A thorough synthetic study on IP effects in AEM data from different systems

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SUMMARY

IP effects in AEM data are subject of current research around the world, due to the recent recognition of their significance for exploration and general (hydro)geological mapping. There have been success stories and it is now practical to model AIP on thousands of line kms of AEM data. However there still is a need to study more accurately the boundaries of the effect and of its relevance, beyond common past acceptance. In this paper we present a systematic, extended analysis of AIP effect in different AEM (TEM) systems' data, , based on synthetic modelling of different pseudo geologies. Its goal is to provide a clear overview of possible AIP effects in the data space, without imposing simplistic assumptions (e.g., fixing some parameters to arbitrary values or limited boundaries). We produce 1D forward responses with dispersive resistivity for hundreds of thousands of combinations of Cole-Cole model parameters and AEM system transfer functions. The results are analyzed using various metrics (e.g., sum of negative voltages, exponential fitting) that capture different AIP signatures in the transients. Experiments include half spaces, 2 and 3 layer models, combined with different waveforms, Rx types (dB/dt and B), Tx-Rx geometries, flying heights, transients' binning, base frequencies. The results, presented as 4D hyperspaces, each with 10^4transients obtained from the combinations of 4 x 10 different Cole-Cole parameters, allow a clear assessment of the AIP effects over a wide range of geophysical situations. Some of the main observations are: AIP effects are increased most often by the presence of a resistive bedrock, often using slow turn-off of the waveform, are generally better observed recording the B field instead of its derivative, and in any most cases lowering base frequencies to 12.5 Hz. In general, they are more pervasive than previously thought and should be carefully considered in virtually any AEM survey. If present, they can often be sensitive to model parameters down to depth.

Key words: IP, AEM, AIP, chargeability, modelling, metrics, inversion

INTRODUCTION

IP effects in AEM data are subject of current research around the world (e.g., Hine and Macnae 2016, Viezzoli et al. 2016, Kaminsky and Viezzoli 2016, Kang et al., 2017), due to the recent recognition of their significance for exploration and general (hydro)geological mapping. Till the last few years, industry believed that IP would not be measurable in AEM but in few special cases, and that its relevance would however be limited to very shallow layers. Such conclusions were often based on the assumption that IP effects, being hard enough to come by in ground EM must be most likely invisible in AEM. E.g., Smith and West, 1988 wrote "Our belief is that most local TEM negatives arise when there is a somewhat special (unusal) geometrical configuration of the conductivity structure". The ground TDEM studies themselves were often based on very simple scenarios, e.g., homogenous half spaces with limited IP parameters variability/ranges (e.g., Raiche, 1983), or 3D bodies with characteristics of limited variance. Flis et al (1989) did show that resistive host would enhance IP response in ground TDEM data, but its effects on AIP were not considered much. Smith and Klein (1996), analysed limited number of responses of (now legacy) GeoTEM system (Fixed wing system with limited bandwidth) accompanied by modelling of actual data. Their generalized conclusion was that "IP effects can only be measured with standard airborne EM systems in very special circumstances: when the conductivity is less than 0.003 S/m and when the dispersion in the off-time bandwidth is very strong". These conclusions are against more recent experiences and need to be re-tested with more systematic and general approach, for modern helicopter EM systems. Of course the computing power available at the times was not inductive to extensive analysis of AIP effects. The actual quality of the AEM data and pre-processing was also often inadequate to safely assess IP effects. The prevalence, at the times, of fixed wing TDEM systems, in which negatives can also be due to geometric factors, most likely also had a role in downplaying the relevance of AIP. Things have now changed significantly in both hardware and software. Recent studies are pushing the AIP boundaries (e.g., Viezzoli et al.) although still often posing somewhat restricting assumptions on parameters (e.g., both Macnae 2016a and Kang et al. 2017 fix c to a predefined value) or modelling approach (e.g., thin sheet). Beside considerations about which is the best model (e.g., other than single Cole Cole, e.g., Kratzer and Macnae, 2012) to describe IP in AEM, some of these restrictions applied arise also from the understandable desire to reduce parameters that we solve for, or CPU time. They might however prevent us from seeing the full picture. Conclusions about IP effects being at all present in the AEM data should therefore be drawn on as unbiased assumptions as possible, and not on what could be later possibly recovered by further modelling/inversion. The industry has been proved wrong a number of times before regarding what we can and can't resolve from AEM data (e.g., very near surface or very deep targets). There is therefore a need to study more systematically the actual general boundaries of the effect and of its relevance, starting from the data space. In this paper we inspect 10^5 forward responses of models with an IP component (described by Cole Cole parameters, Cole and Cole, 1941). Of course "recording" an IP effect in AEM data does not automatically mean that one will be able to recover it through inversion (cfr Viezzoli et al., 2016 for some examples). It does however hold true that if the IP does not have any effect on the transients, it will not be recoverable. This paper addresses this point. We hope that lessons learned from this study will be useful in other steps of the AIP geophysical problem, from recognition to processing, inversion, interpretation and its general applicability to exploration and geological mapping.

