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

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Abstract. Geological, geochemical, and geophysical surveys have been conducted in the area of the Pebble Cu–Au–Mo porphyry deposit in south-west Alaska since 1985. This case study compares three-dimensional (3D) inversion results from Anglo American's proprietary SPECTREM 2000 fixed-wing time-domain airborne electromagnetic (AEM) and Geotech's ZTEM airborne audio-frequency magnetics (AFMAG) systems flown over the Pebble deposit. Within the commonality of their physics, 3D inversions of both SPECTREM and ZTEM recover conductivity models consistent with each other and the known geology. Both 3D inversions recover conductors coincident with alteration associated with both Pebble East and Pebble West. The high grade CuEqn 0.6% ore shell is not consistently following the high conductive trend, suggesting that the SPECTREM and ZTEM responses correspond in part to the sulphide distribution, but not directly with the ore mineralization. As in any exploration project, interpretation of both surveys has yielded an improved understanding of the geology, alteration and mineralization of the Pebble system and this will serve well for on-going exploration activities. There are distinct practical advantages to the use of both SPECTREM and ZTEM, so we draw no recommendation for either system. We can conclude however, that 3D inversion of both AEM and ZTEM surveys is now a practical consideration and that it has added value to exploration at Pebble.

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

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Introduction

Pebble is a calc-alkalic Cu–Au–Mo porphyry deposit located in the Bristol Bay region of south-west Alaska, ~320 km south-west of Anchorage and 27 km west-north-west of the village of Iliamna (Figure 1). Development of the Pebble Cu–Au–Mo mine 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 268,538 m of drilling in 1085 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.

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. Mineralization at Pebble West occurs around small granodioritic stocks that intrude the country rocks. The deposit comprises of the contiguous Pebble West and Pebble East Zones (Figures 2 and 3), discovered in 1986 and 2005, respectively. The Pebble East mineralization occurs within a granodioritic stock and in sills that cut the country rocks (Figure 4). 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 south-east by the major ZG1 dip-slip fault (Figure 3), east of which the deeper Far East Zone has been discovered in 2006.

The deposit hosts potassium-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 (Figure 4). The Cu–Au–Mo mineralization, as it is currently known, extends over an east-elongated area of 4.9 km 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, north-west and south-east; a larger zone of strong alteration and low grade mineralization extends to the north, south and west.

Fig. 1. Pebble location in south-west Alaska, USA.

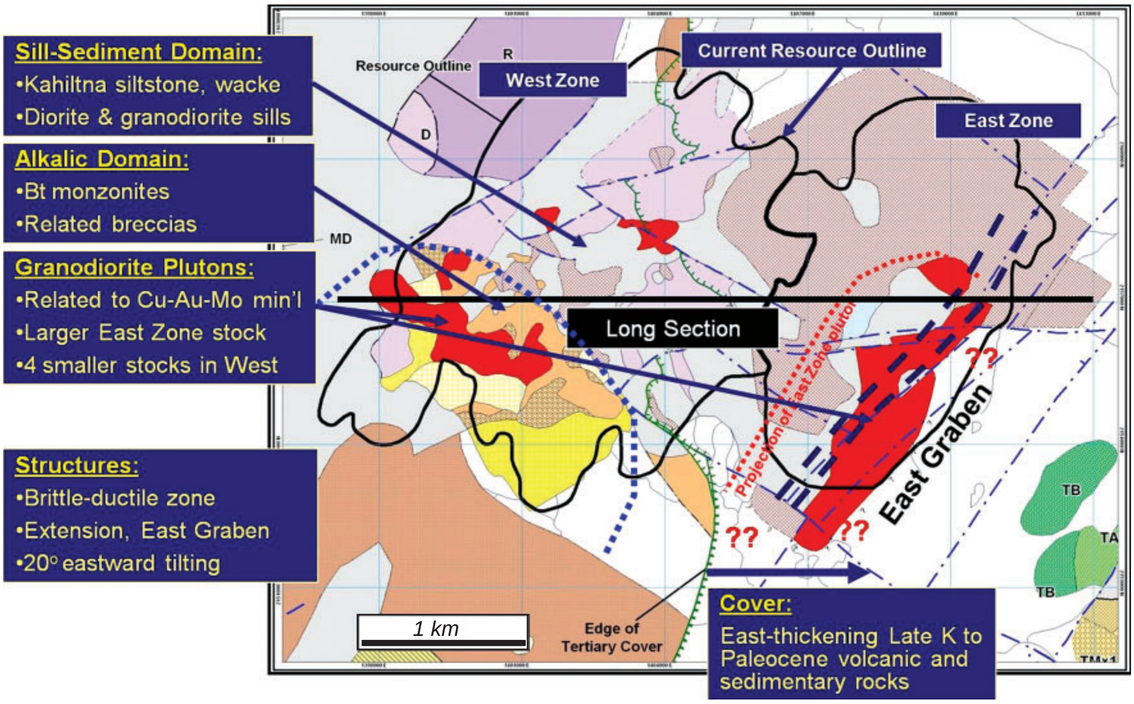

Fig. 2. Geology of the Pebble deposit showing Pebble West and Pebble East zones.

In 2009, Spectrem Air Ltd conducted a SPECTREM 2000 fixed-wing time-domain AEM, magnetic and radiometric survey over the Pebble district (Figure 5). A total of 3840 line kilometres were flown. The survey was done in two stages; a regional survey at 1500 m flight-line spacing, covering an area of ~30 km × 12 km, and a more detailed survey at 250 m flight-line spacing along strike of the Pebble deposit (Figure 6). The SPECTREM 2000 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 and magnetic survey over the Pebble deposit (Figures 5 and 7). ZTEM is an audio-frequency magnetic (AFMAG) system that measured both Z/X (inline) and Z/Y (transverse) tipper components at five frequencies; 30 Hz, 45 Hz, 90 Hz, 180 Hz, and 360 Hz. A total of 250 line km were flown with a flight line spacing of 200 m covering ~60 km^2. At Pebble, the receiver was flown with a nominal ground clearance of 89 m.

Previous analyses (e.g. Pare and Legault, 2010) utilised 1D conductivity depth images, time constants and anomaly picking for interpretation of the SPECTREM$_{2000}$ 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, and are now able to make a more quantitative assessment of the merits of both AEM methods for the exploration of porphyry systems such as Pebble.

Inversion methodology

For 3D AEM inversion, a practical inversion methodology was introduced by Cox et al. (2010) who exploited the limited footprint of AEM systems. The footprint of each transmitter-receiver pair is a sub-domain of the entire 3D earth model, and this

