Magnetotelluric Inversion, Carbonaceous Phyllites and an Ore Zone: Kevitsa, Finland

Cuong V. A. Le*
DET CRC, Curtin University
ARRC/CSIRO Building, H Block,
Level 4, 26 Dick Perry Avenue,
Kensington
v.le3@postgrad.curtin.edu.au

Brett D. Harris
DET CRC, Curtin University
ARRC/CSIRO Building, H Block,
Level 4, 26 Dick Perry Avenue,
Kensington
B.Harris@curtin.edu.au

Andrew M. Pethick
DET CRC, Curtin University
ARRC/CSIRO Building, H Block,
Level 4, 26 Dick Perry Avenue,
Kensington
andrew.pethick@curtin.edu.au

SUMMARY

We invert seven densely sampled magnetotelluric transects at the Kevitsa Ni-Cu-PGE (platinum group elements) deposit in Finland. The geology at the deposit presents at least two high electrical conductivity rock types within a resistive host. We consider the extent to which highly conductive phyllite and an ore zone can be separated through inversion of magnetotelluric data. Multiple inversions were completed with 312 magnetotelluric (MT) stations. It was possible to generate a three-dimensional conductivity volume from the 2D MT derived conductivities sections via volumetric interpolation. We compare the resulting 3D conductivity volume with co-located 2D and 3D seismic data. Comparisons show that an impression of the Ni-Cu-PGE ore-body could be observed in both seismic reflection and conductivity volumes. We discuss methods for constraining MT inversions and the impact they may have in separating proximal but highly conductive units. The inversions were complete as a precursor to full 3D cooperative inversion of the seismic and magnetotelluric data at this site.

Key words: Magnetotelluric, inversion, conductivity.

INTRODUCTION

Electromagnetic methods are able to detect ore bodies when highly electrically conductive minerals are present (Howe et al., 2014). Kevitsa deposit in northern Finland is a large Ni-Cu deposit hosted within a mafic to ultramafic intrusion (Malehmir et al., 2012). A magnetotelluric (MT) survey consisting of 312 stations over seven lines was co-located with both 2D and 3D seismic surveys. Higher frequency information in the electromagnetic wave field is rapidly attenuated with depth. The result is that the resolution of electromagnetic methods such as MT decreases with depth. For this reason it may be difficult to recover sharp contrasts in electrical conductivity as depth increases. Non-uniqueness and equivalence can also limit the methods ability to recover true subsurface conductivity. A particular challenging and important application of MT inversion is the delineation of deep conductive ore bodies. However where such orebodies are proximal to carbonations shales (conductive sheet like bodies) discrete definition of the ore bodies' geometry is even greater. We will consider the exactly this situation.

The MT method detects the naturally occurring electromagnetic fields and calculates a frequency-dependent electrical impedance tensor (**Z**) (Simpson and Bahr, 2005) which contains the transverse electric (TE) and transverse magnetic (TM) modes**.** The apparent effective resistivity can be extracted from the tensor and in turn can validate the quality of MT data over the survey region (Berdichevsky and Dmitriev, 2008)**.** The apparent resistivity and phase data extracted from the tensor are typically plotted against log period prior to inversion for the data quality control (QC).

Unconstrained MT inversion typically creates minimal (smooth) structures due to the fact that smoothness conditions dominate every cell in the resistivity model (i.e., Occam inversion) (deGroot-Hedlin and Constable, 1990). This smoothness is not realistic in regions where sharp boundaries exist between two distinct units of electrical resistivity. Sharp Occam like that of deGroot-Hedlin et al., 2004 have the potential to produces sharp conductivity contrast in the subsurface. Cooperative approaches such as Zhou et al. (2014) and Takam Takougang et al. (2015), apply smoothness weights at boundaries derived from prior information such as geology or 3D seismic reflections images.

The Kevitsa deposit is expected to contain 240 million tons (using a nickel cut-off grade of 0.1%) grading 0.30% nickel and 0.41% copper (Malehmir, Juhlin, Wijns, Urosevic, Valasti and Koivisto, 2012). The hosting intrusion varies from gabbro to dunite composition, with evidence of distinct magmatic pulses responsible for these different phases. The mineralised zone resides in what is dominantly olivine pyroxenite (Figure 1). Mineralisation is largely disseminated and rarely more than a few percent sulphide, with pyrrhotite often the dominant conductive mineral (Chris Wijns, pers. comm. 2016). Horizontal seismic reflectors throughout the resource area have previously been ascribed to internal layering marked by changes in composition resulting from the distinct magmatic pulses (Malehmir, Juhlin, Wijns, Urosevic, Valasti and Koivisto, 2012).