METHOD AND RESULTS

The forward (FWD) responses of layered earth with IP (we use the dispersive Cole Cole model, with low frequency resistivity limit) are obtained with AarhusInv (Kirkegaard and Auken, 2014), for different systems and different layering of electrical properties. Figure 1 shows the AIP effect over a homogeneous half space of different AEM systems. It is obvious that IP affects transients in different ways, depending on system's specs (e.g., waveform). It also shows how small variations of some parameter (e.g., c) can also have major effects. The effect of layering on the distortions of the transients is often very significant (Figure 2). Notice also in figure 2D the ever lasting effect of the shallow chargeable layer on the transient, capable of severely masking even the presence of a deep conductor. As a matter of fact, some of the AIP effects seem, at times, rather unpredictable. This is partly due to the major difference in the time versus depth relationship in a transient in presence of IP, as a consequence of the different decay rates of IP and "pure" induction currents. It is therefore also risky to generalize too much on when is AIP possible. A homogenous half space of $\rho < 10\ \Omega$ m will never give rise to AIP effects in conventional systems, no matter how chargeable it is. Same goes for slow IP phenomena (e.g., $\tau > 1$s). For many other scenarios, though, there are many grey areas. Remember also that AIP effects kick in as transients' distortions well before the latter changes sign. Bottom line is that, in order to assess and appreciate the actual detailed areas of the model(s) spaces that can give rise to measurable IP effects in AEM, one has to look at FWD responses of a representative combination of Cole Cole parameters and different systems, survey height, base frequency, data type, etc. Visual inspection of 10^5 FWD responses is impractical and qualitative only. We therefore designed a number of scalar features (metrics) that summarize the main IP attributes of any given transient and run them on batches of 10^4 transients at once (the combinations of 10 values for each one of the 4 Cole Cole parameters). Parameters we varied in discrete steps within wide ranges ($1 =< \rho <= 10000\ \Omega$m, 0=<m<=900 mV/V, 0.1<=c<=1, 10^{-6} s < =τ<= $5*10^{-2}$ s), aiming at drawing general observations. Table 1 lists the most important of these metrics. They are then grouped in 4D (one dimension per each Cole cole parameter) hypercubes that can readily be inspected in 3D by keeping one of the parameters constant. We performed a thorough investigation of these hypercubes, analysing the effects on AIP of: waveform types/duration, noise levels, gate widths, base frequency, flight height, Tx/Rx offset, layering (i.e., homogeneous half spaces, 2 layers and 3 layers), etc. For example, Figure 3 shows AIP metrics' hypercubes for different layering; Figure 4 for different systems and gate sampling. We list here only some of the observations that can be made from these Figures. A shallow chargeable and conductive layer over resistive bedrock (situation non uncommon to, e.g., large parts of Australia with weathered regolith) is prone to AIP effects (2B); the resistive bedrock enhances the AIP effects compared to homogenous half spaces, but for the more resistive overburden (cfr 2B with 2A); a buried (100m depth) chargeable anomaly below a resistive overburden, can produce strong AIP effects (2C); the sensitivity (based on the Jacobian) of the transients to *m* does not vary linearly with *m* in homogeneous half spaces (2D); in a moderately resistive half space, VTEM produces stronger AIP than HeliTEM (3A and 3B); increasing number of points per decade, whilst reducing the gates' widths, can improve the recoverability and accuracy (both depend on sensitivity) of, e.g., m (cfr 3C and 3D). This is thanks to the better sampling of the very fast decays which, from positive to negative, span double the amount of orders of magnitudes of non IP transients.