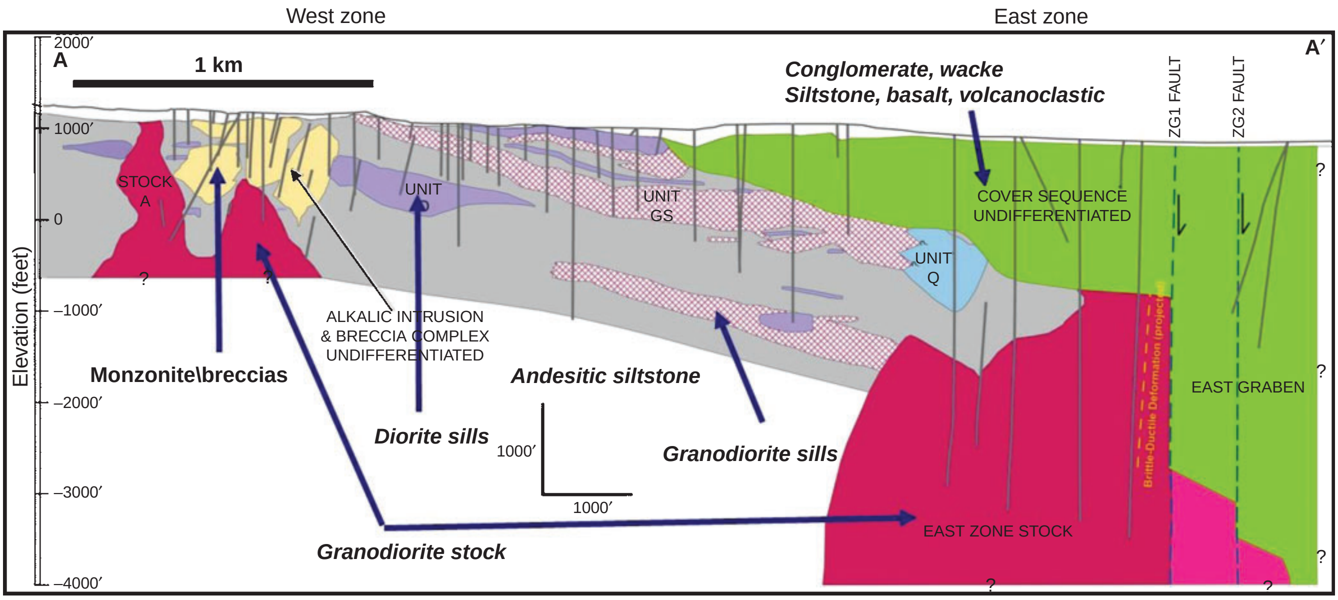

Fig. 3. East–west oriented vertical cross section of the geology of the Pebble West and Pebble East zones.

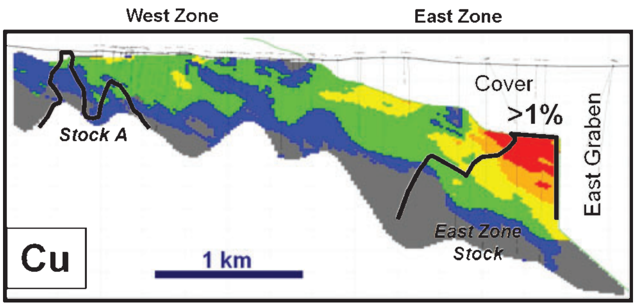

Fig. 4. East–west oriented vertical cross section of the copper mineralization of the Pebble West and Pebble East zones.

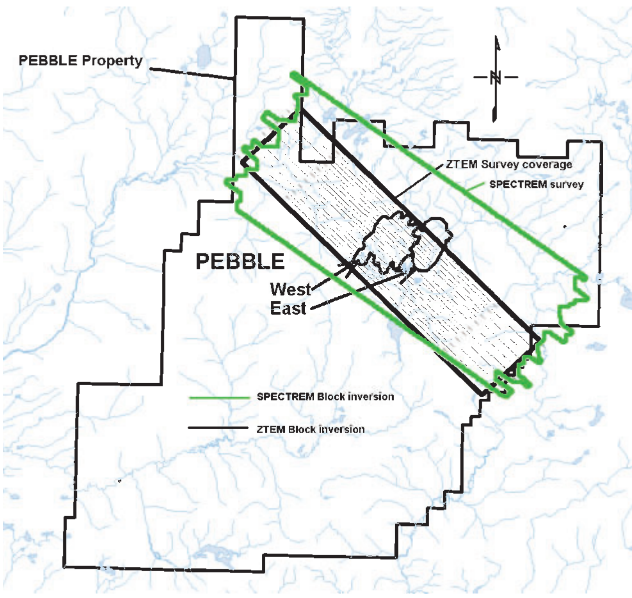

Fig. 5. Plan view of SPECTREM and ZTEM surveys with Pebble deposit and property outlines superimposed.

sub-domain is used for 3D modelling of fields and sensitivities. As the footprints of all the transmitter-receiver pairs superimpose themselves over the entire 3D earth model, the sensitivity matrix

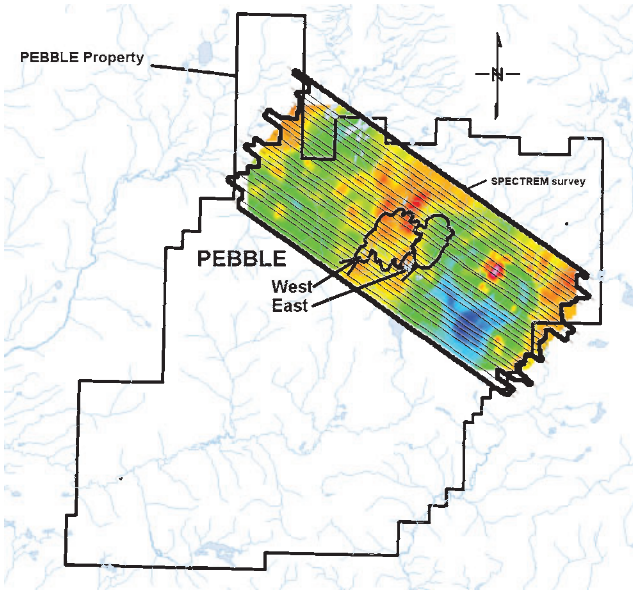

Fig. 6. Plan view of the SPECTREM survey with the time constant (tau), and Pebble deposit and property outlines superimposed.

for the entire 3D earth model is constructed. This sensitivity matrix, for the entire model, is used for updating the model parameters 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 mega-cell earth models 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 employ a footprint approach for each receiver. This permits us to efficiently compute, store and manipulate the sensitivities for very large surveys.

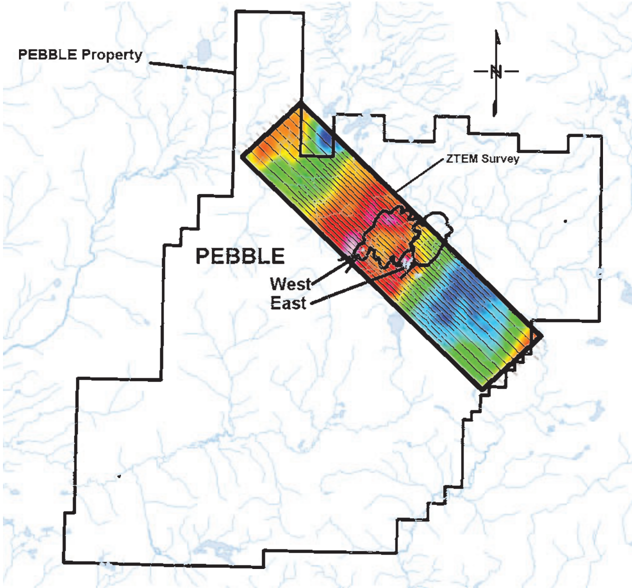

Fig. 7. Plan view of the ZTEM survey with total phase rotation of the inphase component at 30 Hz, and Pebble deposit and property outlines superimposed.

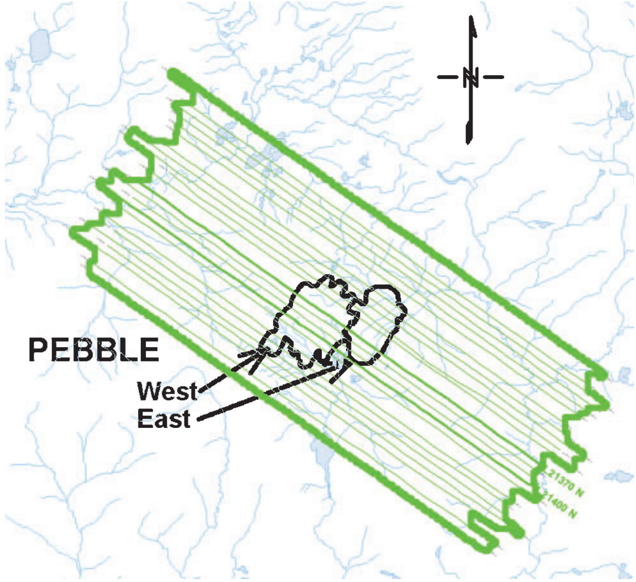

Fig. 8. Plan view of the SPECTREM survey with lines L21310 and L21370 identified.

