Extremely Low Frequency (ELF) System: An Introduction and Case Studies

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ABSTRACT

The extremely low frequency electromagnetic system (ELF) is a new passive ground geophysical technique that excels at high productivity, high efficiency and low cost. Daily production for a two-person crew is typically between two and four line-km per day depending on terrain, station spacing and geomagnetic conditions. The ELF measures vertical and horizontal components of the natural time-varying geomagnetic field originating primarily from global lightning activity. The system calculates the tilt angle or tipper of the magnetic fields from 11 to 1440 Hz which is sensitive to 2D and 3D conductivity contrasts.

This paper introduces the ELF and the inversion methodology and describes case studies to compare ELF results to Slingram TDEM, DC resistivity and CSAMT data sets. Other examples compare ELF results to the known Wellgreen West and Lalor massive sulphide deposits.

Figure 1: Typical deployment of the ELF coils. Approximate diameter is 0.5 m.

INTRODUCTION

The extremely low frequency electromagnetic system (ELF) is a new, passive-source ground geophysical technique, closely related to Geotech's ZTEM airborne system. The ELF measures the vertical and horizontal components of the natural, time varying geomagnetic field. The relative magnitudes of these components comprise the tilt angle, or tipper of the field. The tipper is recorded for 8 frequencies between 11 and 1440 Hz, a frequency band powered primarily by global lightning activity. The ELF is sensitive to 2D and 3D resistivity structures and provides information down to depths of up to 2 km, depending on the subsurface resistivity. It is most sensitive to steeply dipping conductors.

The ELF data can be inverted to provide a full conductivity structure of the earth and efficiently integrated with other geological knowledge. The results are useful in mapping both small shallow features and larger regional geological structures. The Reduced Basis Occam (REBOCC) method is used to invert the data in 2D and 3D. The 2D and 3D REBOCC inversion methods are described by Siripunvaraporn and Egbert (1999) and by Siripunvaraporn and Egbert (2009), respectively. These were designed as magnetotelluric (MT) inversion packages, but are able to invert tipper-only data and are therefore suitable for use with ELF data. Tipper-only inversions do not excel at recovering absolute conductivity values or layered structures, but do very well at identifying lateral conductivity anomalies.

CASE STUDIES

A series of case studies comparing ELF data, inversion results and interpretation to other geophysical methods and bodies delineated by drilling is discussed. Comparisons to Slingram TDEM, DC resistivity and controlled source audio-magnetotellurics (CSAMT) are shown, as well as examination of the ELF response over the known Wellgreen West and Lalor massive sulphide deposits.

Moving Loop TDEM

The Halliday Lake property is located approximately 18 kilometres northwest of the McArthur River uranium deposit in the eastern Athabasca Basin, a Paleoproterozoic sandstone basin in northern Saskatchewan, Canada. The Athabasca Basin hosts high-grade unconformity-type uranium deposits that account for about 28% of the world's primary uranium production. These unconformity-type uranium deposits occur in sandstones at the basement-sandstone unconformity contact (sandstone-hosted mineralization) and within the underlying structurally disrupted crystalline basement (basement-hosted mineralization). The ore grades are high, typically grading 5% to 20% U308.

Modelling

A consequence of measuring only the magnetic field with no measurement of the electric field is that if the starting model is very far from the true conductivity structure of the earth, the inversion may not successfully recover the true conductivity structure. In consideration of this, two inversions using different initial models are run: a 1000 Ohm-m half-space model and a 3-layer model with a high resistivity, high silica layer in the upper sandstone and a discontinuity introduced at 800 m depth to represent the basement unconformity. An underlying sedimentary layer of 500 Ohm-m represents a more 'average'

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basin sandstone, and perhaps weakly altered sandstone. The value of 1000 Ohm-m is assigned to the basement.

Discussion

Previous surveys identified several conductive features on the property and in particular a strong conductor transecting the property; a Slingram large-loop TDEM survey is considered the most robust locator of this feature. The ELF survey was designed in part to mimic the extent and location of the Slingram TDEM survey to determine whether the ELF system could image this strong deep conductor.

