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Electromagnetic and electrical methods applied to mapping coked coal – A case study from the Bowen Basin, Eastern Australia

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SUMMARY

In coal mining it is important to know if localised areas of coal have been rendered worthless through direct contact with volcanic intrusions. To avoid dilution, accurate coked coal boundaries are traditionally mapped by drilling.

BHP has made significant strides in applying geophysical methods to add value at its coal operations. With respect to the mapping of coked coal BHP have tried a suite of electromagnetic and electrical methods; enjoying success at improving the resolution of coked coal boundaries with significant implications on the amount of drilling required.

Recent trials of moving loop and airborne transient electromagnetic (TEM), Sub-audio magnetic (SAM), electrical resistivity imaging (ERI) and induced polarisation (IP) have encouraged the company to ramp up the inclusion of more TEM in its 5-year operational plans.

Unconstrained 1D inversion of moving loop TEM data correlated well to drilled intersections of coked coal. This enabled an improved coked coal boundary to be mapped.

An interesting observation is contrary conductivity sections obtained from moving loop TEM and ERI, with the latter method failing to identify the strong conductive layer mapped in both TEM and drilling. Possible conductivity anisotropy of the coked coal or the overlying sediments is being considered as a likely explanation for the failure of ERI to map the coked coal.

Inversion of SAM TFEM data partially worked to map the coked coal but only when constrained by the TEM inversion results.

The signal to noise ratio in the IP data proved to render the data uninterpretable, suggesting that the coked coal is not chargeable, with the graphite being in massive rather than disseminated form.

It is concluded that moving loop TEM and helicopter TEM both efficiently map coked coal sufficiently to target reduced drilling programs. Hence, where scales are appropriate, helicopter surveying is ideal to maximise efficiency without compromising resolution or results.

Key words: coked coal, electromagnetic, TEM, sub audio magnetic, SAM, electrical resistivity imaging, ERI, Bowen Basin.

INTRODUCTION

In coal mining it is important to know if localised areas of coal have been rendered worthless through contact metamorphism adjacent to volcanic dykes or sills. This high temperature metamorphic process results in “coked” or “cindered” coal.

Coked coal should be excluded from the ore reserve model and is ideally discarded during the mining process. To avoid dilution, accurate coked coal boundaries are traditionally mapped by expensive drilling prior to mine planning. Such mapping is optimised at approximately half the block model scale but drillhole spacings of <50 m are atypical prior to drill and blast holes at BHP coal operations.

Chakrabarti (1969) and Asten et al. (1987) have reported electrical conductivities on the order of 12.5 S/m to 50 S/m for coked coal. This is attributed to contact metamorphism altering the carbon properties of the coal, resulting in graphite which significantly increases the conductivity of coked coal in comparison to unmetamorphosed coal.

Surface and downhole transient electromagnetic (TEM) methods have seen previous application to detection of coked coal in the Sydney Basin (Peacock and King, 1985; Asten, 1986; Asten et al., 1987), but there is little freely-available information on the application of other electrical methods to the mapping of coked coal.

In 2017, BHP commissioned a suite of ground geophysical surveys over an area (~1 km^2) known to contain coked coal, in the Bowen Basin of Eastern Australia. This program included in-loop time domain electromagnetic (TEM), Sub-Audio Magnetic (SAM) Electrical Resistivity Imaging (ERI) and Induced Polarisation (IP) surveys.

Analysis of the data shows that of the methods trialled, TEM data is the most useful. Unconstrained 1D inversion, using University of British Colombia (UBC) code EM1DTM, produced a conductive layer that correlates well with the known coked coal.

BHP commissioned a 2018 HELITEM survey, also in the Bowen Basin. It has been concluded that moving loop and helicopter TEM both efficiently map coked coal.

Together with demonstrations of Tertiary thickness mapping, line of oxidation (LOX) mapping and structural mapping, these

results have encouraged BHP to include more TEM in its 5-year operational planning.

