Comparing responses from different AEM systems and derived models at the Sunnyside nickel project, Botswana

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SUMMARY

The Sunnyside nickel deposit in SE Botswana is a shallow Selebi-Phikwe type deposit composed of disseminated, blebby and massive nickel sulphides. It was discovered by Anglo American in the 70's but considered uneconomic to mine. It is associated with pyroxenite and gabbro, and is an extremely complex orebody. Since that time several nickel companies have explored the body further, trying to improve on the size and grade and confirm whether the body extends to depth. The deposit has been surveyed to date by 4 different AEM systems, being VTEM, Spectrem, SkyTEM and Xcite. In addition, detailed ground geophysics in the form of moving loop TDEM and AMT has been done. In this paper we present a detailed comparison of the EM data measured by the 4 systems, and of the models derived through quasi-3D spatially constrained inversions, and of full 3D inversion of the AEM data. The resulting models are also compared to drilling information and the resistivity models obtained from inversion of the AMT data. The AEM systems display different signal and noise levels, and various types of preprocessing. The inversion results are, in general, in good agreement with each other and with the ancillary drilling and AMT information. SCI results follow the plunging conductor to significant depth. Some systems produce inversion outputs with higher accuracy or depth of investigation than others. IP effects, present in portions of the AEM datasets, add another degree of complexity but can also provide an extra layer of information. Sunnyside represents, defacto, the AEM test site for southern Africa.

Key words: Nickel, AEM, AMT, inversions, comparison, IP.

INTRODUCTION

The Sunnyside nickel deposit was discovered in the 1970's by Anglo American during a regional soil sampling campaign, but was considered by them to be uneconomic. It lies in the same belt as, and not far to the south of, the well-known Selebi-Phikwe nickel mine which has a resource of 68 Mt at 0.8% Ni and 0.88% Cu (see Figure 1). The deposit is small but has some high grade intersections of up to 2.3% Ni and 1.12% Cu over 1m. Because of this, a number of junior exploration companies have since looked at the deposit in order to try and extend the resource. The nickel belt has been flown in areas by numerous airborne EM systems including GeoTEM, Spectrem and VTEM. Albidon (Pty) Ltd. held the prospecting licence over Sunnyside itself during 2008 and flew a VTEM survey over this and other areas. Later they dropped the ground and African Nickel Limited took up the licence. They flew a Spectrem survey over Sunnyside in late 2012, and then invited SkyTEM to survey it as a test survey in early 2013. At the same time, moving loop ground EM survey was undertaken, and then in early 2014 undertook two AMT surveys to further define the sulphide body. The body was drilled extensively to a depth of 200m, but little deep drilling has taken place. In May 2016 NRG offered to fly Sunnyside with their new Xcite heli-EM system, as a test survey. The deposit has thus been flown by 4 different airborne EM systems and as such has become the de facto test site for airborne EM in southern Africa, with companies willing to fly there their upcoming newest developments.

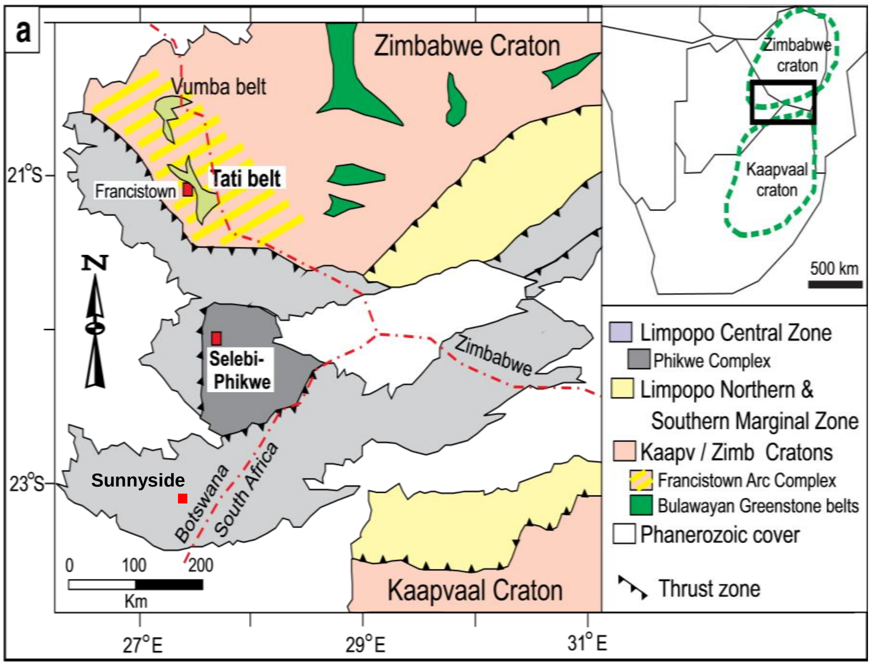

Figure 1 – Location of the Sunnyside nickel deposit.

