The Valen Prospect: It's SPM,… No it's not,…Yes it is!.. No wait….

Tim Munday*
CSIRO DEI
Perth, WA, Australia
tim.munday@csiro.au

Mike McMillan
Computational Geosciences Inc
Vancouver, B.C, Canada
mike@compgeoinc.com

Rod Paterson
Intrepid Geophysics,
Brighton, VIC, Australia
rod@intrepid-geophysics.com

Daniel Sattel
Golden, CO, USA
dsattel@comcast.net

Camilla Sørensen
Aarhus Geosoftware,
Aarhus C, Denmark
camilla.soerensen@seequent.com

Noelene Dorn
ElectroMagnetic Imaging Technology Pty Ltd
Perth, WA, Australia
ndorn@electromag.com.au

SUMMARY

The choice of systems and interpretation approaches for the exploration for critical mineral systems under a complex and varying regolith cover using airborne electromagnetics, can be informed by forward modelling methods. However, the direct assessment of systems and modelling algorithms using data acquired under real survey conditions can be equally informative. For example, it provides an opportunity to assess the effects of real geological variability and noise, arising in a true survey configuration for different systems, and the artefacts that may result from the use of different inversion codes. Here we discuss the application of 1, 2 and 3D inversion approaches to resolving the geometry and complexity of the geology in an area on the South Australian side of the Musgrave province and consider modelled responses from coincident lines of fixed wing (SPECTREM-Plus and TEMPEST – High Moment), and heliborne (VTEM and SkyTEM) time domain EM systems over a known (from ground EM and drilling) deep, steeply dipping, conductor - the Valen Prospect.

All inversion methods and AEM systems contributed to our understanding of geological variability and structural complexity, although all generate smoothed versions of geological reality. Results from the 1D inversions appear to map geological variability and complexity in the near surface (regolith character?) in greater detail compared to those from the 2 and 3D inversions, even though the geology is recognisably 3D in character. The Valen Prospect characterised as a distinct, small, and narrow late time anomaly, is modelled in 1D, albeit deeper than drilling and ground EM suggests. While the 2 and 3D models have good global data fits, in some instances they failed to fit measured data at late time, consequently overlooking Valen. It was suggested that problems with fitting the anomaly at late times may be the result of regolith-related superparamagnetism (SPM) in the near surface which often beset AEM data sets in Australian settings. However, decay-rate analysis of the Valen anomaly suggests a deep conductor response for the SkyTEM, SPECTREM and TEMPEST systems. The decay rate of the corresponding VTEM anomaly suggests an SPM response. However, the shape of the VTEM decay also suggests the presence of deeper conductive material.

Key words: SPM, Critical Minerals, 1, 2 and 3D inversion, Fixed-wing and Helicopter time-domain AEM systems, Regolith

INTRODUCTION

The presence of a thick and complex transported regolith cover in many parts of Australia, represents a significant impediment to critical minerals exploration. The Musgrave Province, located in the far north-west of South Australia (Figure 1), highly prospective with magmatic Ni-Cu-PGE's among key mineral systems being targeted (Woodhouse and Gum 2003), is characterised by such cover. In this region, transported cover can exceed 100m thick, particularly where palaeovalley systems eroded into the Meso-Proterozoic crystalline basement, have been filled with Pliocene to Pleistocene clastic sediments and which have then been covered with Quaternary sand dunes (Figure 1).

Airborne electromagnetics (AEM) is used as a key exploration technology, being employed in the exploration for mafic to ultramafic layered intrusions which are the primary focus for Ni-Cu mineralisation. These intrusions (e.g., of Giles Complex – Figure 1- inset map) which commonly occur as a series of vertically stacked dykes which may act as potential traps for Ni-Cu sulphides.

The motivation for conducting this research was an interest in the application of 1, 2 and 3D inversions on AEM data with non-dispersive, conventional conductivity or resistivity modelling codes, applied to the targeting of conductive 'critical mineral system' targets at depth in complex weathered settings. Their ability to resolve other relevant geological characteristics, such as regolith thickness and spatial variability (also aspects of the "mineral system") was also of concern. Some may argue that the choice of survey technologies and interpretation method can, in large measure, be informed by forward modelling approaches. We accept this has merit, but also believe that more direct assessments with data acquired under survey conditions can be equally informative. In this study we consider the modelling of data from coincident lines of VTEM and SkyTEM helicopter, and SPECTREM and TEMPEST fixed-wing EM systems. System characteristics are discussed in Munday et al. (2023).