All models recover the strong conductive feature, with the top of the feature at a depth of approximately 1000 m. The half-space model also recovers a shallowly north-dipping feature in the sandstone from approximately a depth of 300 m to 700 m below surface as shown in Figure 2.

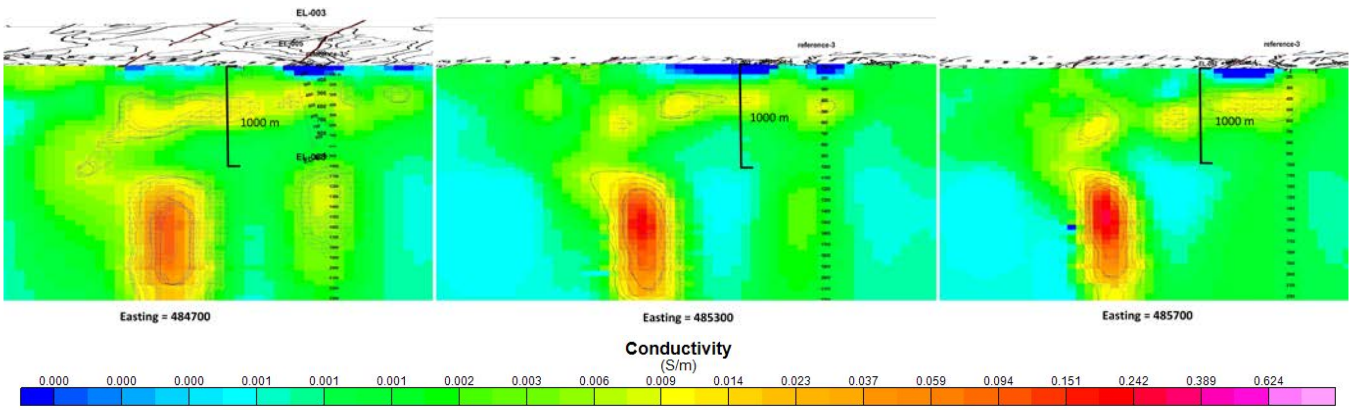

Figure 2: View from the west at easting = 484700, 485300 and 485700. Views are centered at approximately a northing of 6413000. Coordinates are NAD83, UTM Zone 13N coordinates. Both isosurfaces and colour image are of the half-space model.

This feature is shown as discontinuous across the grid in the recovered model, but this is likely a function of sparse across-line data due to the large line spacing for a shallow target. There is some suggestion of a corroborating feature in the 3-layer model but it is tenuous. Whether this feature represents alteration or a stratigraphic layer within the sandstone is difficult to determine from this dataset, particularly with the sparse across-line data.

DC Resistivity

Figure 3 shows a comparison between DC resistivity and ELF surveys on the polymetallic Keg property of Silver Range Resources, Yukon. ELF data are always collected in three dimensions but for the purpose of this example the tilt angle was calculated in the northerly direction (the same direction as the line) for a 2D analysis. Panels A and B of Figure 3 show 2D recovered conductivity from the ELF data using homogenous initial models. Panel C shows a 2D ELF inversion based on an initial model from the DC resistivity inversion. All three 2D inversions fit the ELF data acceptably as seen in predicted versus observed plots on the right (panel E) where the solid lines are observed data and the dotted lines are predicted data. Panel D shows the DC resistivity inversion results using the UBC DCIP2D code, and panel F shows the predicted versus observed data fit of this model.

Although there are differences between the models, the main features are consistent. Of note is the difference at depth between panels A and B and panel D. Even though the DC resistivity used a long-offset array to ensure deep depth of investigation, the ELF survey clearly delineates a conductivity contrast below 1000 m that is not apparent in the DC resistivity-based model. Assuming the average resistivity is 100 Ohm-m in this area, the skin depth of 22 Hz – which is a reasonable order of magnitude estimate for the depth of investigation – would be approximately 1100 m. This is beyond the reasonable depth of investigation of the DC resistivity survey (n=20, 50 m dipoles on the eastern part of the line and n=6, 100 m dipoles on the western part of the line).

On the southern part of the line, there is discrepancy between the shallow conductivity structure of the DC resistivity inversion and the ELF inversion. This part of the line coincides with both large amplitude and large frequency dependence in eastern tipper values indicating significant 3D effects not captured by the 2D inversions.