Generalizing the observation drew from a larger analysis of hypercubes, we conclude that AIP effects:
1) Depend to some degree from the type of waveform (more specifically the duration of the ramp down);
2) Depend heavily on layering (e.g, are greatly enhanced by resistive bedrock);
3) Decrease with higher acquisition height;
4) Can often increase with B field data;
5) Can, under favourable conditions, increase with lower base frequency;
6) Are often better sampled -and resolved- with more, shorter time-gates;
7) Are hugely influenced by *c* and (within a certain range) τ;
8) Are largest when 10^{-4} s < τ < 10^{-2} s; they are however often still present also at largest τ used in this study;
9) Can originate from "deep" (~100 m) chargeable layers, also with standard AEM systems at 25 Hz;
10) Can alter the rate of decay usually associated to deep conductors;
11) In some settings (e.g., weathered regolith over resistive basement) AIP are expected to be rather pervasive;
12) Combination of points 4 and 5 above can increase depth of recoverability of buried chargeable anomalies;
13) Display complementary signatures on the different metrics (e.g., in their equivalence), and can be meaningfully clustered;
14) Are often enhanced by lower noise levels.

Some of these observations are more trivial (e.g., 4, 5, 14) than others. Some had been hinted at before on ground TEM data (e.g., Flis et al., 1989, showed how resistive host would enhance IP effects in ground TEM data), but with a less systematic and general approach. These observations do strongly corroborate recent results on modelling of AIP from actual case studies (e.g., Kaminski and Viezzoli, 2016, Kang et al., 2017). These examples produced convincing results, both in terms of inverted resistivity and chargeability, from near surface down to relevant depths, over different geologies and targets. The observations should also give a clear warning on the relatively large number of combinations of geological scenarios and AEM systems specs which will (but also do, and did in the past) produce measurable AIP effects. Observations prove that AIP in modern AEM systems does go beyond "very special circumstances". The consequences of ignoring IP effects present in AEM data, modelling it with non dispersive (non IP) standard approach, can be dire. They can severely hamper the interpretability of resulting resistivity (conductivity) (cfr Viezzoli et al., 2016, Kamiski and Viezzoli, 2016, Macnae 2016b). As mentioned, even deleting the negatives prior to non IP inversions will not provide a correct resistivity model with a non IP modelling. Finally, notice that this "AIP domain" is bound to get larger on routine surveys, thanks to the ongoing development of "standard" AEM systems with higher dipole moment, lower noise and lower base frequency. E.g., 12.5 Hz surveys are now an option from most contractors of standard EM systems.

Next, it is obvious to attempt making wise use of these metrics for better processing and inversions of real data. For example as solid indicator of AIP effects (cfr point 13 above), for generator of starting models (points 2, 3, 7, 8, 9, 10), for assessment of non uniqueness and of inversion results in general.E.g., point 10 can result in severe artefacts such as missed conductors at depth if AIP is unaccounted for. The goal is to increase further the efficiency and robustness of the entire workflow that revolves around robust approach to the AIP problem/opportunity. Even though some of these aspects have already been applied commercially, they are subject of ongoing research.