This work builds on earlier geophysical studies undertaken in the area (see, for example, Ley-Cooper et al., 2015, Macnae et al. 2020, and Munday et al. 2020). Arising from this assessment was an awareness that in this region, the deployment of high-powered AEM systems for targeting can be challenged by the occurrence of superparamagnetism (SPM) – seen as small late time responses following a noisy 1/t decay, and/or induced polarisation (AIP) effects in the resulting data - seen as rapid decays or negative responses at late time. For SPM-induced effects, these small late-time responses can be confused with potential mineralised targets (Mutton, 2012; Kratzer et al. 2013; Sattel and Mutton, 2015). One such example, examined here, is that associated with the Valen Prospect, a late time "conductor", originally identified as part of an exploration program undertaken by Musgrave Minerals using the VTEM heli-borne EM system and discussed by Macnae (2017).

METHOD AND RESULTS

Several inversion approaches were examined, including 1, 2 and 3D methods. In all cases, the inversions were undertaken with an induction only AEM inversion code, that is no account was taken of IP/SPM effects that are known to be present in the area. In addition, information from the ground TEM and drillhole DHEM and the presence of an inductive target was known prior to modelling using the different codes.

The 1D inversion scheme AarhusInv (Auken et al., 2015), was employed through the Aarhus Workbench to process and invert all four AEM data set. The data were inverted with a smooth 30-layer model. A 2D (or 2.5D) inversion of the four airborne data sets was undertaken using the Moksha-EM 2.5D code (Paterson et al., 2016, and Silic et al., 2015). Modelled responses are shown in Figure 2 for a subset of the data over the Valen Prospect. A 3D inversion of the AEM data sets was also undertaken using an adaptive OcTree mesh refinement, where the mesh spans the full computational domain but uses smaller mesh cells around the selected transmitters and receivers. This mesh refinement methodology results in a forward modelling mesh that has far fewer cells than the full inversion mesh. The approach is discussed Haber et al., (2012), Oldenburg et al (2013), Schwarzbach et al., 2013, and Yang et al., (2014). The 3D inversions for the individual lines were run in "2D-mode", meaning there was additional regularization applied in the crossline direction, while still modelling the full 3D physics. 3D inversions were run with data sets where there were three adjacent lines (in the case of SPECTREM, SkyTEM and VTEM). The lines were inverted as one combined 3D model for each input dataset. Model results are presented in Figure 3.

In the 1D results a deep conductive response is modelled where the Valen conductor had been defined from ground TDEM (fixed and moving loop EM) and from downhole EM in two drillholes. However, the 1D models suggest a much deeper body than was indicated in the ground data. Modelling of the ground data suggested a finite conductor at approximately 100m below the surface, dipping at approximately 60 degrees to the north. The 1D AEM results put the conductor much deeper for all four airborne systems. Drilling intersected minor accumulations of sulphide mineralisation but did not encounter any conductive source at the modelled depth of 65m. However, it intersected a 30cm zone of massive graphite at about 89.5m, which is attributed to the source of the TEM anomalism.

The 2D results from the Moksha (Intrepid) and Computational Geoscience/UBC algorithms show a varied set of results. Valen is not defined in modelling results from any system, except for a suggested presence in the SkyTEM data set inverted using the latter codes. Analysis of the data fits indicate that small amplitude late-time responses for all systems are poorly fitted, even though global data fits appear generally good. Analysis of the 3D models, for data sets where line density permitted the approach (with VTEM, SkyTEM and SPECTREM data sets), three adjacent lines were inverted as one combined 3D model. With relatively small targets it was suggested the 200m spaced lines were too far apart for the "all-at-once" 3D inversion to be better than the individual 2D line inversions. The individual 2D inversions consistently had the best data fits and overall models. If the data had been acquired with 100-150m line spacing, where there is a greater overlap of sensitivities between lines, or if more complex 3D geologic features were encountered, then the all-at-once approach may resolve greater detail.