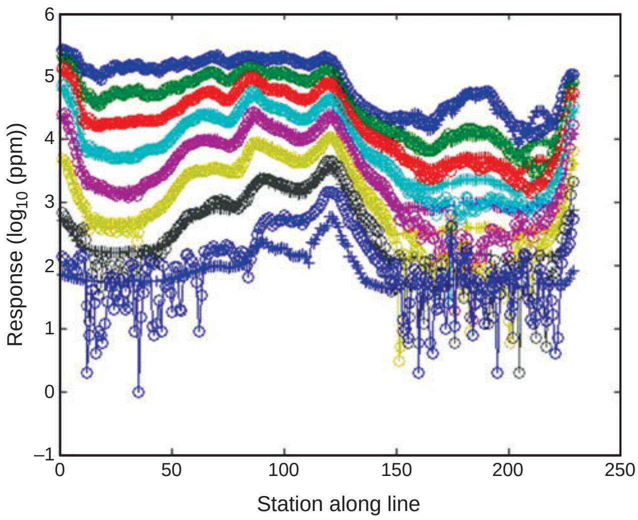

Fig. 9. Observed and predicted data for vertical (Z) component B field channels 1 to 8 from line 21430. The observed data are marked by (o), and the predicted data are marked as (+). This line is representative of the fit for all inline and vertical component data. A noise floor of 200 ppm was used for the inversion.

Both our 3D AEM and ZTEM inversions are based on the re-weighted regularized conjugate gradient (RRCG) method, which updates the vector of model conductivities, ó, with an iterative scheme akin to:

$$\boldsymbol{\sigma}_{i+1} = ó_i + \Delta\boldsymbol{\sigma}_i = \boldsymbol{\sigma}_i + k_i \mathbf{S}_i^{\mathrm{T}} \mathbf{r}_i, \quad (1)$$

where k_i is a step length, $\mathbf{S}_i^{\mathrm{T}}$ is the transpose of the $N_d \times N_m$ sensitivity matrix $\mathbf{S}_i$, and $\mathbf{r}_i$ is the N_d length vector of the residual fields between the observed and predicted data. Data and model weights are introduced to reweigh the inverse problem in logarithmic space so as 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 stabilisers, and do not require those boundaries to be enforced *a priori* (Zhdanov, 2002, 2009).

Our 3D frequency-domain modelling 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). This implementation reduces storage and complexity, and lends itself to large-scale parallelization. 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).

Interpretation

3D SPECTREM inversion

We inverted 350 line km of SPECTREM data acquired at 250 m flight-line spacing along strike of the Pebble deposit (Figure 8). This corresponded to 4659 stations with eight channels of inline and vertical component B field data. The 3D earth model was discretized to ~700,000 cells of 25 m inline by 50 m transverse discretization, where the vertical cell size varied from 10 m near the surface to 130 m at 700 m depth. The 3D inversion contained neither geological constraints nor *a priori* geological information. A noise floor of 200 ppm was used for all data. Figure 9 is an example of the data fit for all eight channels of vertical component B field data.

From a 3D sensitivity analysis, the depth of investigation for SPECTREM was ~750 m below the surface. The 3D SPECTREM inversion has recovered Pebble's main alteration pattern and the known structures ZF, ZC, ZE and ZG1 to depths consistent with the system's sensitivity (Figures 10 and 11). As shown in Figures 5 and 6, the 3D inversion produced better lateral model continuity from line-to-line than 1D inversion (Raiche et al., 2007) and CDIs (e.g. Macnae et al., 1998). Studying the 3D

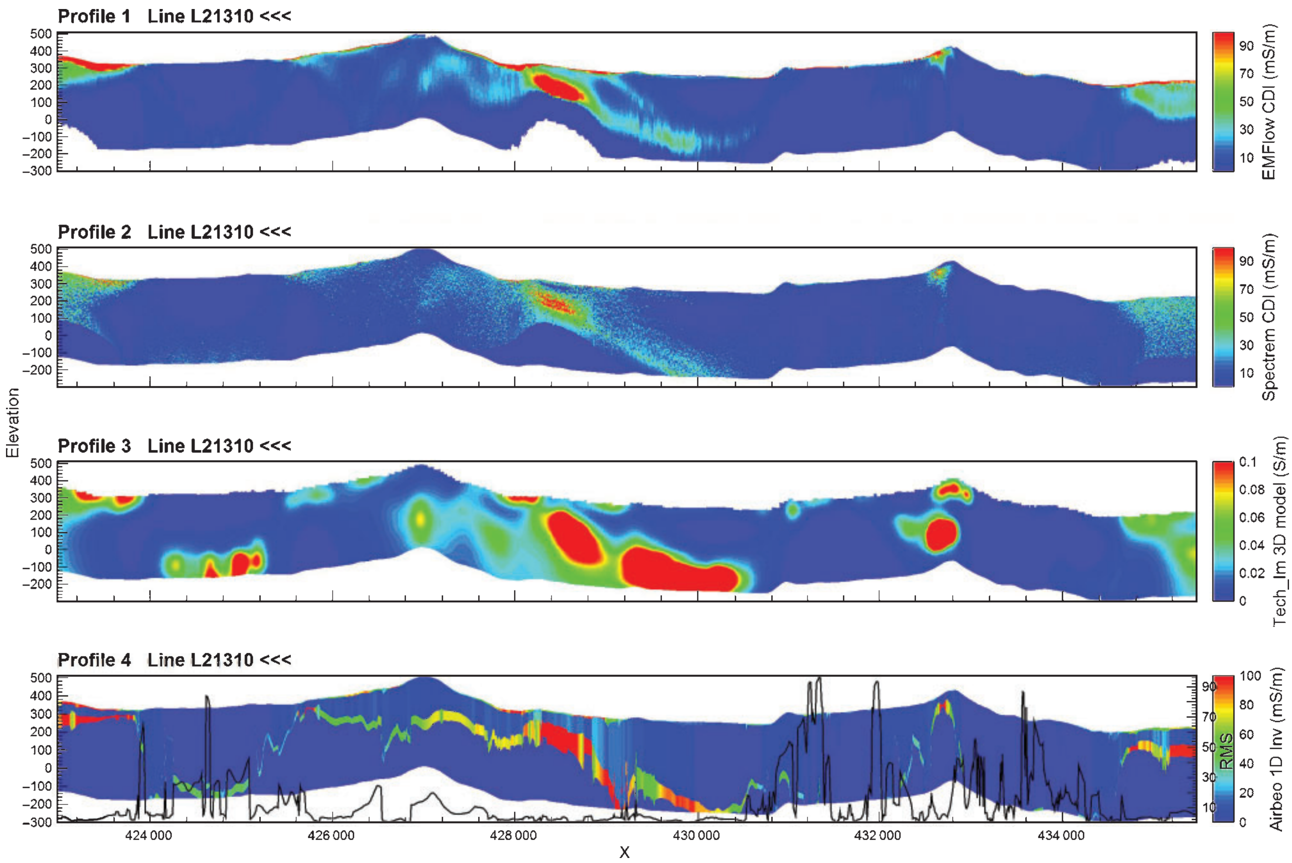

Fig. 10. Comparison of EMFlow CDI (profile 1), SPECTREM CDI (profile 2), 3D inversion (profile 3), and AirBeo 1D inversion (profile 4) for SPECTREM line L21310. Note that the RMS misfit is superimposed for the AirBeo profile.