METHOD AND RESULTS

A moving loop ground EM survey was carried out with a50m grid spacing over the entire body. A 3-component fluxgate sensor was used with a Zonge transmitter and Smartem 24 receiver. The moving loop size was 100m x 100m, with an average current of 26 amps in the loop. Anomalies were modelled using EMIT's Maxwell software, and drill sites placed on the thin conductive plates. The Maxwell modelling proved very effective at pinpointing the intersected sulphides.

In order to explore the Sunnyside deposit at greater depth, four AMT lines across the deposit were initially surveyed in orthogonal directions. The initial work was very successful is delineating the sulphide body, so this was followed up with a more detailed regular grid survey. 13 lines spaced 100m apart were surveyed in N-S direction across the body. A 50m spread with two Ex, two Ey and central Hx-Hy was designed, with both Tm and Te mode data measured every 25m. Data was recorded in the range 1 Hz to 8192 Hz. This survey is possibly one of the most detailed AMT surveys ever carried out in base metal exploration worldwide. The data were inverted by GSS using Zonge's SCS2D software. An unconstrained 1D inversion was done first, and this was used as a starting model for the Tm, Te and 2D vector inversions. A sample of AMT inversion results are shown in Figure 3 (background). They provide very good agreement with depth to top of deposit.

There is a wealth of Airborne TDEM data over this deposit. It comprises, in order of acquisition, VTEM, Spectrem, SkyTEM and Xcite. Table 1 summarizes the system's main specs at time of the surveys.

	VTEM	Spectrem	SkyTEM (HM)	Xcite
Year flown	2008	2012	2013	2016
Base frequency	25 Hz	25 Hz	25 Hz	25 Hz
Duty cycle	37%	100 %	50%	25%
Number of gates	27	9	35	50
First to last gate (centre) time range	83-7,828 microsecs	26-9,987 microsecs	85-8,916 microsecs	32-12,515 microsecs
Dipole moment	438,000 A.m2	400,000 A.m2	150,000 A.m2	255,268 A.m2
Line spacing	300m	200m	100m	100m
Along line data density	10 Hz	5 Hz	Resampled to either 1 or 10 Hz	50 Hz

Table 1: Different systems' main specs at Sunnyside.

All of the AEM data was processed and inverted, in parallel, both with quasi 3D Spatially constrained Inversion (Viezzoli et al., 2008) and with full 3D. David Khoza of Spectrem Air undertook the unconstrained full 3D inversions of each dataset using VPEM3D (Fullagar Geophysics) and UBC software (cfr Oldenburg et al., 2013).

In the SCI approach, the AEM data were first processed to increase S/N, assess Noise and eliminate it, prior to inversions. Spatial resolution of the different systems at different time gates was also analysed and compared to geology and ground EM. For SkyTEM we used the raw, binary, non preprocessed data. It is obvious that some of the comments below depend also on different line density (cfr with table 1). SkyTEM's (high moment) and Xcite's responses over the peak of the anomaly has the highest vertical range and absolute values, thanks to their relatively fast ramp down (Figure 2). The AEM system's responses at early and late times (Figures 3) compared against the ground EM response show, among the others, a) a more focused response of the Xcite system, b) a lower noise on the VTEM late times, c) subtle secondary anomalies picked by both SkyTEM and Xcite, d) wide strong anomalies for Spectrem.

No a-priori was added to any of the realizations. In case of the Spectrem data, the total field was modelled and inverted for, fitting both Z and X components (9 gates each). In all other systems we modelled the off time only, dB/dt data, Z only. Results are accompanied by measure of data misfit and of depth of Investigation (DOI, Christiansen and Auken, 2012)
The helicopter TDEM systems show some rather clear airborne IP effects (cfr Kaminsky and Viezzoli, 2016, Kang et al., 2017, Macnae and Hine, 2016) in parts of the survey, mainly away from the deposit. The deposit area was therefore modelled with standard, no IP modelling approach. The Xcite data was however also modelled with AIP (see details on methodology in Kaminsky and Viezzoli, 2016) over selected lines. This approach improved the match between "IP corrected" AEM derived resistivity and AMT derived resistivity (not shown). Figure 3 displays vertical resistivity of SCI inversion results of VTEM, SkyTEM, Xcite overlaying AMT derived resistivity and top of deposit. The inversion results are presented as individual 1D models, without interpolation, shaded with DOI and with associated data misfit. AMT and geology (top of deposit, in magenta) show a good general correlation with all AEM systems. The DOI marks , in most inversion, the bottom end of the conductor. The match is quantitatively excellent with SkyTEM and Xcite, with VTEM overestimating the depth to the top of the conductor. VTEM's results are also associated to the highest misfit. All systems show a conductive body plunging to the west to significant depths (in excess of 500 m for Xcite) confirmed by the AMT models.