It was suggested that the difficulty in fitting the Valen late time "anomaly" in the higher order inversion codes might be attributed to it being a superparamagnetic (SPM) response in the regolith, near surface. The decay rate of the Valen feature in VTEM indicates an SPM response. However, detailed analysis of VTEM and SkyTEM dB/dt responses suggests powerlaw decay rates similar to and different from SPM, respectively. However, even the VTEM decay does not show a constant powerlaw decay, suggesting the presence of conductive material at depth. The absence of a correlation between low system elevation and anomaly location further supports the absence of SPM, as SPM effects drop off strongly with the AEM system ground clearance. Decay-rate analysis of a late-time anomaly recorded in the Musgrave Province by AEM systems also suggests a deep conductor response for the SkyTEM, SPECTREM and TEMPEST systems.

CONCLUSIONS

This study suggests that, at a coarse scale, comparable results can be obtained for different systems, regardless of the modelling approach used. However, at a finer scale significant differences are apparent, and higher order inversion methods may struggle to fit small, late-time conductors such as Valen. Their absence in inversion products may erroneously be attributed to, for example, SPM effects, to explain poor data fits at late times. In the case of the Valen Prospect, a decay-rate analysis of the late-time anomaly for the systems tested suggests a deep conductor response rather than one attributable to SPM, which supports interpretations of the ground geophysical data The choice of exploration technologies and their incorporation in an exploration workflow will naturally vary with the experience and preferences of those involved, but in a geological setting such as found in the Musgrave Province, the application of AEM in the search for Ni-massive sulphides or other critical minerals will almost always be a case of "bump-finding", including some fast modelling (i.e. 1D LEI) and the ground follow-up.

ACKNOWLEDGMENTS

We acknowledge the support of CSIRO's Deep Earth Imaging Future Science Platform in facilitating the conduct of this work and thank the participating companies/individuals involved.

REFERENCES

Auken, E, Christiansen, A, Kirkegaard, C, Fiandaca, G, Schamper, C, Behroozmand, A, Binley, A, Nielsen, E, Effersø, F, Christensen, N, Sørensen, K, Foged, N, and Vignoli, G, 2015, An overview of a highly versatile forward and stable inverse algorithm for airborne, ground-based and borehole electromagnetic and electric data: Exploration Geophysics, 46:3, 223-235.

Haber, E. Holtham, E., Granek, J., Marchant, D., Oldenburg, D., Schwarzbach, C. and Shekhtman, R., 2012., An adaptive mesh method for electromagnetic inverse problems. SEG Technical Program Expanded Abstracts 2012: pp. 1-6.

Kratzer, T., Macnae, J. and Mutton, P., 2013., Detection and correction of SPM effects in airborne EM surveys, Exploration Geophysics, 44:1, 6-15,

Ley-Cooper, A. Y., Viezzoli, A., Guillemoteau, J., Vignoli, G. Macnae, J., Cox, L. and Munday, T., (2015). Airborne electromagnetic modelling options and their consequences in target definition: Exploration Geophysics, 46,74–84,

Macnae, J., Munday, T.J, and Soerensen, C., 2020, Estimation and geologic interpretation of regolith chargeability and superparamagnetic susceptibility in airborne electromagnetic data, Geophysics 85: E153-E162.

Macnae J., 2017., Definitive superparamagnetic source identification through spatial, temporal, and amplitude analysis of airborne electromagnetic data. Geophysical Prospecting 65, 1071-1084.

Munday, T., Macnae, J., and Viezzoli, A., 2020., Consequences for the Geological Interpretation of AEM data when Inverted for, and Stripped of, Airborne IP and Superparamagnetism Effects. KEGS Symposium 2020 “Exploration for Strategic Minerals” Toronto, Canada, February 28th.

Munday, T., McMillan, M., Paterson, R., Soerensen, C., and Dorn, N., 2023., AEM modelling and system options in the search for critical mineral systems in a regolith dominated environment – the Musgrave Province, Central Australia.” KEGS Symposium 2023 Toronto, Canada, March 4th, 2023.

Mutton, P., 2012., Superparamagnetic effects in EM surveys for Mineral Exploration, ASEG Extended Abstracts, 2012:1, 1-6,

Oldenburg, D. W., E. Haber, and R. Shekhtman, (2013), Three dimensional inversion of multisource time domain electromagnetic data: Geophysics, 78, no. 1, E47–E57.

Sattel D. and Mutton P. 2015., Modelling the superparamagnetic response of AEM data. Exploration Geophysics 46, 118–129.

Schwarzbach, C., Holtham, E. and Haber, E., 2013. 3D inversion of time domain electromagnetic data. ASEG Extended Abstracts 2013, 1-4.