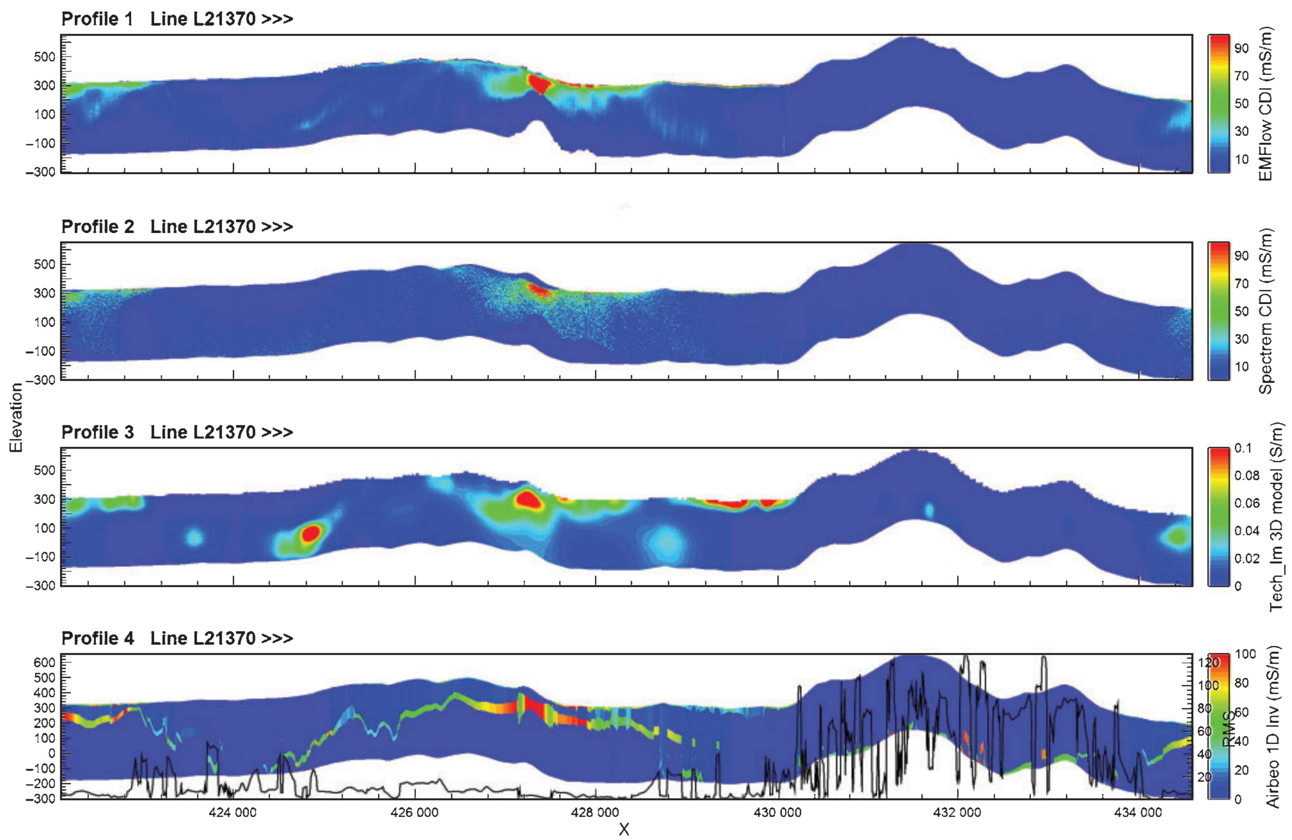

Fig. 11. Comparison of EMFlow CDI (profile 1), SPECTREM CDI (profile 2), 3D inversion (profile 3), and AirBeo 1D inversion (profile 4) for SPECTREM line L21370. Note that the RMS misfit is superimposed for the AirBeo profile.

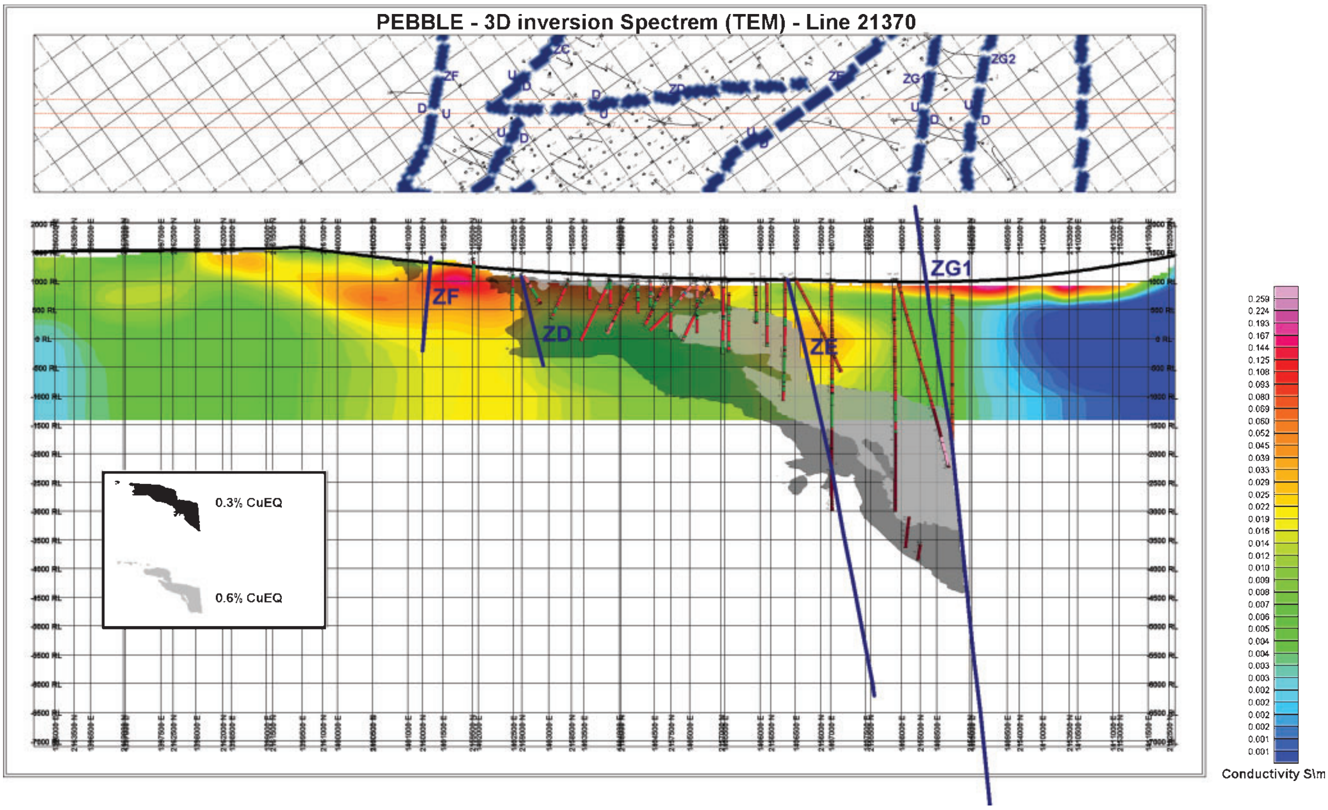

Fig. 12. 3D SPECTREM inversion for SPECTREM line L21370, with CuEqn 0.3% (black) and CuEqn 0.6% (grey) mineralization shells superimposed.

