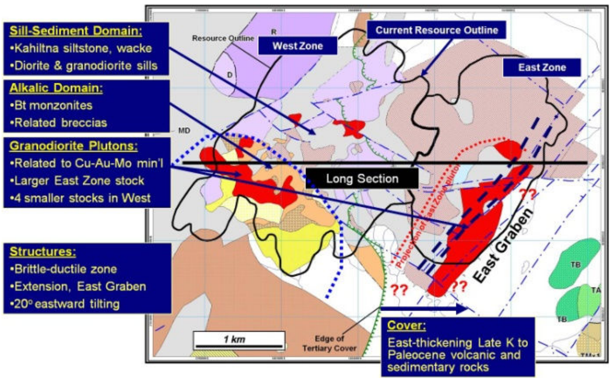

Figure 2. Geology of the Pebble deposit.

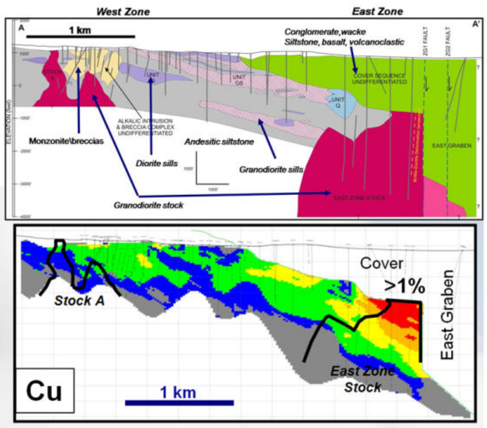

Figure 3. East-west oriented vertical cross section of the geology (upper panel) and mineralization (lower panel) of the Pebble West and Pebble East zones.

The deposit hosts K-silicate alteration and associated quartz-sulphide veins, overprinted by phyllo-silicate alteration. Sulphides mainly consist of hypogene pyrite, chalcopyrite, molybdenite and bornite; supergene and thin oxide zones also occur at Pebble West. High grade mineralization at Pebble East is associated with advanced argillic alteration. The Cu-Au-Mo mineralization, as it is currently known, extends over an east-elongated area of 4.9 by 3.3 km, and to a depth of 610 m at Pebble West, and at least 1525 m at Pebble East. The deposit is open to the east, south, northwest and southeast; a larger zone of strong alteration and low grade mineralization extends to the north, south and west. The Pebble deposit mineral resource, at a 0.30% Cu equivalent cut-off, consist of 5.942 billion tonnes of measured and indicated resources grading 0.42% Cu, 0.35 g/t Au, and 250 ppm Mo.

From 1988 to 2001, induced polarization (IP) and resistivity surveys utilized both time-domain and phase IP in both dipole-dipole and pole-dipole configurations. These surveys defined a chargeability anomaly within the Cretaceous rocks that was about 91 km2 in extent, measuring approximately 21 km north-south and nearly 10 km east-west. This contained 11 distinct centers reflected by stronger chargeability anomalies, many of which were later demonstrated to be coincident with extensive Cu, Au and Mo soil geochemical anomalies. All known zones of Cretaceous age mineralization occur within this broad IP anomaly. In 2009, a time-domain IP survey utilized a larger, deeper penetrating array. Analysis of that data is beyond the intended scope of this paper.

In 2009, Spectrem Air Ltd conducted a SPECTREM AEM, magnetic and radiometric survey over the Pebble district. A total of 3,840 line kilometres were flown. The survey was done in two stages; a regional survey at 1500 m flight-line spacing, covering an area of approximately 30 km x 12 km, and a more detailed survey at 250 m flight-line spacing along strike of the Pebble deposit. The SPECTREM system is a 100% duty cycle square wave of 45 Hz base frequency measuring inline and vertical B-fields (Leggatt et al., 2000). At Pebble, the transmitter was flown with a nominal ground clearance of 107 m, with the receiver towed 37.1 m below and 122.2 m behind.

Also in 2009, Geotech Ltd conducted a helicopter ZTEM AFMAG and magnetic survey over the Pebble deposit. A total of 250 line km were flown with a flight line spacing of 200 m covering approximately 60 km^2. ZTEM is an audio-frequency magnetic (AFMAG) system that measured both Z/X and Z/Y tipper components at five frequencies; 30 Hz, 45 Hz, 90 Hz, 180 Hz, and 360 Hz. At Pebble, the receiver was flown with a nominal ground clearance of 89 m.