The SCI results for all 4 systems were also studied in 3D voxels and compared to the drilled sulphide body, deep AMT results and full 3D inversion of AEM. The SCI results were gridded into 3D for this purpose. The 3D inversions done by David Khoza (no indication of data misfit provided) were essentially in 3D already but had to be converted to voxel space. The full 3D inversion results were compared with the drilled sulphide body in 3D space, as well as with the AMT resistivity shells and the SCI inversion results (no DOI shown). Some results are shown in Figures 5-9 below. Both the UBC and VPEM3D code returned very similar results. Full 3D inversions and SCIs gave complementary results, with SCIs better defining the top of the bulk of the deposit and its flanks, and full 3D better resolving the bottom of the main body of the deposit, but missing other features. In general, the SCIs better matched the AMT results, both near surface, around the extremities of the deposit, and at depth, showing a plunging conductor.

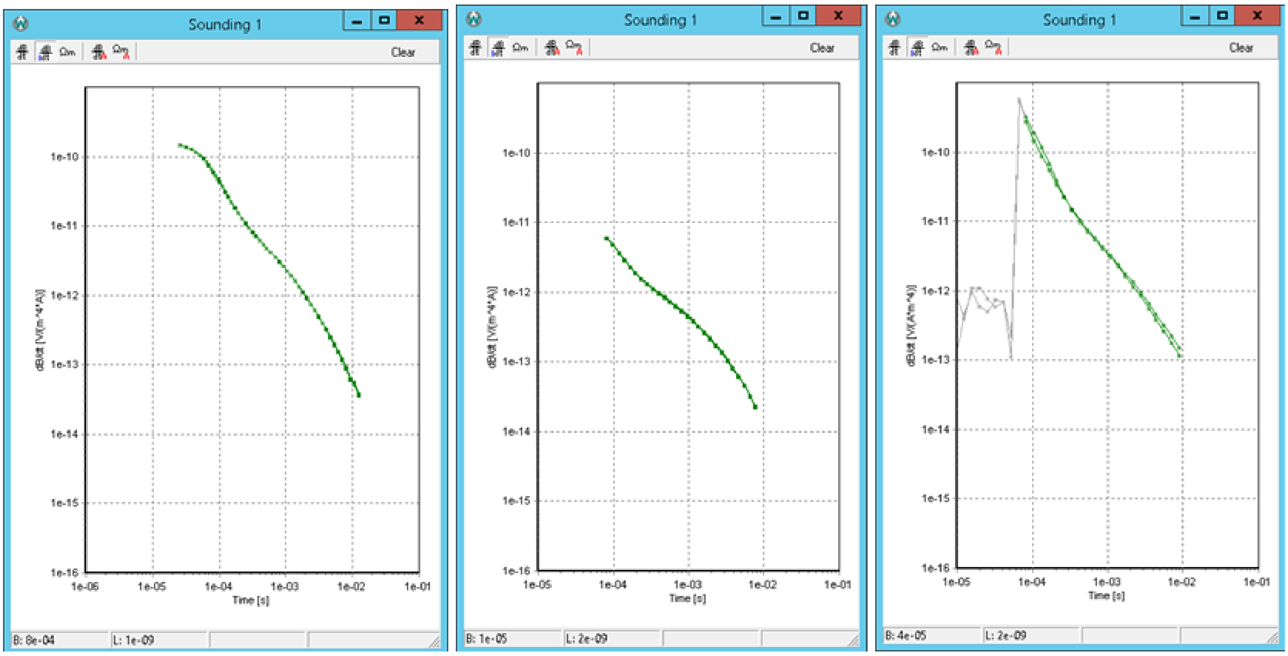

Figure 2: Different systems' responses: Xcite (left) – VTEM (center) – SkyTEM HM (right) at the peak of their anomalies over the deposit, normalized by dipole moment.