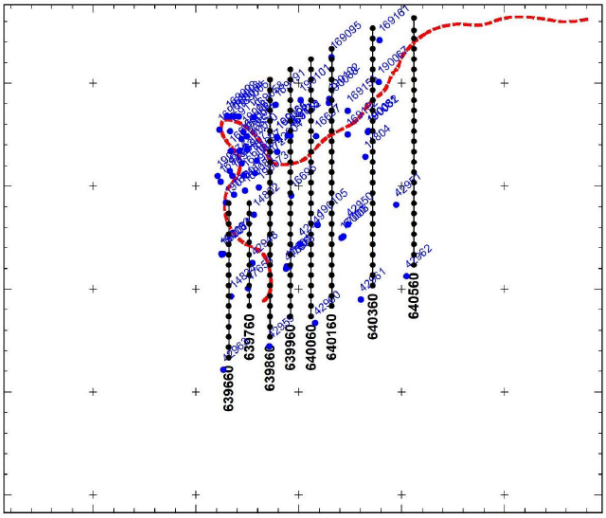

Figure 1. Location map for the moving loop TEM survey. Drillhole collars and names are shown in blue. TEM survey lines and stations are shown in black. The red dashed line shows the approximate northern and western extent of the coked coal). Grid ticks are 500 m apart.

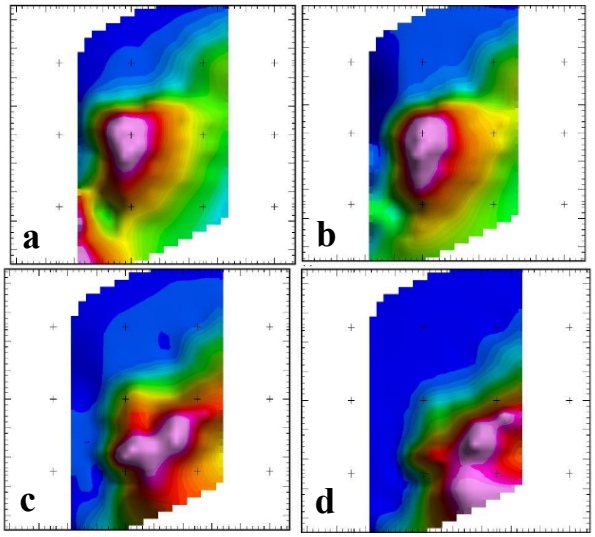

Figure 2. Grids of in-loop TEM B_z-component at delay times of 2.07 ms, 6.09 ms, 53.99 ms and 156.27 ms (a – d). These delay times correspond to SMARTEM channels 15, 20, 30 and 35. Grid ticks are 500 m apart.

METHOD AND RESULTS

Moving Loop TEM Survey

In-loop TEM data were acquired using 100 m × 100 m transmitter loops and an along line station spacing of 50 m (Figure 1). A GAP GeoPak EMTX-200 Transmitter was used with a SMARTEM-24 Receiver and an EMIT fluxgate magnetometer (B-Field sensor). The Transmitter base frequency was 0.5 Hz, giving an offtime of 500 ms. Decays were recorded at 39 channels with delay times ranging from 0.0995 ms to 371 ms from the base of the turn-off ramp.

Figures 2, 3 and 4 show that there is a very strong TEM response associated with the known coked coal. Decay curve analysis results in a typical late time exponential decay constant of more than 100 ms. The main anomaly due to the coked coal migrates to the east-southeast with increasing delay time, consistent with the observed dip of the coal seams (<3°).

Z-component (B_z) TEM data were inverted for a layered earth using the UBC inversion code EM1DTM. The noise level assumed for the fluxgate sensor was 0.2 pT/A. The modelling employed a step current waveform, with the effects of four previous transmitter turn-ons/offs accounted for (Asten, 1986).

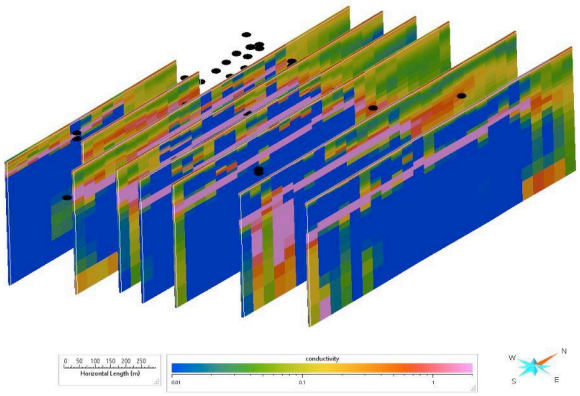

Figure 3. 3D view of TEM inversion results, looking to the northwest. The black discs are markers showing the top of the coked coal.