METHOD AND RESULTS

Method

The ModEM2D code developed by Egbert and Kelbert (2012) was applied in our inversions**.** ModEM2D's objective function minimises both data misfit and smoothness parameters, as given by (Egbert and Kelbert, 2012) :

$$\Phi(m,d) = (d - f(m))^T C_d^{-1}(d - f(m)) + \nu(m - m_0)^T C_m^{-1}(m - m_0) \qquad (1)$$

where,

$\boldsymbol{m}$ – earth conductivity model parameter
$\boldsymbol{d}$ – field data
$\boldsymbol{C_d}$ – covariance of data errors,
$\boldsymbol{f(m)}$ – forward modelling operator
$\boldsymbol{m_0}$ – the initial model
ν – Lagrange multiplier
$\boldsymbol{C_m}$ – smoothing operator

The Lagrange multiplier, ν , balances the trade-off between the misfit and smoothness requirements. $\boldsymbol{C_m}$, the model covariance or regularisation term, is known as a smoothing operator (Siripunvaraporn and Egbert, 2000). It dictates sharpness or smoothness between the geo-electrical cells.

Results

A detailed quality control (QC) process was completed prior to inversion. Every tensor MT sounding was reviewed and erroneous data removed. The QC process was applied to 312 MT stations over 7 lines. In the end a set of 312 MT records, as shown in Figure 2, were used for inversion. The final dataset consisted of 29 periods ranging between 0.001 and 1 s. The depth of investigation is estimated by the electromagnetic skin depth equation. It provides a rough guide of investigation depths for each recorded period that is used within the inversion workflow. Assuming a representative resistivity in the order of 25 Ω•m and MT periods in the range of 0.001 to 1 s, the skin depth suggests an approximate investigation depth range between 80 m and 2500 m (i.e., skin depth, $\delta = 503\sqrt{\rho \cdot T}$, where ρ is electrical resistivity in Ω·m and T is period in s).

TM mode apparent conductivities are shown in Figure 2 for periods, 0.0002 s, 0.01 s, 0.1 s, and 0.67 s. Complex 3D geo-electrical structures are identified by many highly conductive and resistive zones. Interpretation of multiple 2D lines could be misleading because of the 3D geo-electrical setting at Kevitsa (see geological map in Figure 1). For this reason we compare inversion with modEM2D and modEM3D. For both cases we assume that no drillhole or other information is available. In this respect our example is truly baseline and may represent the raw deep greenfields exploration scenario where unconstrained inversion is a necessary start point. Inversions were performed on the Pawsey Centre Magnus Cray XC30 supercomputer.

2D inversion uses a 100 Ohm·m half space prior model. The dataset includes both off-diagonal tensor impedances components (i.e., TE and TM modes). Note that the error floors for the off-diagonal elements (Zxy and Zyx) are set to 10% of the root mean square of absolute of their complex multiplication. The root mean square (RMS) misfit reduces to approximately 3 for all MT transects (see Figure 3). Considering the size (i.e. 312 stations) and complexity of the data set we achieve RMS less than 3 for this setting is difficult.

2D and 3D seismic data are overlain by 2D MT derived conductivity distributions as shown in Figure 4. A well log showing nickel percentage is overlaid on the seismic and conductivity sections for comparison. The zone of higher nickel content (which includes higher pyrrhotite as well) correlates with the high conductivity zone seen in the 2D MT overlay. However, separation of the orebody from conductive carbonaceous phyllite is far from clear. According to the profile E4 (Figure 4), high conductivity stripes indicate the existence of many carbonaceous phyllite units as seen in the geology map (Figure 1). Also, the profile E5 could "sense" both the position of the higher sulphide zone (i.e., see nickel content) as elevated conductivity and carbonaceous phyllite (see geology map). Both correspond with zones of high conductivity. Delineating between the ore body and carbonaceous phyllite at depth is still under investigation but 3D cooperative inversion is expected to yield interesting results. Meanwhile, low conductive zones seen in the resulting MT conductivity volume correspond to the mapped volcanic or gabbro rocks (See E4 and E5 in Figure 4). In the 3D view (Figure 4) two zones appear to show correlation between the seismic reflection and MT conductivity images. These include a higher conductivity zone possibly related to the ore body that seems to match a high reflectivity zone. The ore body was not explicitly delineated in the seismic, but the MT could offer additional information when placed in the seismic structural context. Cooperative inversion strategies for seismic and MT data are being developed in the hope of that these discrete and highly conductivity zones can be accurately defined.