The time required to complete the ELF survey is considerably less than the DC resistivity survey. This 3.4 km line is easily achievable in a single day with a two-person ELF crew. For the DC resistivity survey, three days of a four-person crew plus line-cutting would typically be required.

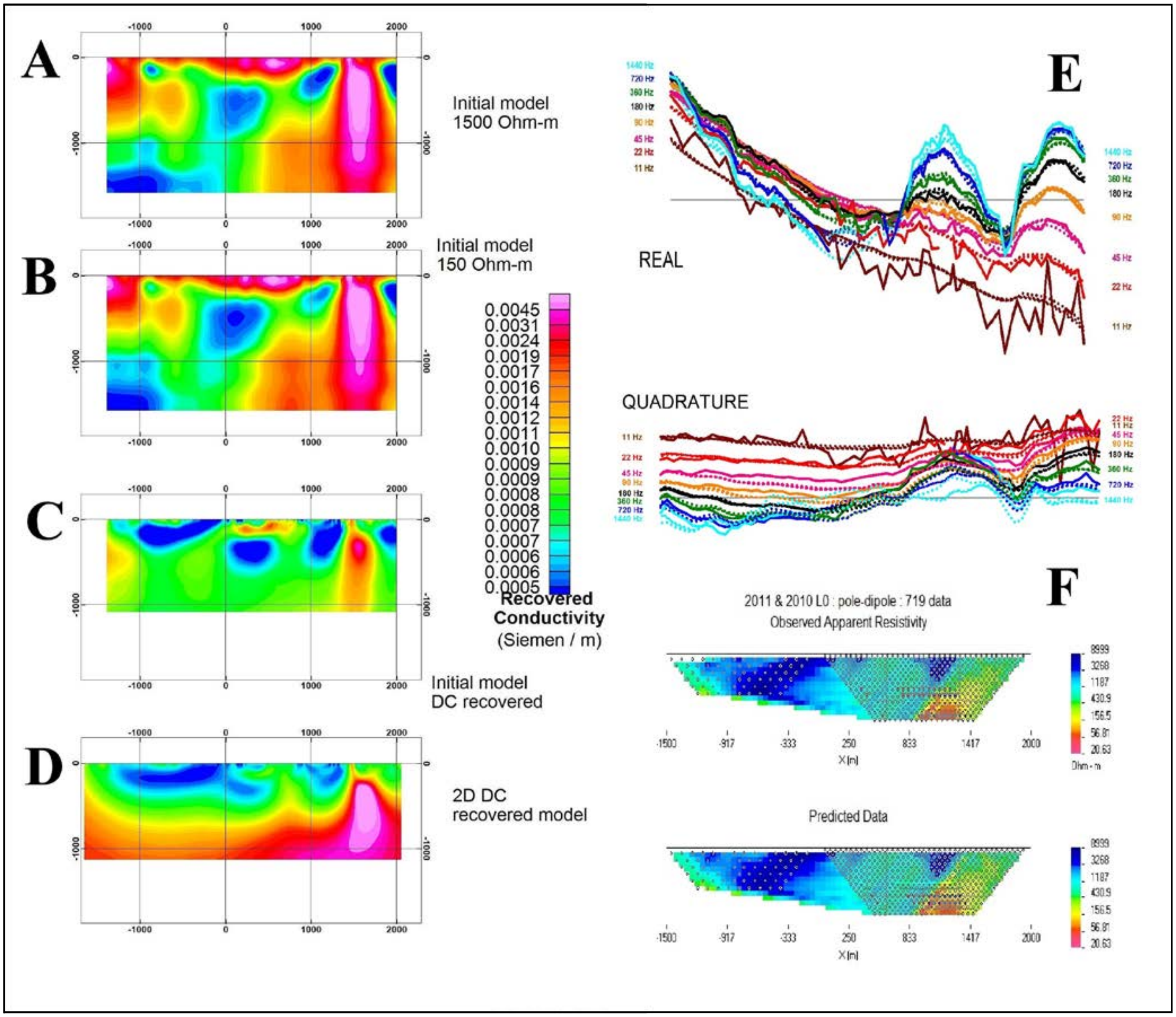

Figure 3: Recovered 2D models and predicted/observed plots for ELF and DC resistivity surveys at the Keg Property, Yukon. North is to the right of all sections and south is to the left. Panels A and B show recovered conductivity models from ELF data using homogenous initial model of 1500 Ohm-m and 150 Ohm-m respectively. Panel C shows a recovered conductivity model from ELF data using a recovered conductivity model from DC resistivity data (panel D) as an initial model. Panel E shows observed ELF data (solid lines) and predicted data (dotted lines) derived from the inversions shown in panels A, B and C. Panel F shows observed DC resistivity data and predicted data derived from the inversion shown in panel D.

CSAMT

The third case study is an intrusion-related gold target from Rackla Metal's Sixty Mile property, Yukon, where a coincident CSAMT survey was conducted. Figure 4 shows a comparison of 2D ELF and CSAMT inversions. The salient features are present in both models derived from the different datasets. There is a strong conductive feature between stations 750 and 1000, followed by a resistive break and then a second less conductive feature between stations 500 and 750. A shallow resistive feature is modelled between stations 25 and 500 in both inversions. There are differences: the second conductor at approximately station 600 recovered by the ELF model is stronger and more extensive than the one from