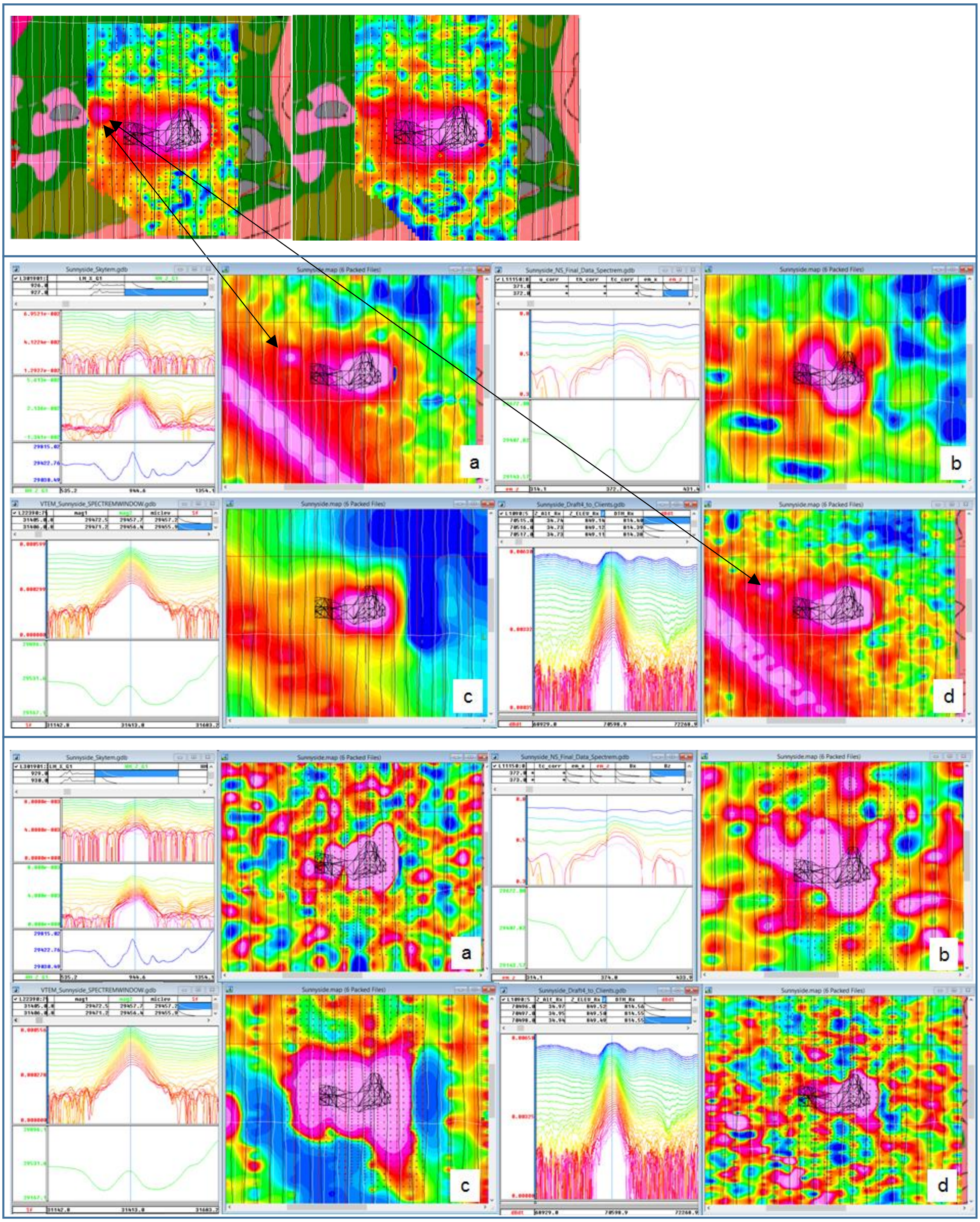

Figure 3 Spatial variability of ground EM response at 1.08 (left) and at 7.56 ms (right), over wireframe of deposit (top panel) . Voltage response at 1 ms (central panels) and at 10 ms (lower panels). SkyTEM HM (a) – Spectrem (b) – VTEM (c) – Xcite (d). For each slice maps, an example of raw flight data, collected over the deposit, is shown on the left. The black polygon in each slice outlines the Sunnyside deposit. Arrows correlate early time secondary anomalies.