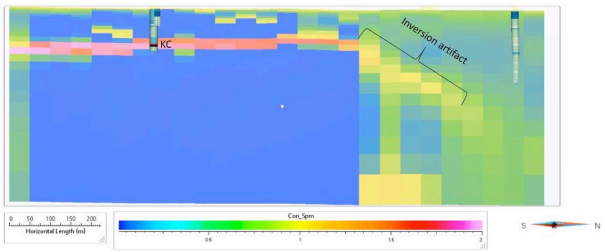

Figure 4. An example of TEM inversion results from Line 6401060 (no vertical exaggeration). The black unit on the southernmost drillhole (denoted KC) represents coked coal and coincides closely in depth with a strong horizontal conductor in the 1D inversion.

Electrical Resistivity Imaging (ERI)

The ERI method involves injecting a direct current into the earth through a pair of transmitter electrodes, and measuring the resulting potential difference at a series of receiver electrodes. This is effectively a measurement of the electric field resulting from the flow of subsurface current. From ERI data measured at a series of offsets between the transmitter and receiver dipoles and/or for a variety of dipole sizes it is possible to determine the variation of subsurface resistivity, both laterally and with depth. The method has high lateral resolution due to the small dipole sizes that can be used.

ERI data were acquired on four survey lines using an Iris Syscal Pro resistivity system (Figure 5). The electrode spacing was 10 m, and a combination of pole-dipole, Werner and dipole-dipole data was acquired. Induced Polarisation (IP) data was acquired on Line 639750 and Line 1000. Transmitter base

frequency was 0.25 Hz for the lines on which IP data was acquired, and 1 Hz on the other lines.

RES2Dinv Inversions of the ERI failed to map the coked coal as illustrated in Figure 6.

Despite good resistivity data, there was an insufficient chargeability response in the IP data to interpret.

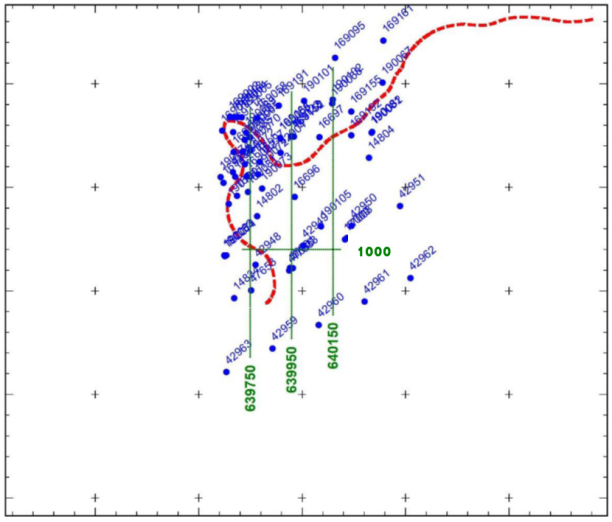

Figure 5. Location map for the ERI survey. Drillhole collars and names are shown in blue. TEM survey lines and stations are shown in black. The red dashed lines shows the approximate northern and western extent of the coked coal (derived only from drilling data). Grid ticks are 500 m apart.

Sub Audio Magnetics (SAM)

The Galvanic source SAM method allows simultaneous mapping of electrical and magnetic properties of the subsurface (Cattach 1993). Current is injected into the earth through a pair of widely-spaced electrodes and a fast-sampling mobile magnetometer measures the total magnetic field in the region between the electrodes.

Galvanic source SAM data were acquired with a single transmitter dipole, on 20 m spaced lines, using a GAP Geophysics TM-7B SAM receiver and GAP HPTX-70 transmitter. Base frequency was 7.5 Hz. Transmitter current electrode locations and the survey lines are shown in Figure 7.

A number of electrical parameters can be extracted from the recorded data in addition to the total magnetic intensity. These include electrical parameters such as Total-field Magnetometric Conductivity (TFMMC), Magnetometric Conductivity (MMC) and galvanic source Total Field Electromagnetics (GSEM). These data were inverted using H3DTDinv as illustrated in Figure 8.

An important characteristic of SAM MMC and TFMMC data is that a horizontally stratified earth produces no anomaly. The most geologically-meaningful inversions of the SAM data are those constrained by the MLTEM inversion. (Figures 9 and 10).