Metrics on gate numbers	First gate which shows a negative voltage
	Gate which shows the maximum negative voltage
	Number of gates which show a negative voltage
Metrics on voltages	Maximum negative voltage
	Sum of negative voltages
	Area below the curve (integral of absolute values)
Metrics on slopes	Straight line best fitting in a log-log plot –Early times
	Straight line best fitting in a log-log plot – Mid times
	Straight line best fitting in a log-log plot – Late times
Metrics on sensitivity	Based on covariance matrix between model parameters and data

Table 1, types of metrics used to summarize the AIP effects on both synthetic and real data

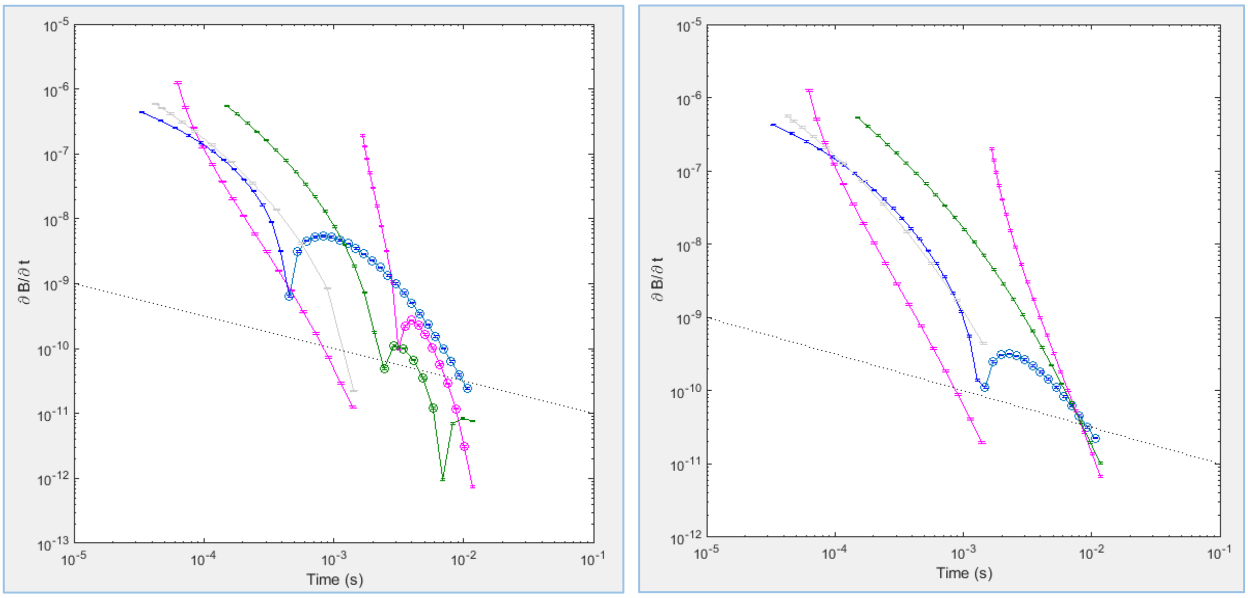

Figure 1: FWD response of different AEM systems (VTEM=blue, SkyTEM = purple, Helitem=green, Equator=grey), over a polarizable homogeneous half space with ρ=500 Ωm, m=200 mV/V, τ=1ms, c=0.5 (left) and c=0.7 (right). Circles represent negative values, and the dash line a typical noise envelope.