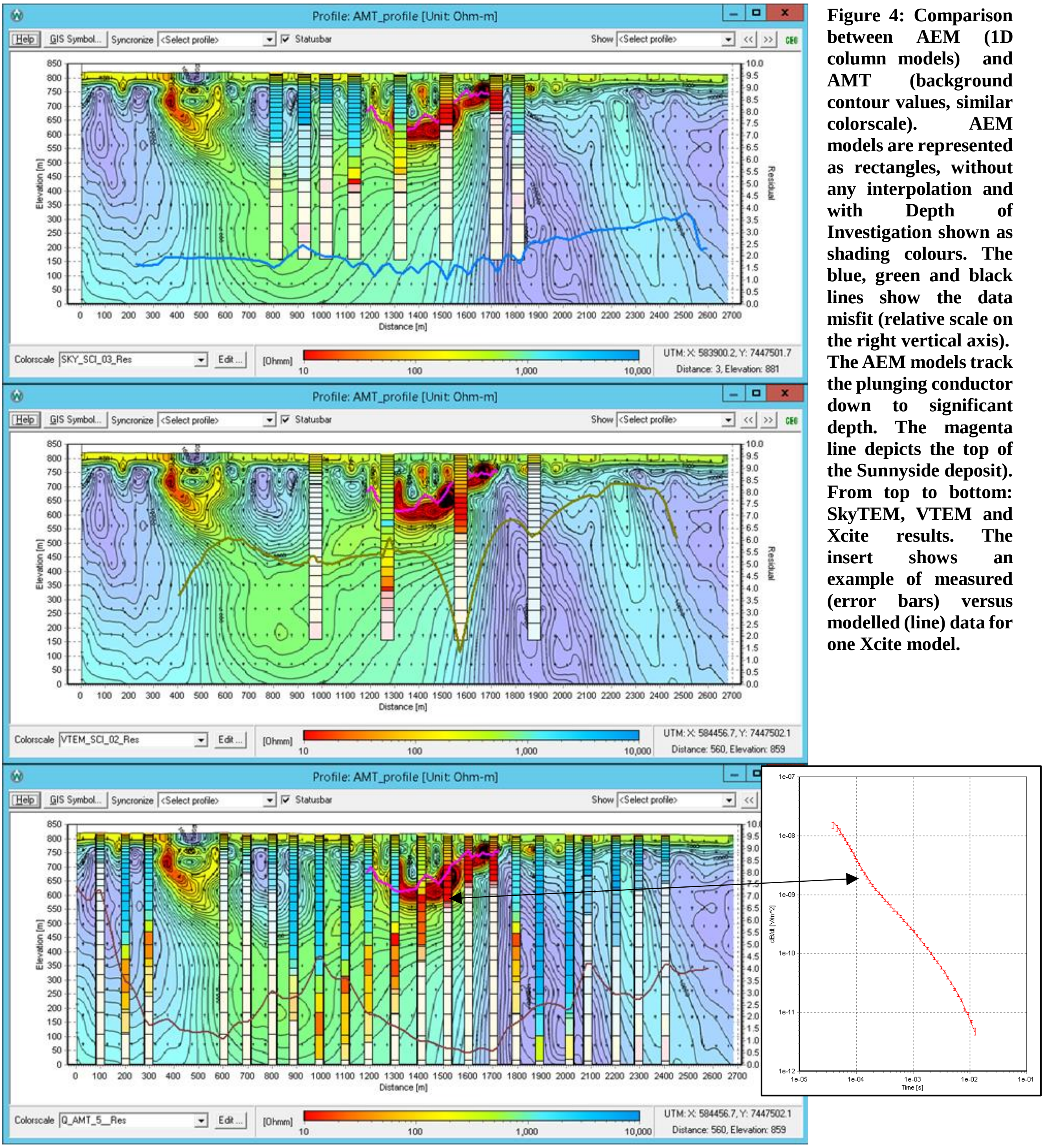

Figure 4: Comparison between AEM (1D column models) and AMT (background contour values, similar colorscale). AEM models are represented as rectangles, without any interpolation and with Depth of Investigation shown as shading colours. The blue, green and black lines show the data misfit (relative scale on the right vertical axis). The AEM models track the plunging conductor down to significant depth. The magenta line depicts the top of the Sunnyside deposit). From top to bottom: SkyTEM, VTEM and Xcite results. The insert shows an example of measured (error bars) versus modelled (line) data for one Xcite model.