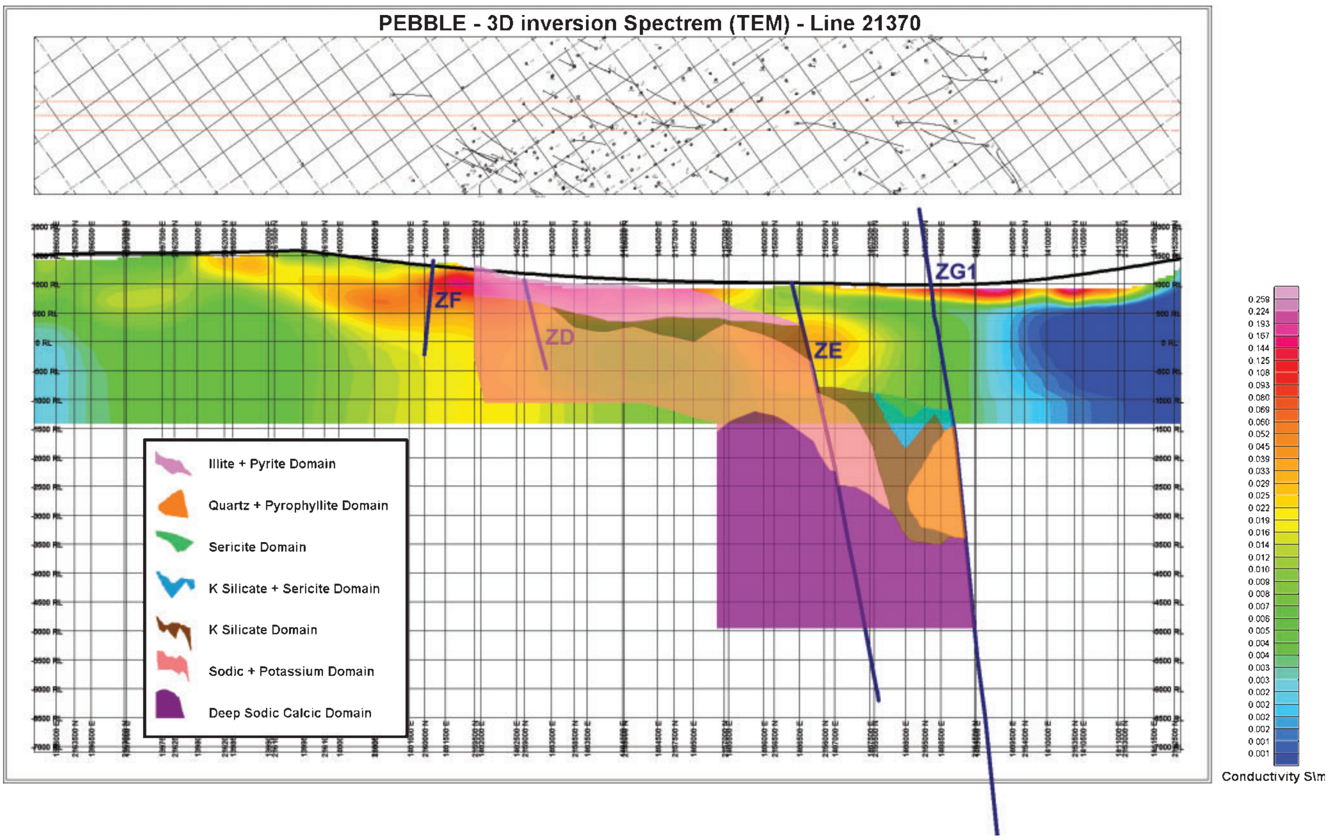

Fig. 13. 3D SPECTREM inversion for SPECTREM line L21370, with alteration patterns superimposed.

SPECTREM inversion for lines L21370 (Figures 12 and 13) we can highlight the following correlations between the known geology of the Pebble deposit and the 3D conductivity model obtained from the 3D SPECTREM inversion:

- The highly conductive zones correlate to the known illite-pyrite and advanced argillic alteration parts of the Pebble system;
- The weak conductive zone and resistive high beneath the Pebble West and East zones are characterised by sodic-potassic, potassic-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 ore grades;
- The moderately conductive layer near the surface above the Pebble East zone and to the east appears to be related to the tertiary cover;
- The main known structures (ZF, ZC, ZE and ZG1) are well resolved to the depth of the SPECTREM system's sensitivity, and correlate with the breaking pattern of the 3D conductivity model; especially the ZG1 fault to the east of Pebble East.

The geometry of the 3D SPECTREM inversion follows the general trend of the alteration and ore geometry to the depth of the SPECTREM system's sensitivity. However the correlation between conductivity and mineralization is not as directly coincident as with the alteration pattern. This suggests that the ore mineralization (i.e. economic content) is not a major factor in the SPECTREM response. The high grade CuEqn 0.6% is not consistently following the high conductive trend. The conductive zones contrasts are mostly coincident with alteration change.

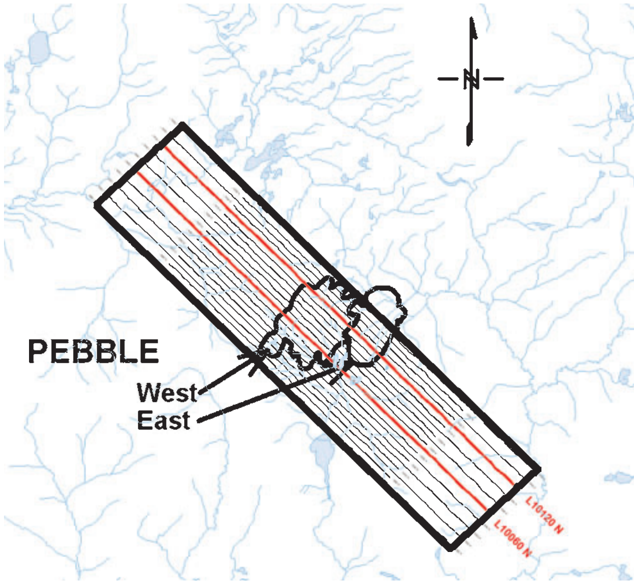

Fig. 14. Plan view of the ZTEM survey with lines L10060 and L10120 identified.

3D ZTEM inversion

We inverted 250 line km of ZTEM data acquired at 200 m flight-line spacing along strike of the Pebble deposit (Figure 14). This corresponded to 5472 stations with both Z/X (inline) and Z/Y (transverse) tipper components at five frequencies; 30 Hz, 45 Hz, 90 Hz, 180 Hz, and 360 Hz. The 3D earth model was discretized to ~570,000 cells of 50 m inline by 50 m transverse discretization,

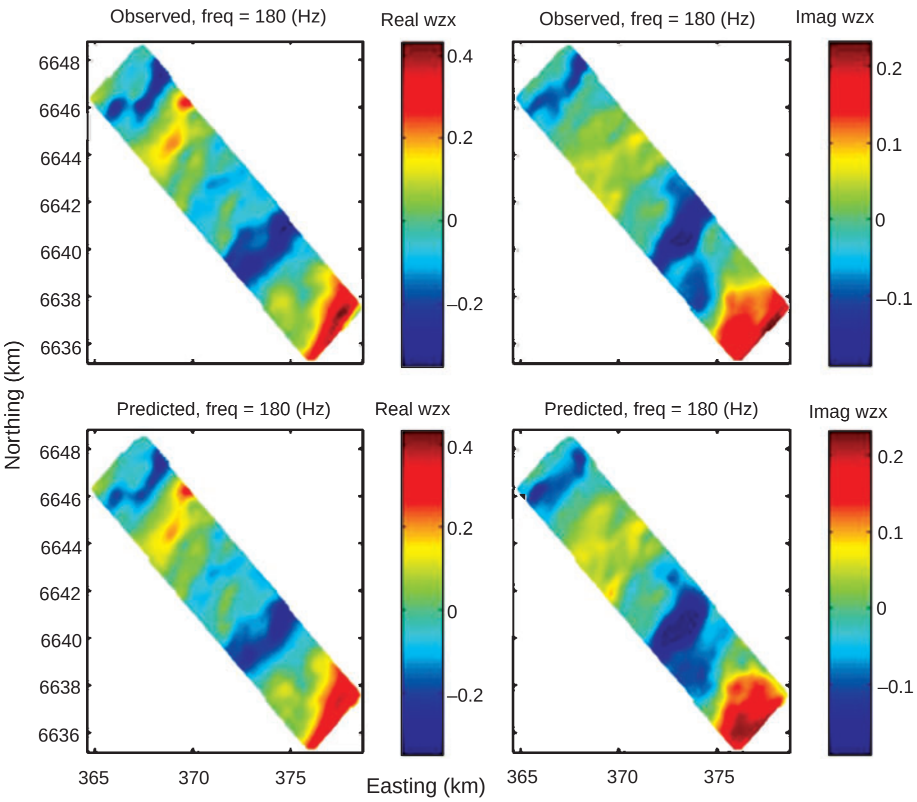

Fig. 15. Observed (upper panels) and predicted (lower panels) data for the real (left panels) and imaginary (right panels) components of the 180 Hz Z/X (inline) tipper component. This map is representative of the fit for all inline and vertical component data.

where the vertical cell size varied from 10 m near the surface to 100 m at 2000 m depth. The 3D inversion contained neither geological constraints nor *a priori* geological information. Figure 15 is an example of the data fit for the 180 Hz X/Z (inline) tipper component.