Silic, J., Paterson, R., FitzGerald. D. and Archer, T., 2015., Comparing 1D and 2.5D AEM inversions in 3D geological mapping using a new inversion solver. 14th International, Congress of the Brazilian Geophysical Society, Extended Abstracts

Woodhouse AJ and Gum JC (2003) Musgrave Province — geological summary and exploration history, Report Book 2003/00021. Department of Primary Industries and Resources South Australia, Adelaide.

Yang, D., Oldenburg, D. and Haber, E., 2014, 3-D inversion of airborne electromagnetic data parallelized and accelerated by local mesh and adaptive soundings, Geophys. J. Int., 196 (3), 1492-1507

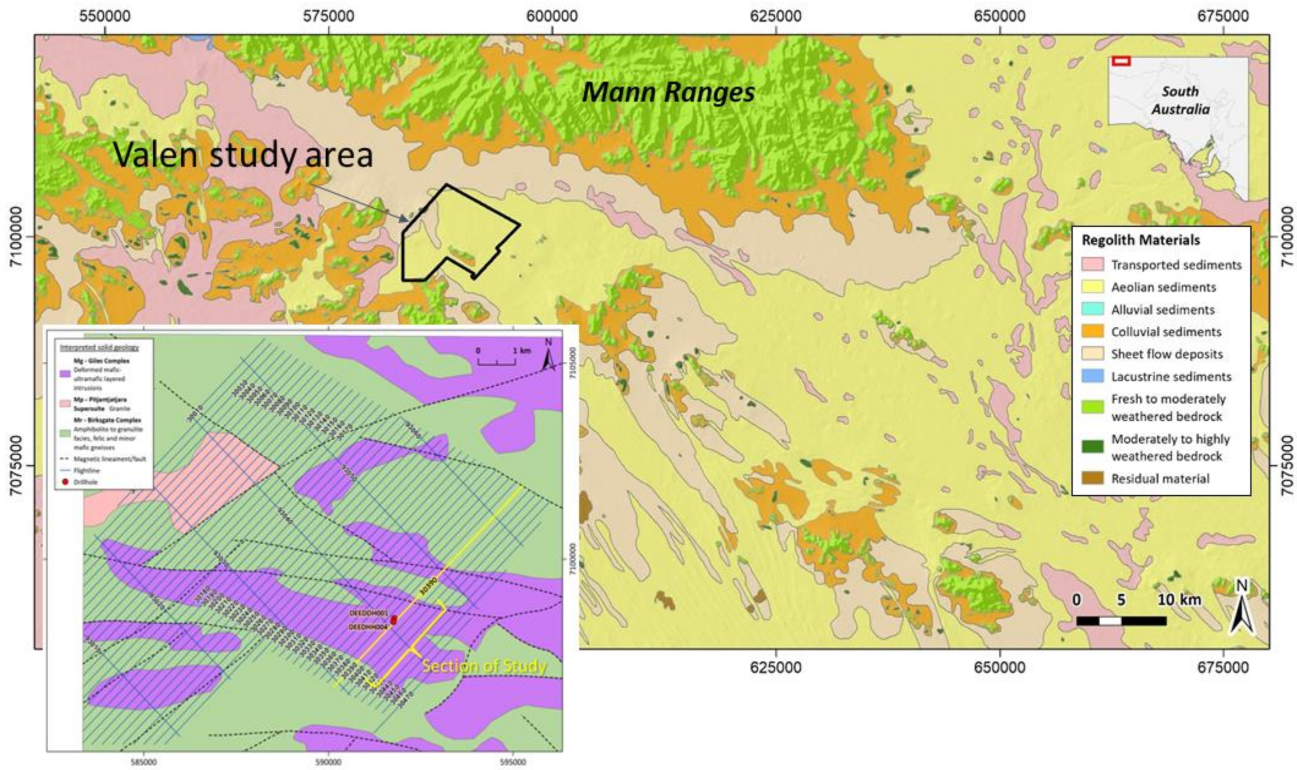

Figure 1: Regolith geology of Valen Prospect area with inset map showing flight lines form VTEM survey and sub-set of the line investigated here. The drillholes marked by the red circles are coincident with the Valen late-time anomaly observed in the AEM data sets.