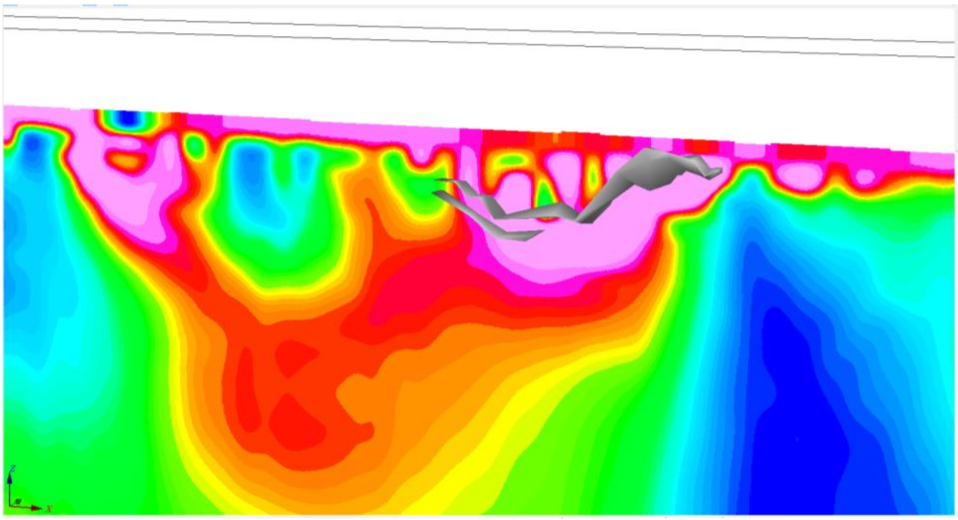

Figure 5 – W-E AMT section through the orebody which is shown in grey. Section looking north. Resistivity derived from 2D inversion of the Tm data. Colours are reversed to show conductive zones in red. It can be seen that the inversion matches the orebody shape very well, although the conductive zone is much thicker than the drilled sulphides. The data show a conductive zone plunging to the west to around 700m depth, and then coming back up to surface to meet another small, known sulphide body in the west.

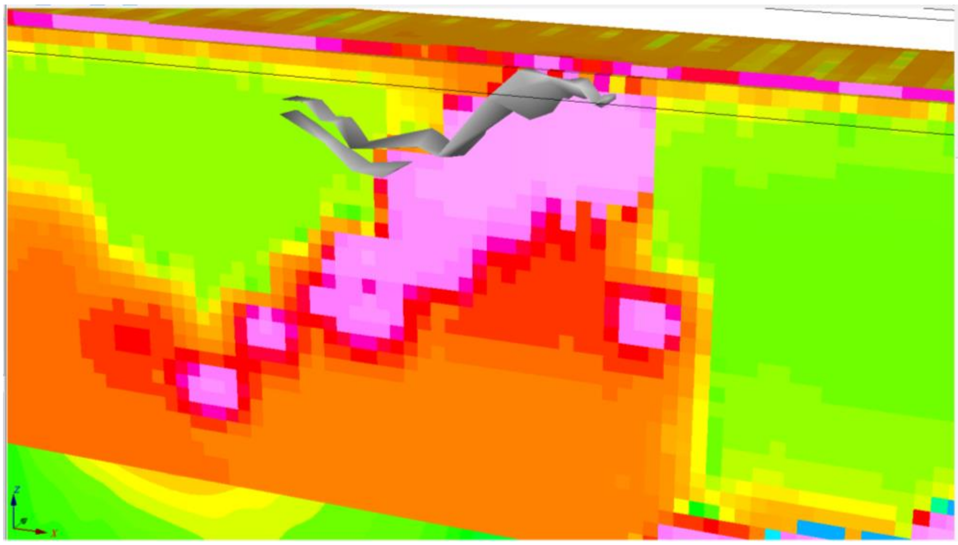

Figure 6 – Spatially constrained inversions for the Xcite data, gridded into voxel space to maximum discretized depth (no DOI shown). E-W section, view looking north. The drilled orebody is shown in grey. This quasi 3D inversion shows a deep body plunging to the west (left), matching what the AMT shows (in the background, and in Figure 4). It also matches the top of the deposit. The bottom of the main deposit's body seems overestimated, partly due to absence of DOI clipping.