CONCLUSIONS

Inversion was completed on seven magnetotelluric transects completed over the Kevitsa Ni-Cu-PGE deposit in Finland. The magnetotelluric data was inverted in 2D and a 3D interpolated conductivity volume was generated. The conductivity volume is also compared with 2D and 3D seismic data. Generally there is a fair correlation between boundaries in the seismic image and MT derived electrical conductivity distribution. One of the challenges in this survey area is to differentiate a high conductivity ore body from thin high conductive carbonaceous phyllites using only unconstrained 2D and 3D inversion. Both unconstrained 2D and 3D inversion appeared to extend a conductive zone to the locations of the ore body. However as expected it was difficult to separate the different highly conductive units and we are encouraged to apply full cooperative inversion strategies at this site as the next phase of research.

ACKNOWLEDGMENTS

The work has been supported by the Deep Exploration Technologies Cooperative Research Centre whose activities are funded by the Australian Government's Cooperative Research Centre Programme. This is DET CRC Document. We also acknowledge and thank First Quantum and in particular Chris Wijns for use of their comprehensive geophysical datasets. We also thank Schlumberger for providing the useful software. This work was supported by resources provided by the Pawsey Supercomputing Centre with funding from the Australian Government and the Government of Western Australia.

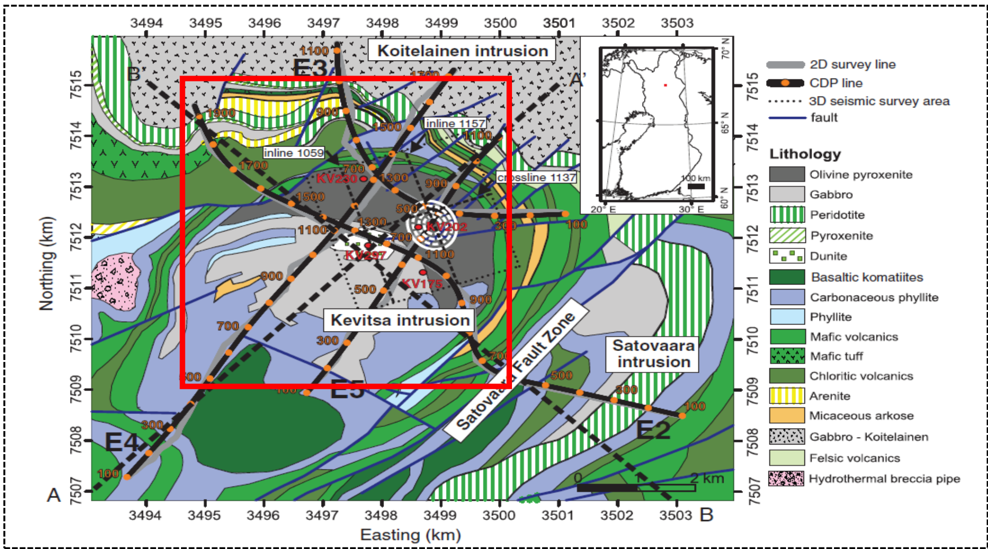

Figure 1: Geological map of the Kevitsa Ni-Cu-PGE deposit. The location of the 3D survey area (black dotted box), four seismic 2D profiles (black lines) and 2D MT profiles (dashed red rectangular box) are shown. (Figure is modified from Koivisto et al. (2012)).