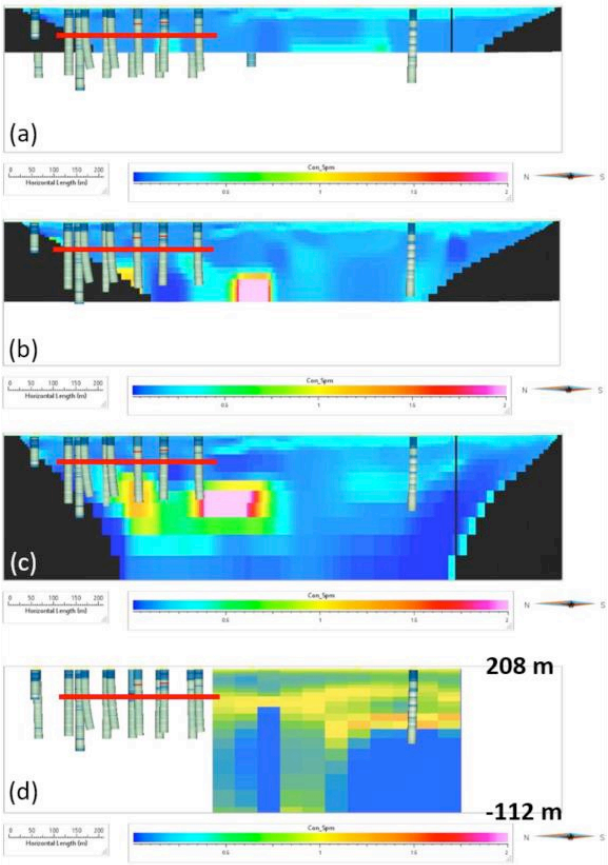

Figure 6. Comparison of (a) Wenner (b) dipole-dipole (c) pole-dipole and (d) TEM inversions from line 639750. The horizontal red line shows the elevation of the coked coal intersected in the drillholes that are within 50 m of the survey line. The colour bar shows conductivity in S/m and is linear with range 0.01 – 2 S/m. It is apparent that the ERI survey has not been as successful at mapping the coked coal.

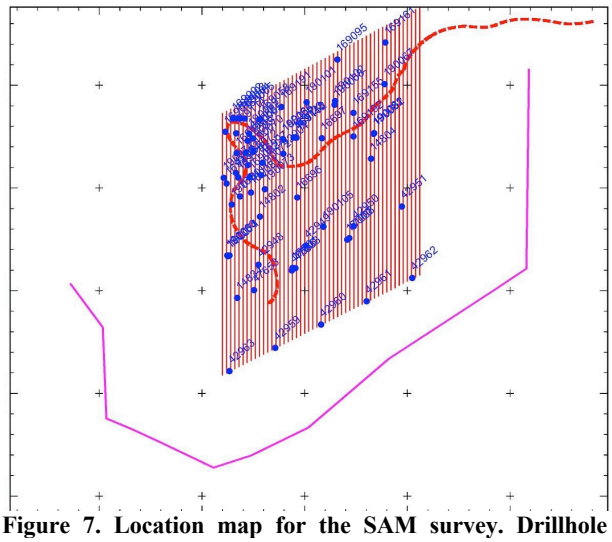

Figure 7. Location map for the SAM survey. Drillhole collars and names are shown in blue. SAM lines are shown in solid red. The transmitter current wire path is shown in heavy pink. The red dashed lines shows the approximate northern and western extent of the coked coal (derived only from drilling data). Grid ticks are 500 m apart.

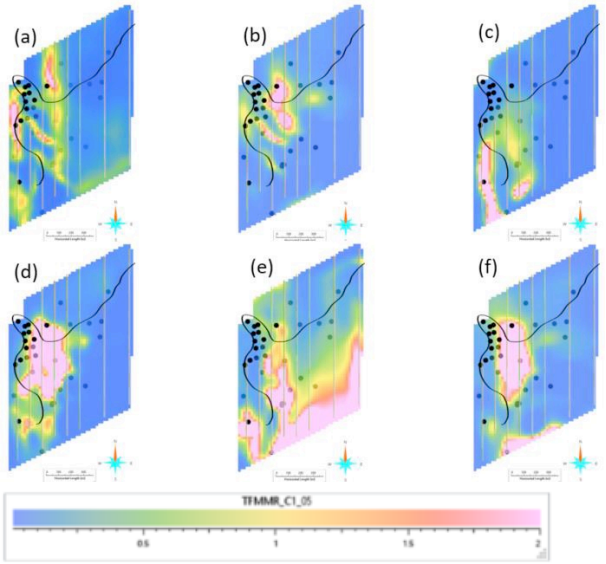

Figure 8. Comparison of 145 m depth layer for unconstrained SAM data (a) – MMC180, (c) - TFMMC and (e) – GSEM and constrained (b) – MMC180, (d) – TFMMC and (f) – GSEM inversions of SAM data. The constrained inversions were constrained by the moving loop TEM inversion.