From a 3D sensitivity analysis, the depth of investigation for ZTEM was ~1500 m below the surface. We note this is significantly deeper than SPECTREM's depth of investigation. However, such simple comparisons can be misleading as SPECTREM has a broadband frequency response, compared to the narrower band frequency response of ZTEM. The 3D ZTEM inversion has recovered Pebble's main alteration pattern and the known structures ZF, ZC, ZE and ZG1 to depths consistent with the system's sensitivity. Generally speaking, the 3D ZTEM inversion recovered the geological features and structures with better accuracy than the 2D ZTEM inversions of the same data (Figures 16 and 17). 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.

ZTEM line L10120 and SPECTREM line L21370 are essentially coincident, and cross both the Pebble West and the East zones. Studying the 3D ZTEM inversion for lines L10120 (Figures 18 and 19) highlights the following correlations between the known geology of the Pebble deposit and the 3D conductivity model obtained from the 3D ZTEM inversion:

- 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 characterised by sodic-potassic, potassic-silicate and deep sodic-calcic domains;
- The high conductive zone on line L10120 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;

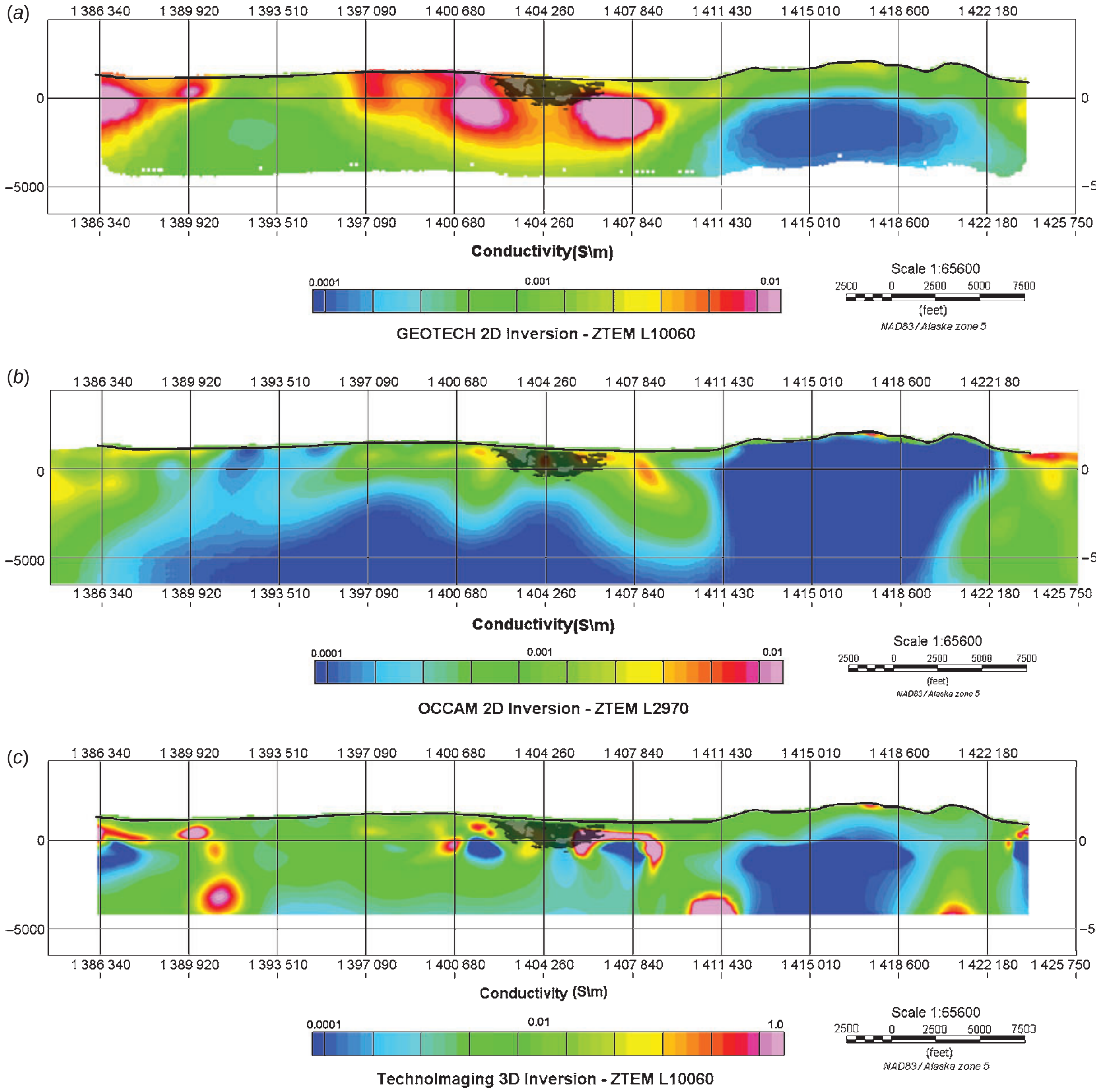

Fig. 16. Comparison of (*a*) 2D inversion (by Geotech Ltd), (*b*) 2D inversion (by Condor Consulting, Inc.) and (*c*) 3D inversion for ZTEM line L10060. The CuEqn 0.3% (black) and CuEqn 0.6% (grey) ore shells are superimposed on each model.