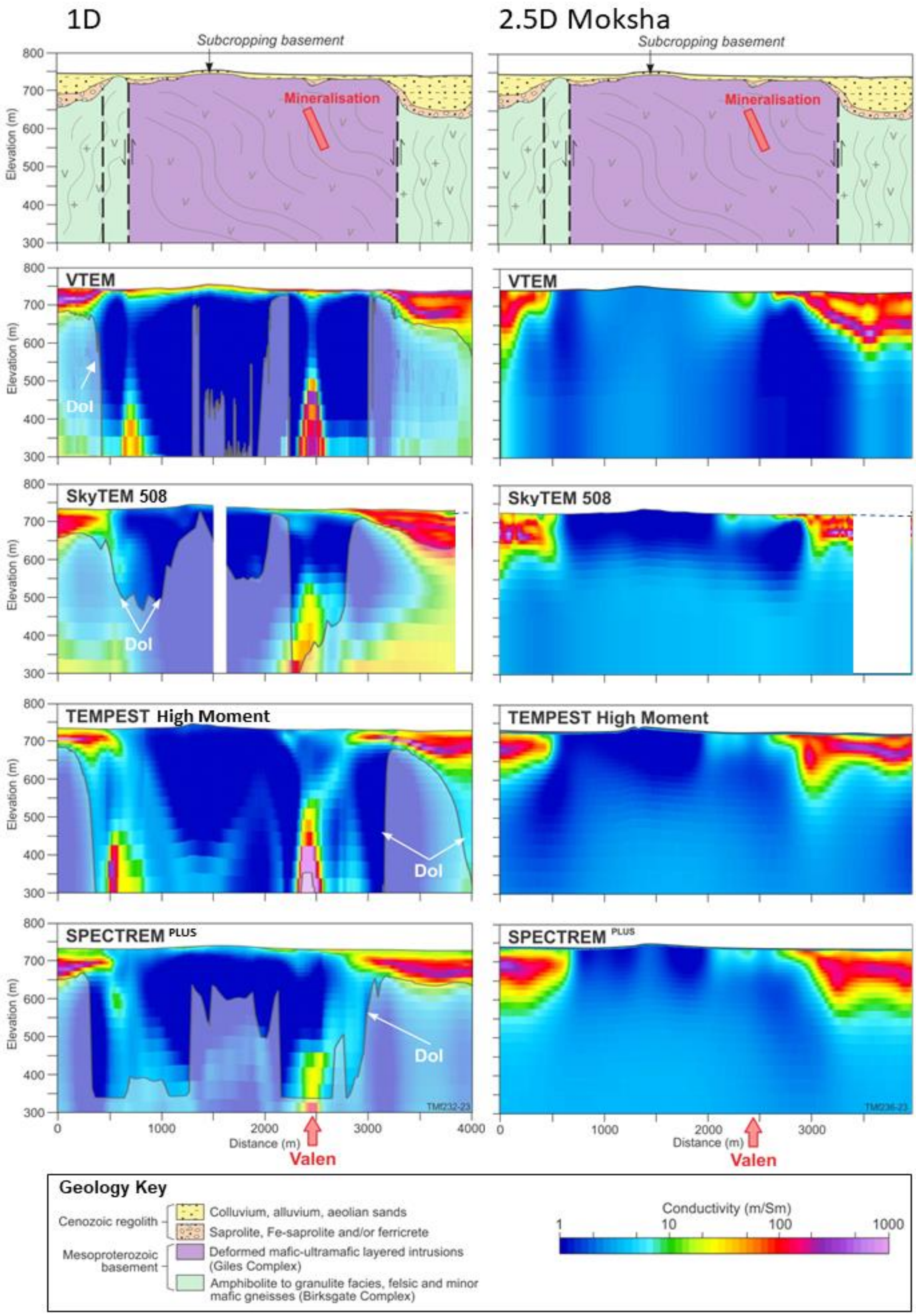

Figure 2: 1D smooth model (AarhusInv) inversion results (Left column)- presented as conductivity-depth sections for data acquired from a sub-set of coincident lines from different AEM systems across the Valen prospect. The right column shows inversion results from inversion using the 2.5D Moksha code for the systems considered. The location of the Valen conductor along the section is indicated at the bottom of the stitched sections.