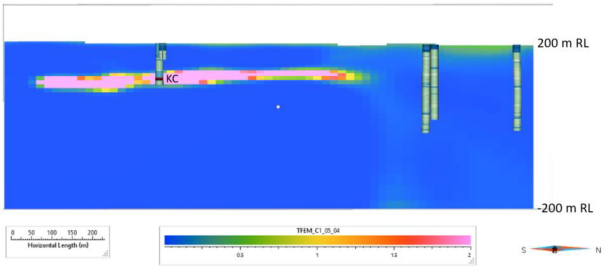

Figure 9. Conductivity section through the moving loop TEM constrained GSEM inversion at line 640131. The corresponding MLTEM 1D inversion is shown in Figure 4 and it is evident that the constrained GSEM inversion has greatly supressed the 1D inversion artifact. Drillholes within 50 m of the section are shown with the black horizon marked KC denoting coked coal.

Helicopter TEM Survey

There is no airborne electromagnetic data over the ground geophysics survey area; However, BHP commissioned CGG to fly their HELITEM survey over another site also in the Bowen Basin, in 2018.

The survey was flown in three blocks with different orientations, a line spacing of 50 m and a nominal transmitter and magnetometer altitude of 35 m. Figure 12 and 13 show a magnetic image and a conductivity depth slice from the survey respectively.

The magnetic intrusion (sill) evident in the south west of the magnetic image correlates well with a strong, thin, sub-horizontal conductor that is attributed to coked coal.

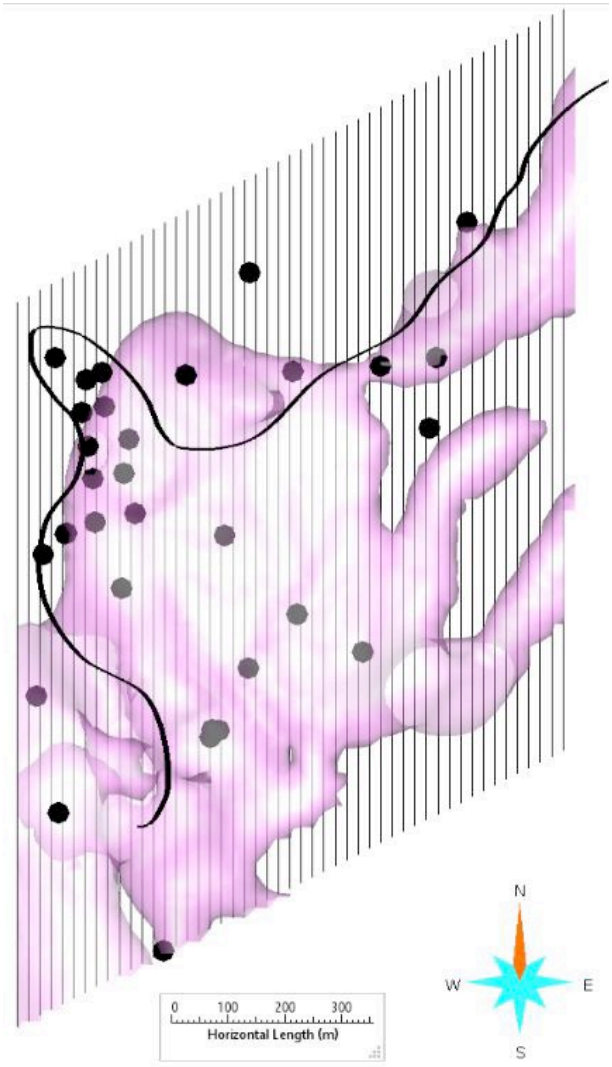

Figure 10. Plan view of the 0.3 S/m isosurface derived from the interpolated MLEM-constrained GSEM inversion models. The isosurface has been edited to remove surficial conductors and residual 1D inversion artefacts introduced by the constraining model. The SAM survey lines and pre-survey extent of coked coal are shown for reference. Black discs show drillhole intersections of coked coal.

CONCLUSIONS

Of the methods trialled the TEM method has proven to be the most effective method of mapping coked coal.