the CSAMT data, and there are small-scale features recovered in the CSAMT model that do not appear in the ELF-derived model. Additionally, the absolute scales of the recovered resistivity are different. It should not be surprising that the two surveys illuminate the Earth in different ways. This CSAMT survey measures a single component of electric and magnetic fields from a single polarized source, while the ELF measures the magnetic field ratio in both directions from a non-polarized source. Nevertheless, the models are broadly consistent with each other.

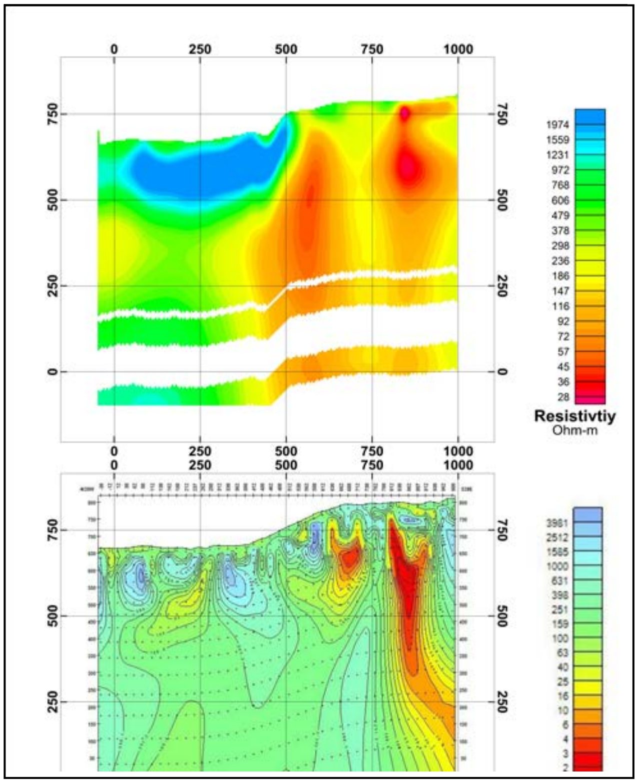

Figure 4: Recovered 2D inversions from ELF (top panel) and CSAMT (bottom panel) surveys at Rackla Metal's Sixty Mile Property.

There is a difference in logistics. The CSAMT requires cut-lines, a crew of five and surveys approximately one line per day. For the same line the ELF requires less than half a day with a crew of two and no cut-lines.

Wellgreen – Drilled Massive Sulphide

Figure 5 shows the results from a test grid surveyed over the West Zone of Wellgreen Platinum's past-producing Wellgreen project, Yukon. In panel A, drill holes are shown with copper (orange) and nickel (green) assays and the view of the recovered model shows excellent correlation of the conductor with the massive sulphide mineralization. Note that the section is viewed from an inclined angle and the intercepts of high copper that appear to be coincident with moderate recovered resistivity are out of the plane of the conductivity section and are in fact within the recovered conductive structure. Panel B is a plan view displaying the real 180 Hz tipper data as arrows and the horizontal divergence of the tipper as a colour grid which is a good proxy for conductivity.