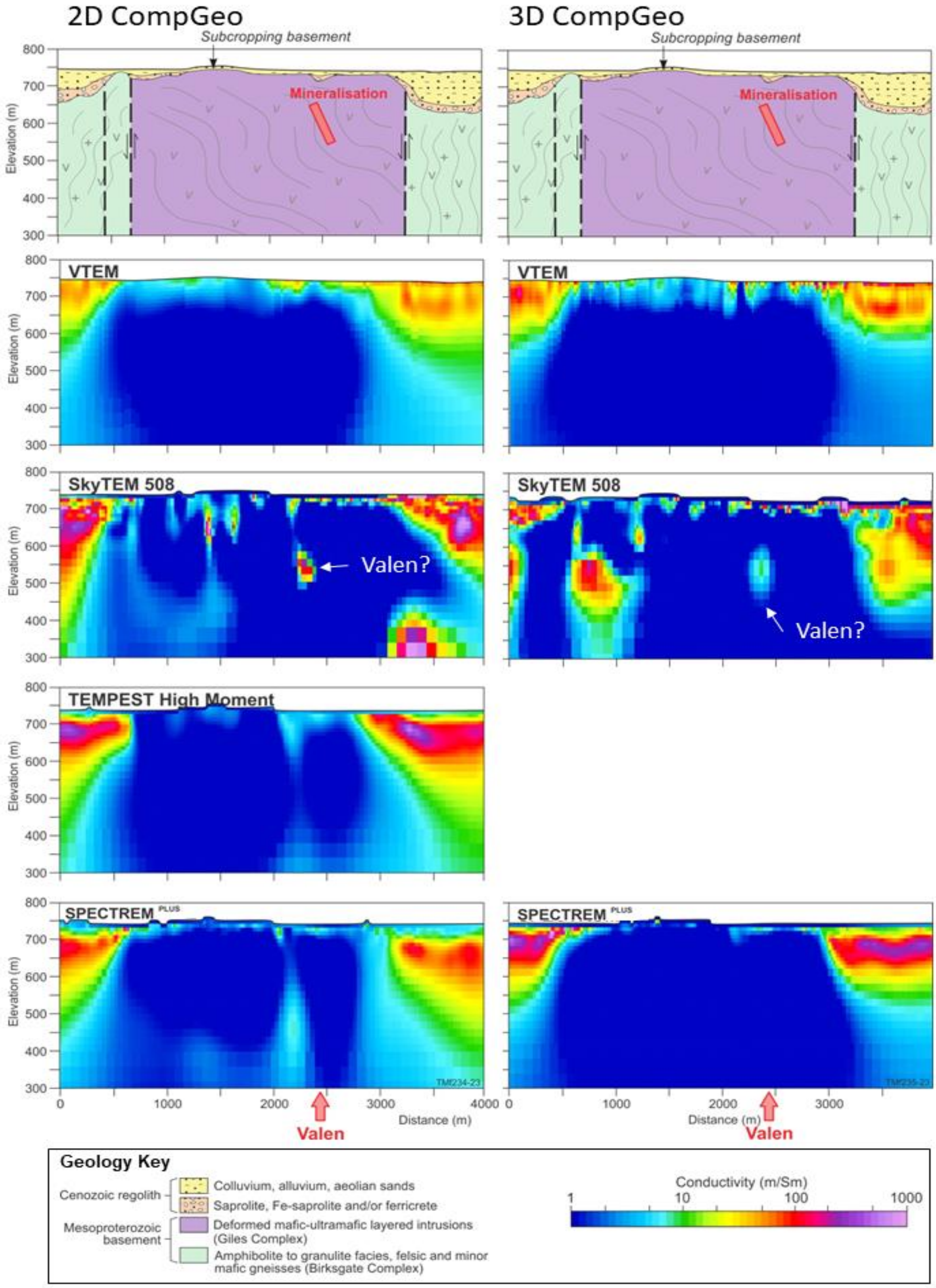

Figure 3: 2D smooth model inversion results for different AEM systems (Left column) generated form the application of the CompGeo/UBC codes, where individual lines were run in "2D-mode" where additional regularization was applied in the cross-line direction, while still modelling the full 3D physics. The right column shows model results from inversion using an "all at once" (where three adjacent lines were modelled with 3D physics. The location of the Valen conductor along the section is indicated at the bottom of the stitched sections. Suggested location of the Valen conductor is indicated in the SkyTEM data for both inversion approaches. TEMPEST High Moment data were not modelled in 3D as only a single line was acquired.