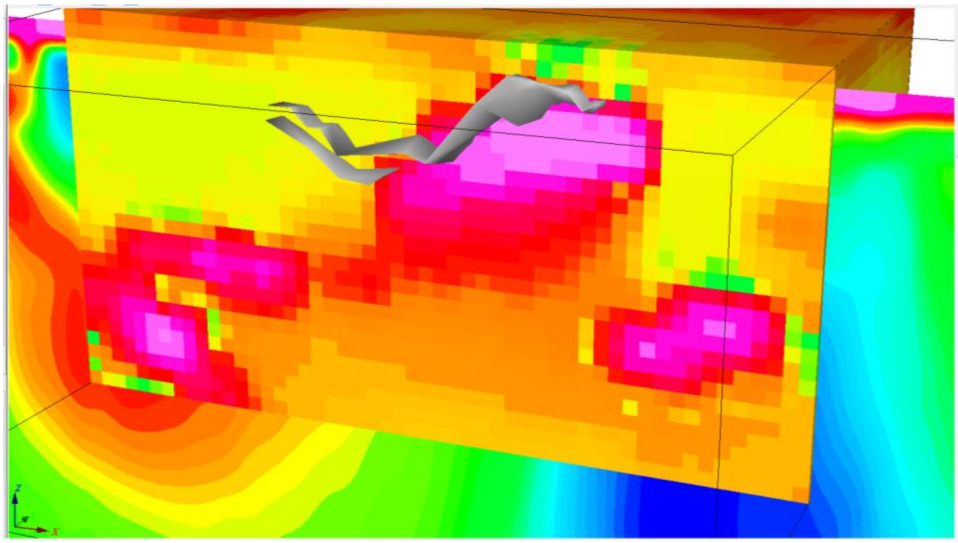

Figure 6 – Spatially constrained Inversion for the SkyTEM data, gridded into voxel space to maximum discretized depth (no DOI shown). The drilled orebody is shown in grey. E-W section, view looking north. This quasi 3D inversion shows a deep body plunging to the west, matching what the AMT shows. The result can be compared with Xcite's result shown in Figure 5. The AMT profile of Figure 4 is shown in the background for reference. The bottom of the main deposit's body seems overestimated, partly due to absence of DOI clipping.

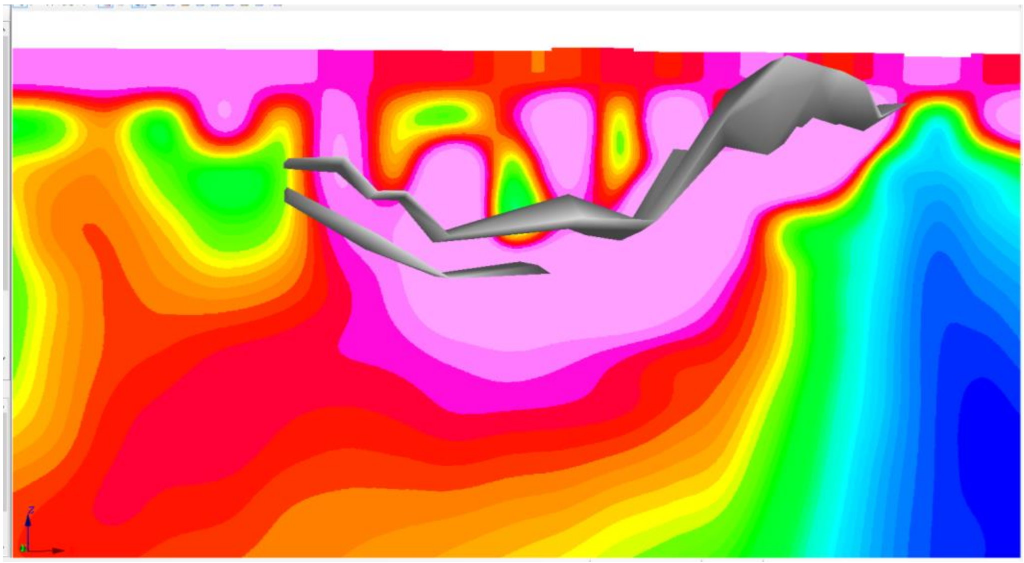

Figure 7 – 2D resistivity inversion of the AMT data. Reversed colours to show conductive zones. This figure can be compared with the two that follow of full, unconstrained 3D inversions of airborne EM data. The AMT inversion matches the sulphide orebody extremely well at the top, but not so well the bottom.