The theoretical advantage of ERI in terms of survey resolution has not proved useful because the ERI method did not reliably map the strong conductor. We speculate that this failure of ERI may be due to strong conductivity anisotropy within the horizontally layered coked coal or overlying sediments. In the transversely isotropic case, in which the horizontal conductivity differs from the vertical conductivity, EM measurements with an ungrounded source are sensitive only to the horizontal conductivity. In contrast, grounded source measurements are influenced by both the horizontal and vertical conductivity. In the latter case, errors in the interpreted depth of electrical layers occur when the data are interpreted using models which assume isotropic electrical conductivity (e.g. Reid et al., 2006). Chakrabarti (1969) has reported strong electrical conductivity anisotropy in coked coal.

The lack of an IP response suggests that the graphite is massive rather than disseminated, which is in keeping with the very high decay constants observed.

The flat-lying geometry of the conductor is generally unfavourable for SAM, given that there is no MMR anomaly from a 1D earth. The most geologically-meaningful inversions of the SAM GSEM data are those constrained by the MLTEM inversion.

Extracting an isosurface of conductivity from the in-loop, moving loop TEM survey, as a proxy for coked coal allows us to generate a geo-body of interpreted coked coal.

Within the ~1 km^2 ground survey area there are 66 drill holes, only half of which intersected coked coal. Despite this drilling it was still possible to refine the extents of the coked coal using electrical methods. If the TEM data had been collected first, we estimate that 20 follow up drill holes would have sufficed to map the coked coal to the necessary resolution.

Helicopter TEM is a practical and efficient method of achieving similar results; albeit with a compromised ability to estimate the thickness of the coked coal due to the higher frequencies of those systems.

By using the TEM method in a more regional approach, coking coal can be mapped even if the intrusions that have coked the coal are too small or horizontal to express themselves in high resolution aeromagnetic data.

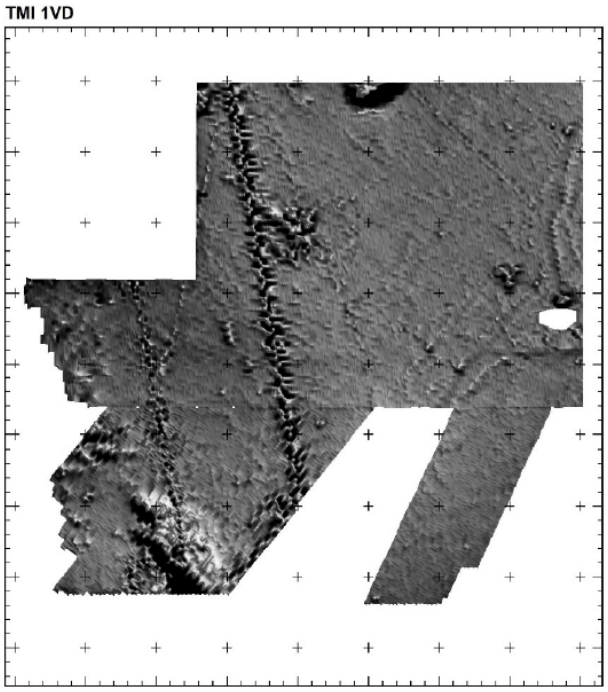

Figure 11. HELITEM first vertical derivative of the total magnetic intensity showing a magnetic sill in the bottom left corner. Tick marks are 1 km apart.

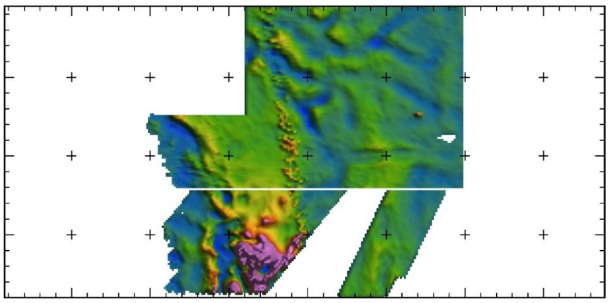

Figure 12. Elevation slice (~100 m depth) of conductivity from the HELITEM survey, derived from VPem1D inversion of the half-sine data. Tick marks are 1 km apart.

ACKNOWLEDGEMENTS

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Dan Eremenco of GAP Geophysics ran the ground geophysics acquisition program and it is their ERI inversion results that are presented in this extended abstract.

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