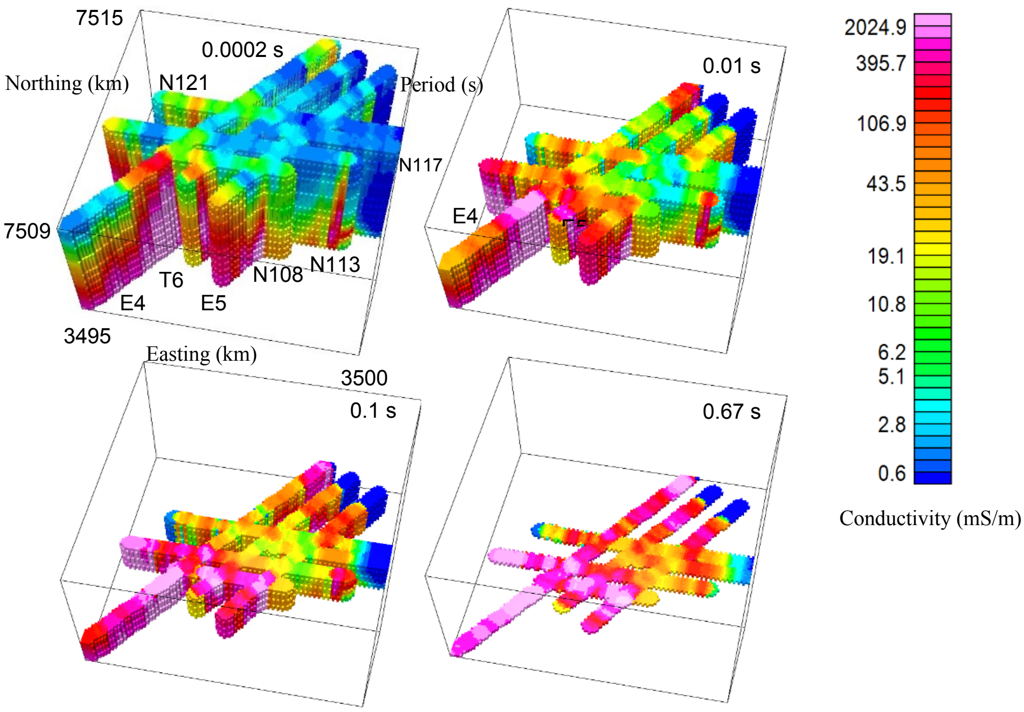

Figure 2: Observed apparent conductivity of the transverse magnetic MT mode at varying source periods (i.e., 0.0002 s, 0.01 s, 0.1 s, and 0.67 s). The Kevitsa resource contains complex 3D geo-electrical structures.

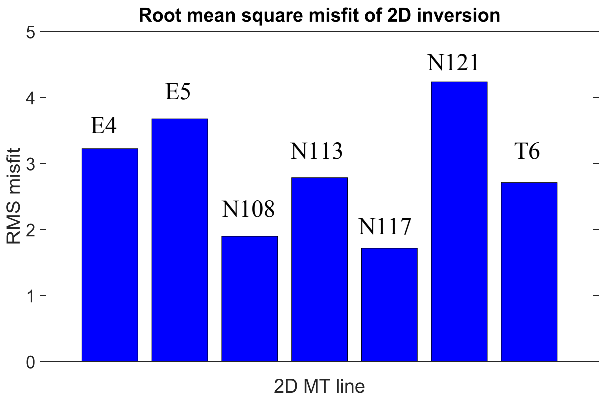

Figure 3: Root mean square misfit of 2D inversion for seven 2D MT lines.