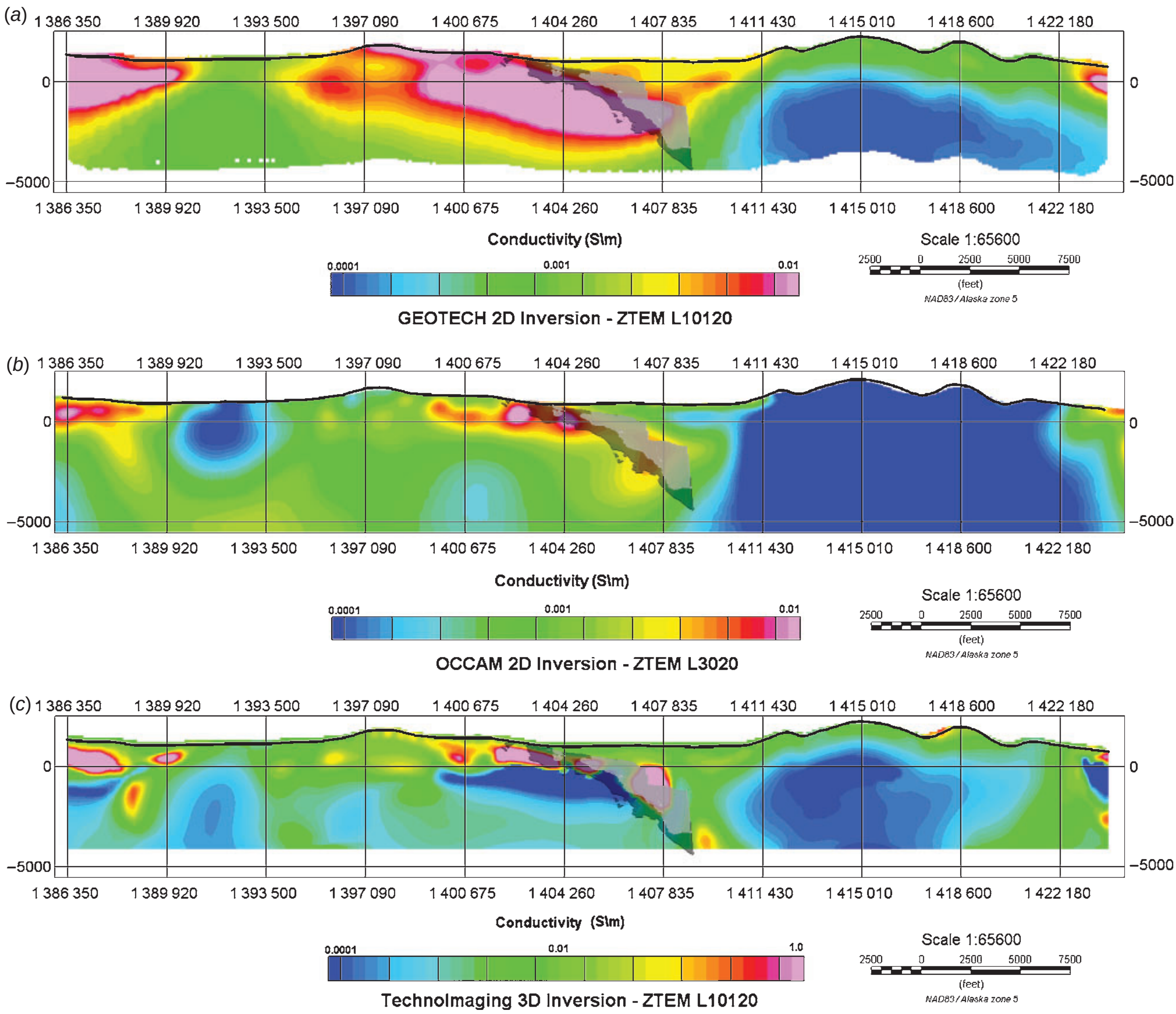

Fig. 17. Comparison of (*a*) 2D inversion (by Geotech Ltd), (*b*) 2D inversion (by Condor Consulting, Inc.) and (*c*) 3D inversion for ZTEM line L10120. The CuEqn 0.3% (black) and CuEqn 0.6% (grey) ore shells are superimposed on each model. Models are shown in Alaska State Plane projection.

- 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 model; especially the ZG1 fault to the east of Pebble East.

We note that these correlations are very similar to those observed in the 3D SPECTREM inversion. However, it is important to emphasise there is a significant difference in the depth of investigation between the two models. For example, it is interesting to note the conductive zone at depth to the east of the ZG1 fault on line L10120, which was not apparent in the 3D SPECTREM inversion. Another strong conductive response appears on L10060 at 1,411,430 and seems to be the continuity of the deep conductive zone highlighted on L10120 east of the ZG1 fault. This is currently being investigated further and if real, could potentially be a deep extension of Pebble East.

The geometry of the 3D ZTEM inversion also follows the general trend of the alteration and ore geometry. Similar to 3D SPECTREM inversion, the mineralization is not in direct correlation with the conductive zones resolved by the 3D inversions. The conductive zones are mostly coincident with alteration change. The high grade CuEqn 0.6% is not consistently following the high conductive trend. As per the 3D SPECTREM inversion, this suggests that the ore mineralization (i.e. economic content) is not a major factor in the ZTEM response.

Comparison of 3D SPECTREM and 3D ZTEM inversions

In both cases, 3D inversion has succeeded by producing accurate models from sub-horizontal structures where both SPECTREM and ZTEM are normally expected to have less resolution. Figures 20 and 21 present south-west-looking perspective views of the 3D SPECTREM and ZTEM derived conductivity models with the ore mineralization superimposed. As has been discussed, the 3D inversions have been very efficient in resolving the alteration pattern and major structural features of the Pebble deposit. This suggests that the interpretation for Pebble-like porphyry exploration requires a solid understanding of the expected alteration patterns rather than the actual sulfide distribution. However, we note that the 3D SPECTREM

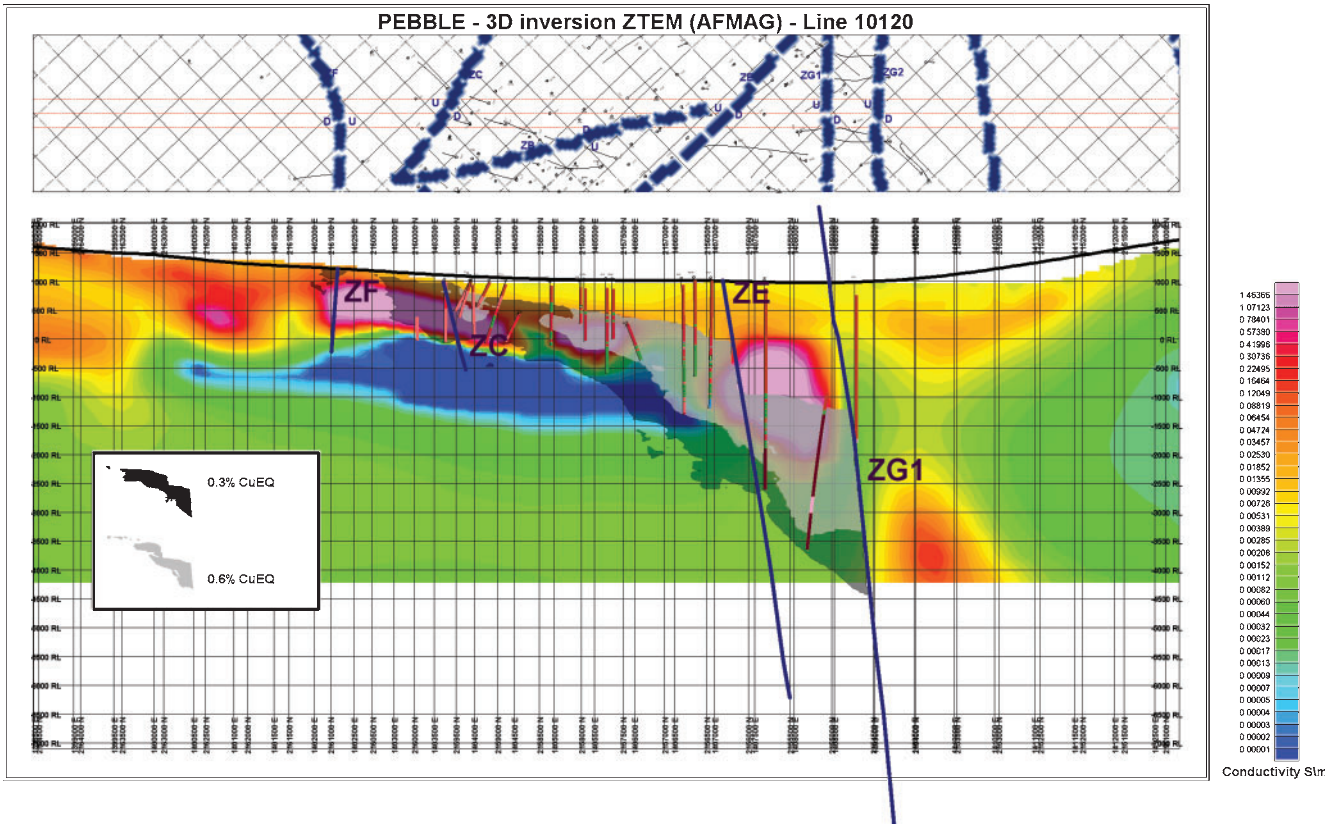

Fig. 18. 3D ZTEM inversion for ZTEM line L10120 with CuEqn 0.3% (black) and CuEqn 0.6% (grey) mineralization shells superimposed.