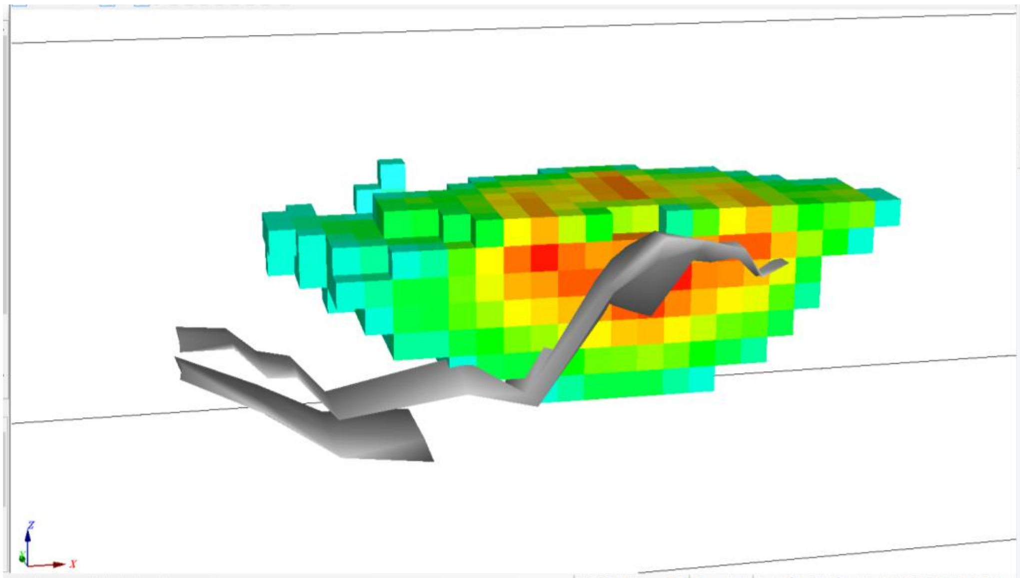

Figure 8 – VPEM3D inversion result for the Spectrem dataset in voxel space. E-W section, view looking north. The system has seen the main part of the orebody (in grey) very well. The unconstrained 3D inversion matched the bottom of the centre of the orebody very well. On the other hand it does not recover the side of the deposit, nor the plunging conductor.

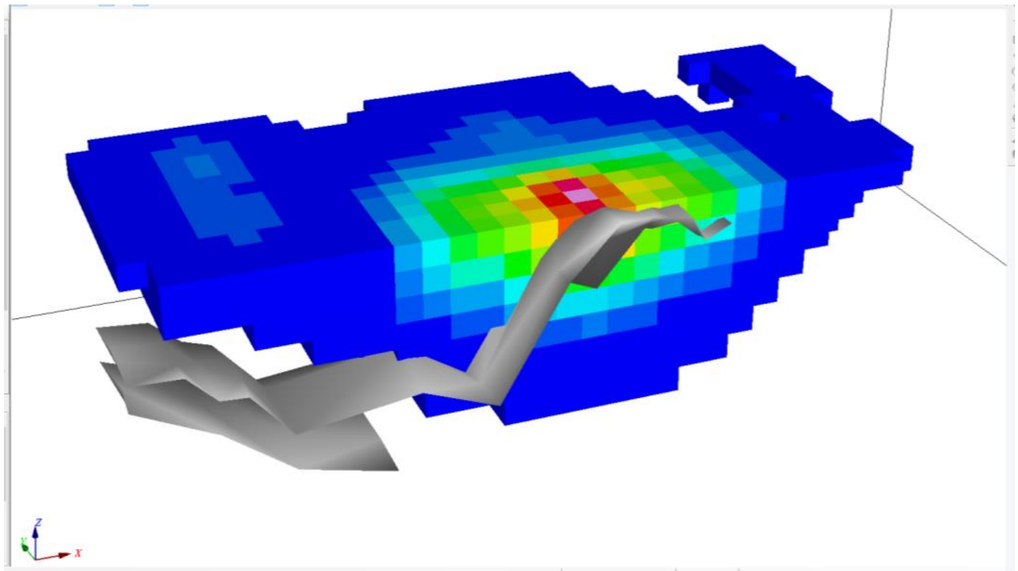

Figure 9 – UBC inversion result for the VTEM dataset in voxel space. E-W section, view looking NNE. The system has seen the main part of the orebody (in grey) very well. The unconstrained 3D inversion matched the bottom of the centre of the orebody very well. On the other hand it does not recover the side of the deposit, nor the plunging conductor.

CONCLUSIONS

The Sunnyside project has come to represent a de facto world class AEM test site for southern Africa, with 4 (and counting) different AEM datasets available, accompanied by extensive drilling and ground geophysics. We carried out a rather extensive comparisons across systems, between results of different inversion types, between AEM data/models and ground EM data/models. The outcome is that all AEM systems provided fair performances, some of them excellent. Correlation with geology (drilling) and with ground geophysics were satisfactory. Quasi 3D SCI versus full 3D inversions (both unconstrained) gave complementary results, with full 3D better resolving the depth to the bottom of the main part of the deposit, SCI better matching top of the deposit, its edges and AMT derived results.

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