The marginal gabbro and inter-fingered gabbro-clinopyroxenite that host the massive sulphide mineralization correlate very well with the recovered conductivity model.

Lalor – Drilled and Modelled Massive Sulphide

Data over the Lalor Deposit, Manitoba were collected in a small orientation survey with a prototype of the ELF-EM system in the fall of 2010. Two lines running SW-NE, approximately 250 metres apart and one cross line were surveyed with a station spacing of 100 metres. Data quality was relatively low for this survey, attributable to the small receiver coils of the ELF prototype and seasonally low input signal. The quadrature and high frequencies (720 and 1440 Hz) were particularly affected and these data are not used in any of the final 3D inversions.

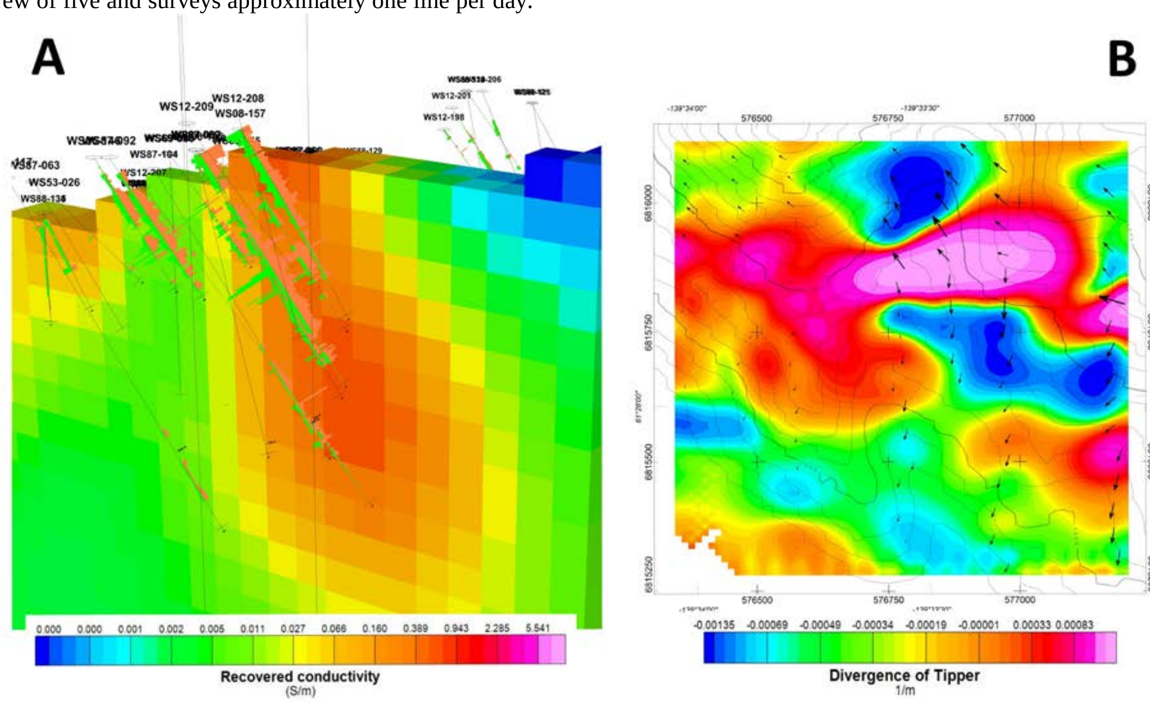

Figure 5: Test ELF survey on the West Zone of the Wellgreen deposit with 3D inversion results (conductivity) shown in Panel A with drill hole results. Panel B shows a plan view of 180 Hz real data and the real tipper divergence.

A suite of starting models for the 3D inversions was developed by combining the parallel 2D models over a width of 500 m. This blended model is inserted into a 1000 Ohm-m half-space at a variety of depths; each model was used as an initial and reference model for a 3D inversion giving a suite of recovered models.

A 50 metre horizontally-discretized mesh was used for all 3D inversions. The recovered models converge to a common depth regardless of the initial model indicating the robustness of the solution.