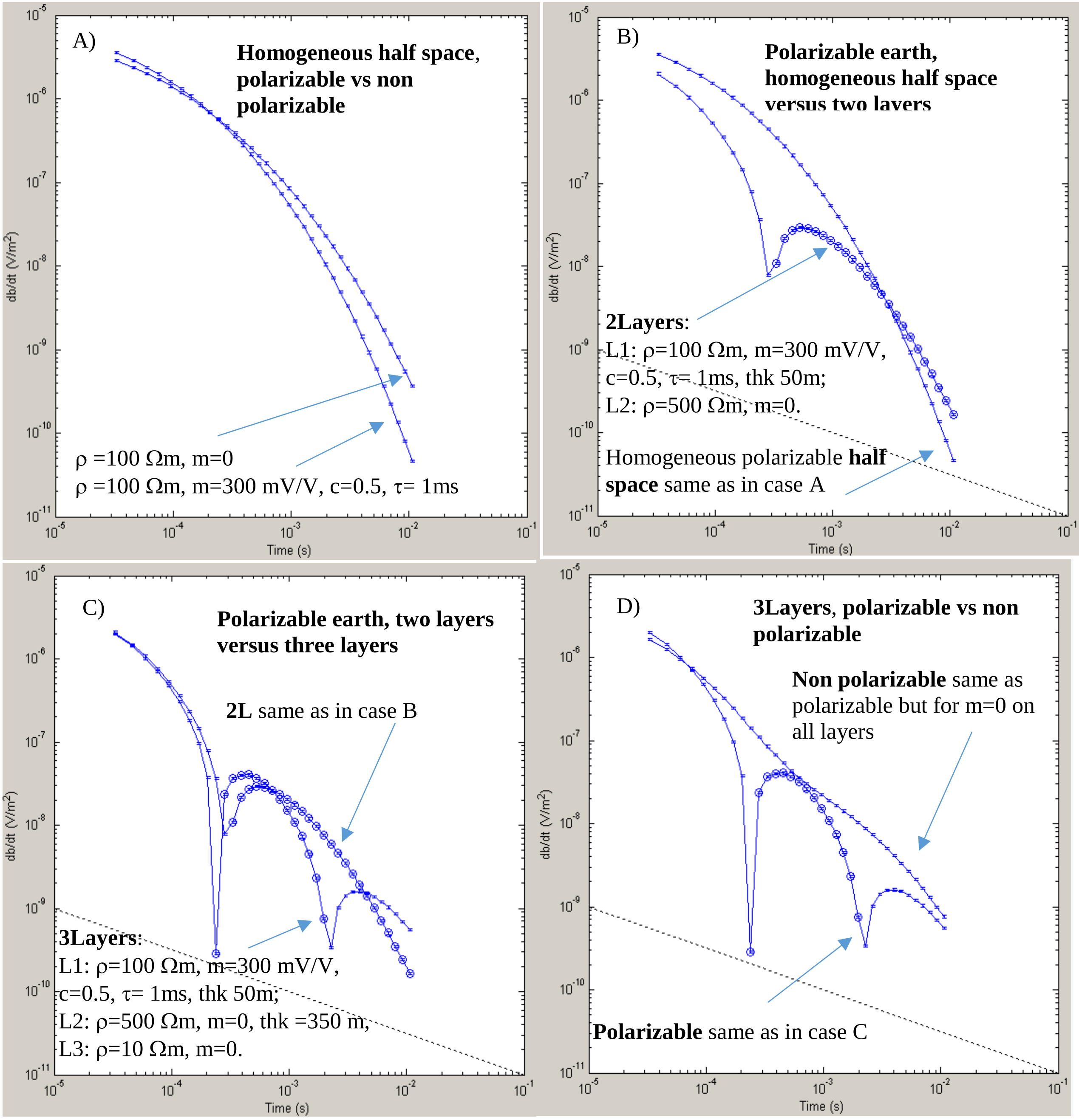

Figure 2: FWD response of VTEM over a polarizable (and not) layered earth with different combinations of layering of electrical properties. Circles represent negative values, and the dash line a typical noise envelope. Cfr details in legends, from A to D.