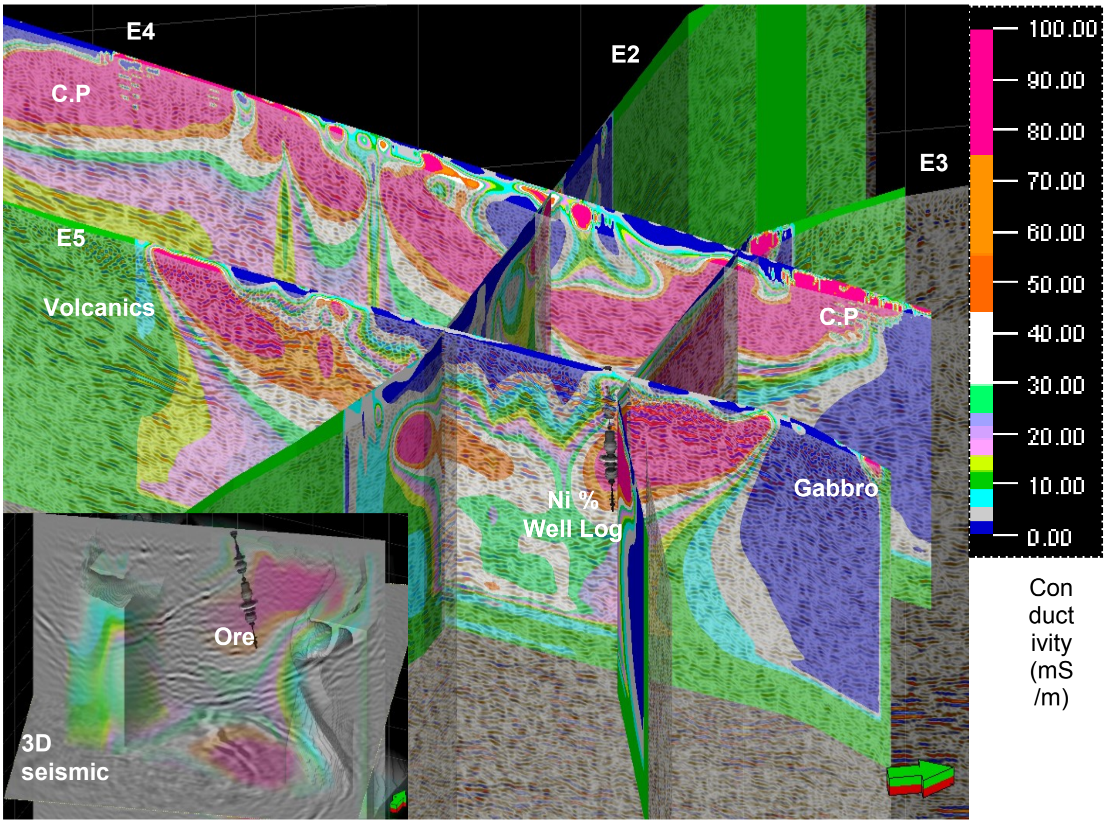

Figure 4: 2D and 3D seismic data overlaid by 2D MT derived conductivity distribution. The well log shows nickel percentage. The ore body broadly correlates with a high nickel content / high conductivity zone seen in the 2D MT overlay. However, the conductivity distribution is complicated by carbonaceous phyllite (C.P) units (see Figure 1). Note: (i) high conductivity zones may relate with carbonaceous phyllite or conductive part of the ore body but tend to be highly smeared; (ii) low conductivity zones tend to correlate with volcanic or gabbro rocks; (iii) some rapid transitions in conductivity correspond with seismic boundaries.

REFERENCES

Berdichevsky, M. N., and V. I. Dmitriev, 2008, Models and methods of Magnetotellurics: Springer.

deGroot-Hedlin, C., and S. Constable, 1990, Occam's inversion to generate smooth, two-dimensional models from magnetotelluric data: GEOPHYSICS, **55**, 1613-1624.

Egbert, G. D., and A. Kelbert, 2012, Computational recipes for electromagnetic inverse problems: Geophysical Journal International, **189**, 251-267.

Howe, B. D., J. Townsend, B. Doerner, and P. Patraskovic, 2014, Three-dimensional magnetotelluric inversion and petrophysical interpretation of the Turquoise Ridge gold deposit, Nevada, USA: Presented at the SEG Technical Program Expanded Abstracts 2014.

Koivisto, E., A. Malehmir, P. Heikkinen, S. Heinonen, and I. Kukkonen, 2012, 2D reflection seismic investigations at the Kevitsa Ni-Cu-PGE deposit, northern Finland: GEOPHYSICS, **77**.

Malehmir, A., C. Juhlin, C. Wijns, M. Urosevic, P. Valasti, and E. Koivisto, 2012, 3D reflection seismic imaging for open-pit mine planning and deep exploration in the Kevitsa Ni-Cu-PGE deposit, northern Finland: GEOPHYSICS, **77**.

Simpson, F., and K. Bahr, 2005, Practical Magnetotellurics.

Siripunvaraporn, W., and G. Egbert, 2000, An efficient data-subspace inversion method for 2-D magnetotelluric data: GEOPHYSICS, **65**, 791-803.

Takam Takougang, E., B. Harris, A. Kepic, and C. V. A. Le, 2015, Cooperative joint inversion of 3D seismic and magnetotelluric data: With application in a mineral province: GEOPHYSICS, **80**, 1-13.

Zhou, J., A. Revil, M. Karaoulis, D. Hale, J. Doetsch, and S. Cuttler, 2014, Image-guided inversion of electrical resistivity data: Geophysical Journal International.