Vertical slices of one of the recovered models are shown in Figure 6 along with the lenses of mineralization (grey surfaces). A north- and shallowly-dipping conductive feature, similar to the true geometry of the Lalor Deposit is consistently recovered; however, the conductor is imaged as shallower than the Lalor Deposit. The resistive hanging wall above the imaged conductor is consistent with the barren Chisel Lake Formation. The most conductive feature recovered in the 3D inversions is immediately to the SW and up-dip of the Lalor Deposit.

CONCLUSIONS

The ELF system successfully located a previously identified deep conductor at Halliday Lake and also revealed a shallowly dipping sandstone-hosted conductor. ELF results at test sites with existing DC resistivity and CSAMT data show that the ELF data produce results that are consistent with the other geophysical techniques.

Direct detection of mineralization is successfully achieved at both the Wellgreen West and Lalor deposits, although the conductive anomaly at Lalor is above the actual deposit and the most conductive area is imaged immediately up-dip, likely because of poor data quality at this site.

The ELF-EM system excels as an efficient, deep-penetrating EM survey. The crew is small, no cut-lines are required and production is high. The ELF-EM data are consistent with other geophysical methods and offers a very cost effective alternative to other deep-looking EM techniques.

ACKNOWLEDGEMENTS

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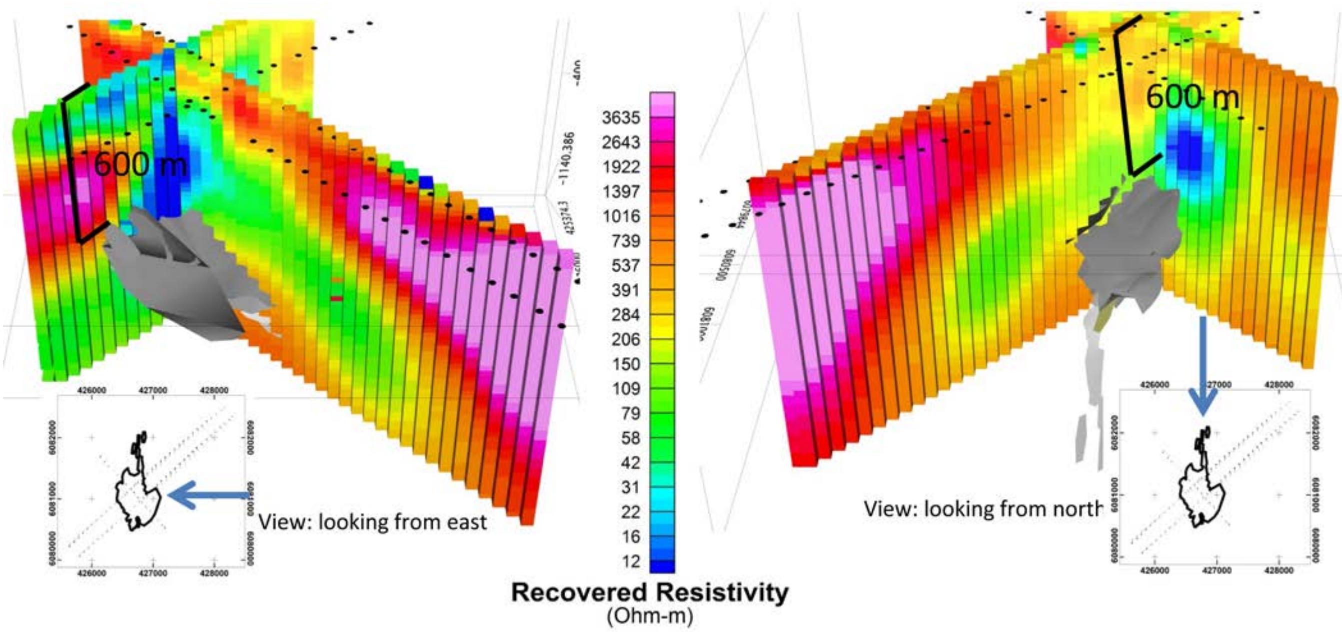

Figure 6: 3D ELF inversion results at the Lalor Deposit: two views of a recovered model.