3D INVERSION METHODOLOGY

Our 3D frequency-domain modeling of fields and their sensitivities is based on an implementation of the contraction integral equation method that exploits the Toeplitz structure of large, dense matrix systems in order to solve multiple source vectors on the right-hand side using an iterative method with fast matrix-vector multiplications provided by a 2D FFT convolution (Hursán and Zhdanov, 2002). Once the Green's tensors have been pre-computed, they are stored and re-used, further reducing run time. Once computed, the magnetic fields and their sensitivities can be transformed to the AEM system response (for AEM) (e.g., Raiche, 1998) or tipper components (for ZTEM) (e.g., Holtham and Oldenburg, 2010).

Both our 3D AEM and ZTEM inversions are based on the re-weighted regularized conjugate gradient (RRCG) method. Data and model weights which reweigh the inverse problem in logarithmic space are introduced in order to reduce the dynamic range of both the data and the conductivity. Traditional regularized inversion methods recover smooth solutions, and thus have difficulties recovering sharp boundaries between different geological formations without having a priori information about those boundaries enforced. Our use of focusing regularization makes it possible to recover subsurface models with sharper resistivity contrasts and boundaries than can be obtained with smooth stabilizers, and do not require those boundaries to be enforced a priori (Zhdanov, 2002, 2009).

For 3D AEM inversion, Cox et al. (2010) introduced a practical inversion methodology which exploited the AEM system's limited footprint. The footprint of each transmitter-receiver pair is a sub-domain of the 3D earth model, and this sub-domain is used for 3D modelling of fields and sensitivities. As the footprints of all the transmitter-receiver pairs superimpose themselves over the 3D earth model, the sensitivity matrix for the 3D earth model is constructed. This sensitivity matrix is used for updating the model parameters for the 3D earth model so as to minimise the misfit between the observed and predicted data. This strategy makes it practical to invert tens of thousands of stations of time- or frequency-domain AEM data to models with millions of cells within just hours on multi-processor workstations.

3D ZTEM inversion is an analogue of 3D magnetotelluric (MT) inversion. For example Holtham and Oldenburg (2010) introduced their 3D ZTEM inversion based on modifications of the 3D MT inversion by Farquharson et al. (2002). Similarly, our 3D ZTEM inversion is an analogue of the 3D MT inversion by Zhdanov et al. (2011). One key difference between our 3D ZTEM inversion and that of Holtham and Oldenburg (2010) is that we also employ a footprint approach for each receiver. Unlike the footprint for AEM, the footprint for ZTEM is only applied to the computation of the sensitivities and not the modelling. This permits us to efficiently compute, store and manipulate the sensitivities for very large surveys.

INTERPRETATION

The depth of investigation for SPECTREM was about 750 m below the surface, and for ZTEM was about 1500 m below the surface. Both 3D SPECTREM and ZTEM inversions recovered Pebble's main alteration pattern and the known structures ZF, ZC, ZE and ZG1 (Figures 6 and 7). Generally speaking, the 3D SPECTREM inversion recovered the geological features and structures with better accuracy than the 1D inversion and CDIs. As expected, the 3D inversion produced better lateral model continuity from line to line than the non-3D inversions (e.g., Figure 4). Also, the 3D ZTEM inversion recovered the geological features and structures with better accuracy than the 2D inversions of the same data (e.g., Figure 5). As expected, the 3D inversion with focusing regularization produced sharper contrasts and better lateral model continuity from line to line than the 2D inversions with smooth regularization.

Further analysing the 3D SPECTREM and ZTEM inversions, we can make the following correlations between conductivity and known geology:

- The highly conductive zones to the known illite-pyrite and advanced argillic alteration parts of the system;
- The weak conductive zone and resistive high beneath the Pebble West and East zones are characterized by sodic-potassic, K-silicate and deep sodic-calcic domains;
- The high conductive zone on line L21370 above the Pebble East zone and confined between the ZE and ZG1 faults is associated with the advanced argillic alteration that overprints the highest grades;
- The moderately conductive layer near the surface above the Pebble East zone and to the east appears to be related with the tertiary cover;
- The main known structures (ZF, ZC, ZE and ZG1) are well resolved, and correlate with the breaking pattern of the 3D conductivity models; especially the ZG1 fault to the east of Pebble East.

The geometry of the 3D SPECTREM and ZTEM inversions follow the general trend of to the alteration and ore geometry. However the correlation between conductivities and mineralization is not as directly coincident as with the alteration pattern. This suggests that the sulphide content is not a major factor in either the SPECTREM or ZTEM responses. The high grade CuEq 0.6% is not consistently following the high conductive trend. The conductive zones contrasts are mostly coincident with alteration change.