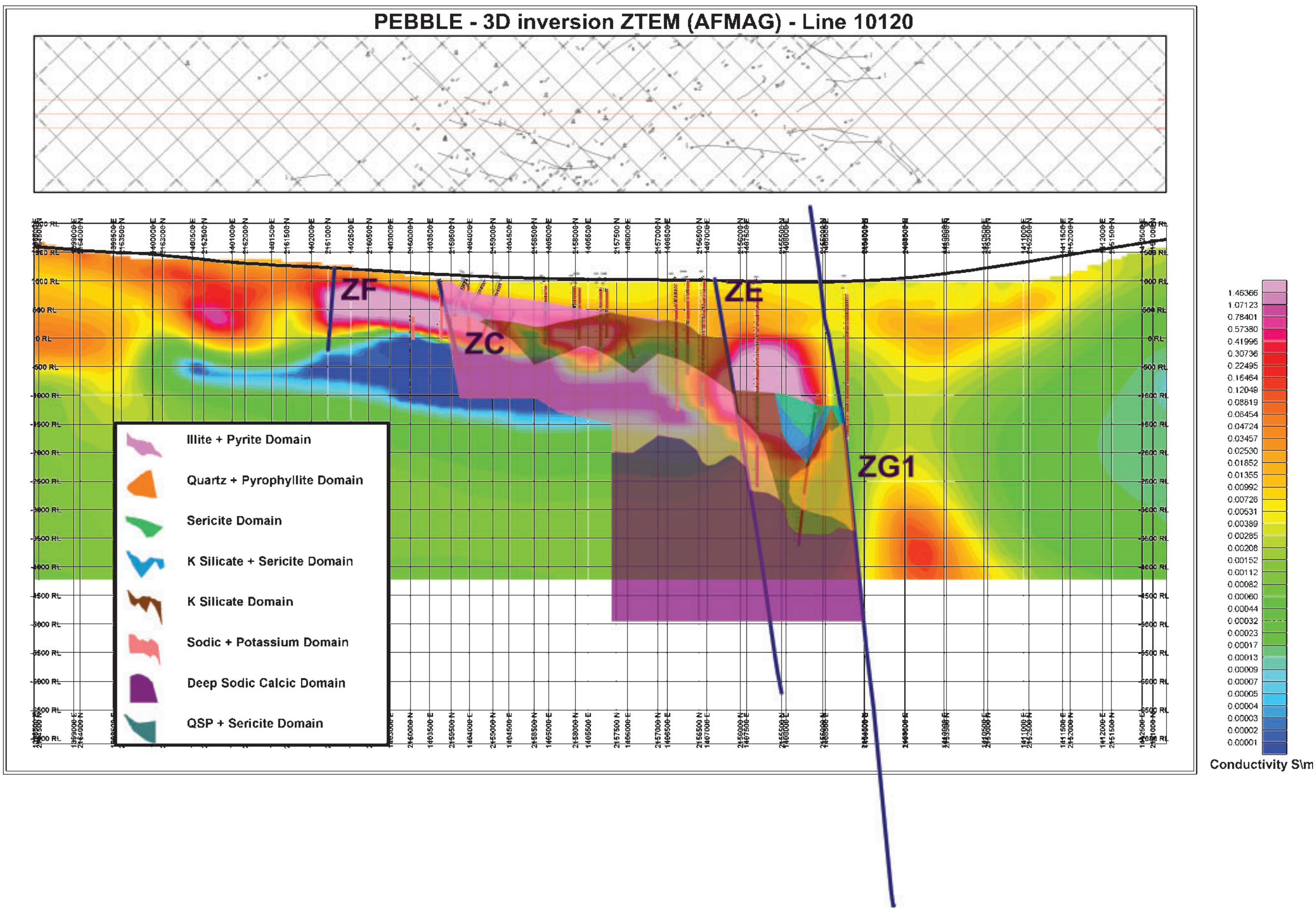

Fig. 19. 3D ZTEM inversion for ZTEM line L10120 with alteration patterns superimposed.

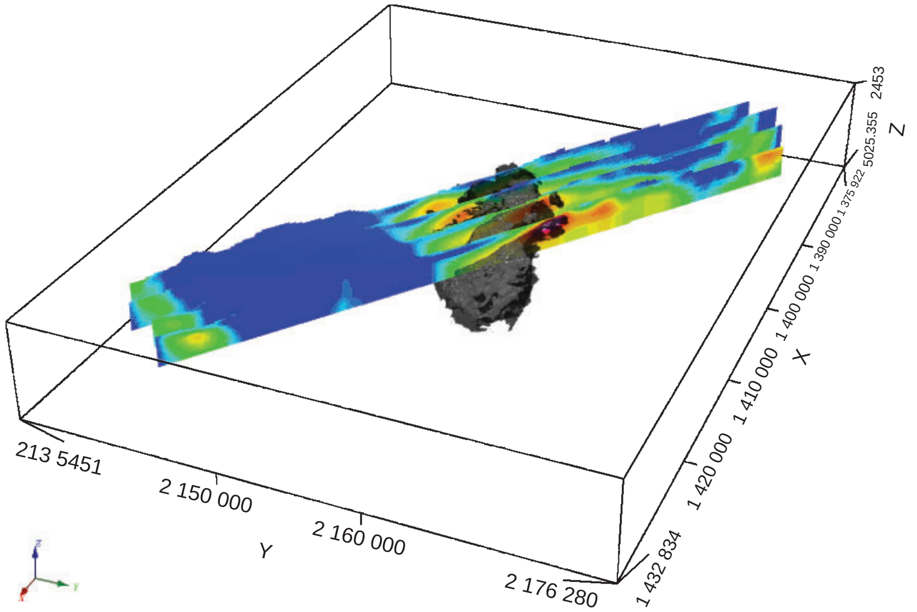

Fig. 20. South-west-looking perspective view of 3D SPECTREM inversion looking with CuEqn 0.3% (black) and CuEqn 0.6% (grey) mineralization shells superimposed.

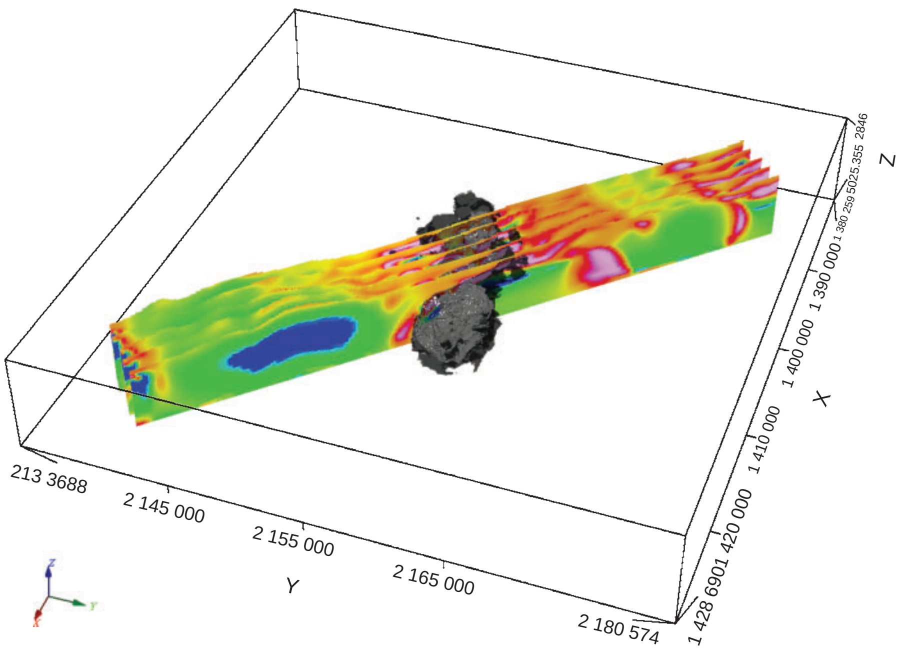

Fig. 21. South-west-looking perspective view of 3D ZTEM inversion with CuEqn 0.3% (black) and CuEqn 0.6% (grey) mineralization shells superimposed.

inversion has not recovered the location of the main structural corridor with the same accuracy of the 3D ZTEM inversion.

Conclusions

3D inversions of SPECTREM and ZTEM surveys over the Pebble deposit have been interpreted with respect to the known geology. 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. The 3D SPECTREM and ZTEM inversions were also compared to each other. Both of the 3D inversions recovered conductivity models more consistent with the known geology than those obtained from non-3D methods. Moreover, both SPECTREM and ZTEM inversions recovered conductivity models that were consistent within the commonality of their physics, and which corresponded well with the known geology. This adds confidence not only to the 3D inversions, but to the quality of data produced by both systems. As in any exploration project, the interpretation of the data from both surveys has yielded an improved understanding of the geology, alteration and mineralization of the Pebble deposit and this will serve well for on-going exploration activities. In particular, the 3D inversions have been very efficient in resolving the alteration pattern and major structural features of the Pebble deposit. This suggests that the interpretation for Pebble-like porphyry exploration requires a solid understanding of the expected alteration patterns rather than the actual ore mineralization distribution. There are distinct practical advantages to the use of both SPECTREM and ZTEM, so we draw no recommendation for either system. We can conclude however, that 3D inversion of both AEM and ZTEM surveys is now a practical consideration and that it has added value to exploration at Pebble.

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