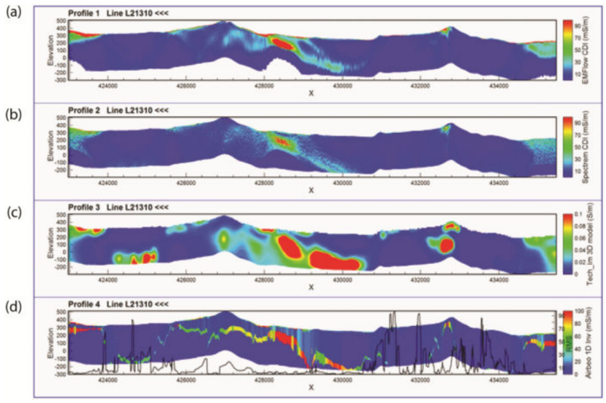

Figure 4. Comparison of (a) EMFlow CDI, (b) SPECTREM CDI, (c) 3D inversion, and (d) AirBeo 1D inversion for SPECTREM line L21310.

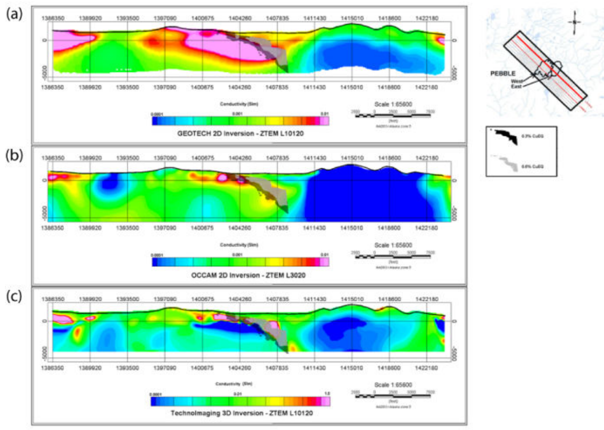

Figure 5. Comparison of (a) 2D inversion (by Geotech), (b) 2D inversion (by Condor Consulting) and (c) 3D inversion for ZTEM line L10120. The CuEq 0.3% and CuEq 0.6% ore shells are superimposed on each model.

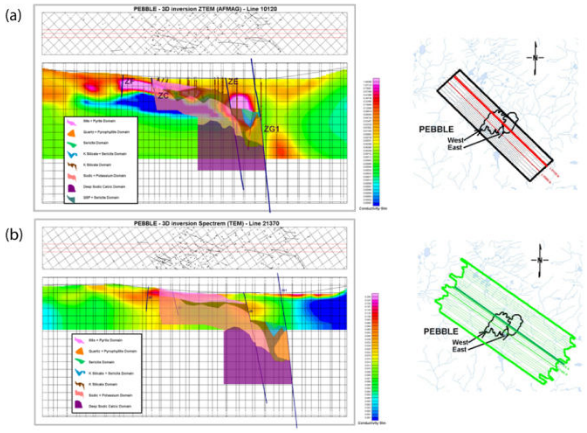

Figure 6. Comparison of (a) 3D ZTEM inversion for ZTEM line L10120 and (b) 3D SPECTREM inversion for SPECTREM line L21370, with alteration patterns superimposed.

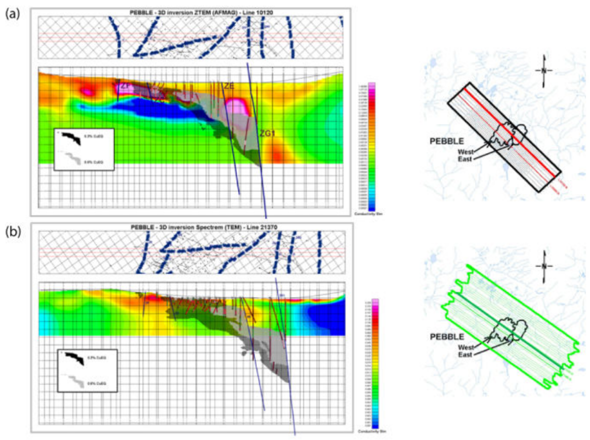

Figure 7. Comparison of (a) 3D ZTEM inversion for ZTEM line L10120 and (b) 3D SPECTREM inversion for SPECTREM line L21370, with CuEq 0.3% and CuEq 0.6% mineralization shells superimposed.

CONCLUSIONS

3D inversions of SPECTREM and ZTEM surveys over the Pebble deposit have been examined. For SPECTREM, we compared our 3D inversion results with conductivity depth images and 1D inversion results. For ZTEM, we compared our 3D inversion results with 2D inversion results. Both of our 3D inversions recovered models more consistent with the known geology than those obtained from non-3D methods. Moreover, both SPECTREM and ZTEM inversions recovered 3D models that were consistent within the commonality of their physics, and which corresponded well with the known geology. As in any exploration project, interpretation of both surveys has yielded improved the understanding of the geology, alteration and mineralization of the Pebble system. There are distinct practical advantages to the use of both SPECTREM and ZTEM, so we draw no recommendation on either system. We can conclude however, that 3D inversion of AEM and ZTEM surveys adds significant value to exploration.

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