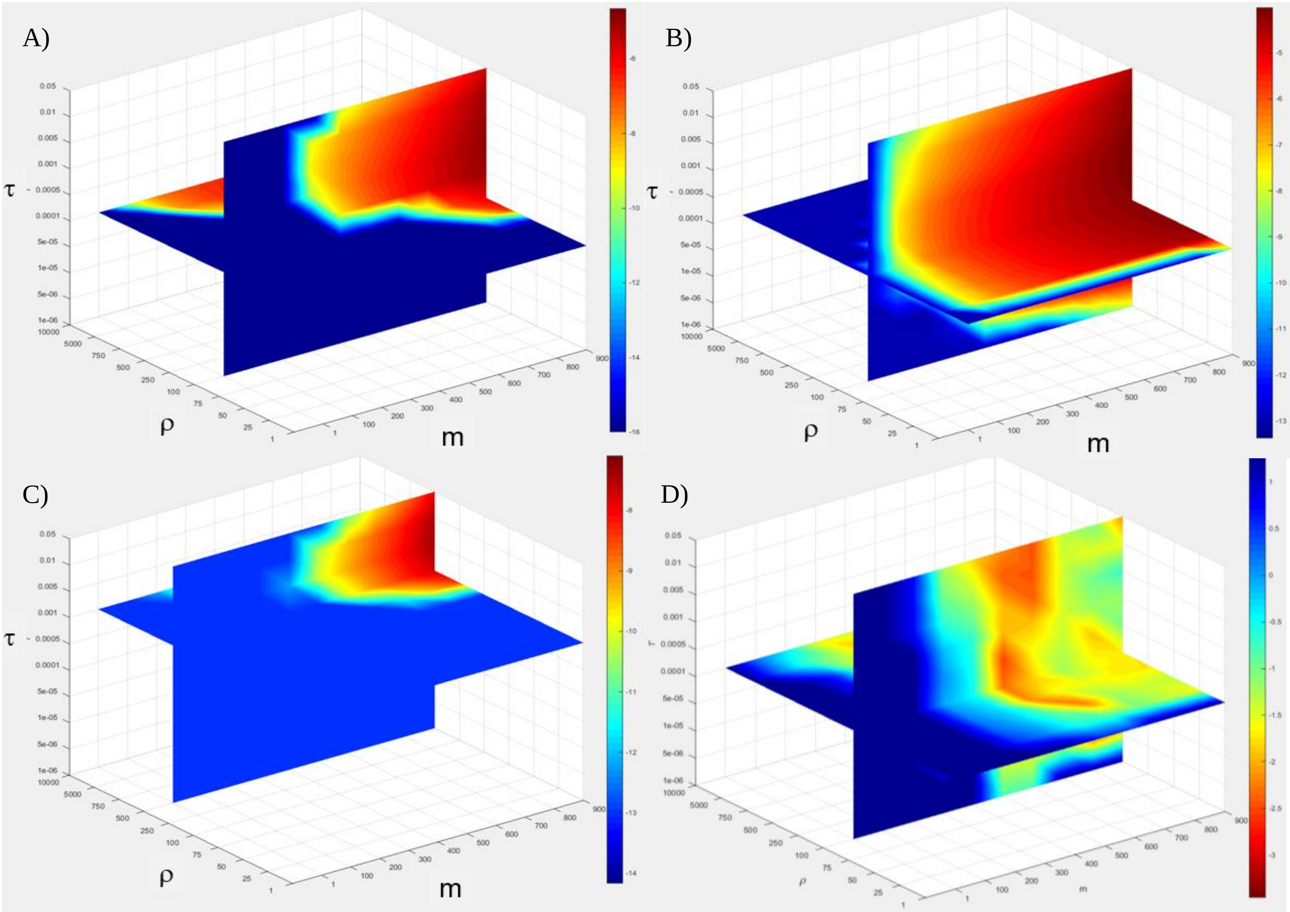

Figure 3: multidimensional plots (A-C) showing the combined effects of Cole-Cole parameters (c kept fixed to 0.5 in these views) on the transients. Areas in warm colours represent strong negative anomalies (Log 10 of sum of negative values). A) homogeneous half space, B) 2 Layer models, with chargeable shallow layer (thk 50m) of varying Cole Cole parameters over resistivity, non polarizable bedrock, C), non chargeable, resistive overburden (100 m), chargeable bedrock. D) sensitivity.(linked to recoverability) on *m* in homogeneous half space (red indicating higher sensitivity domains).

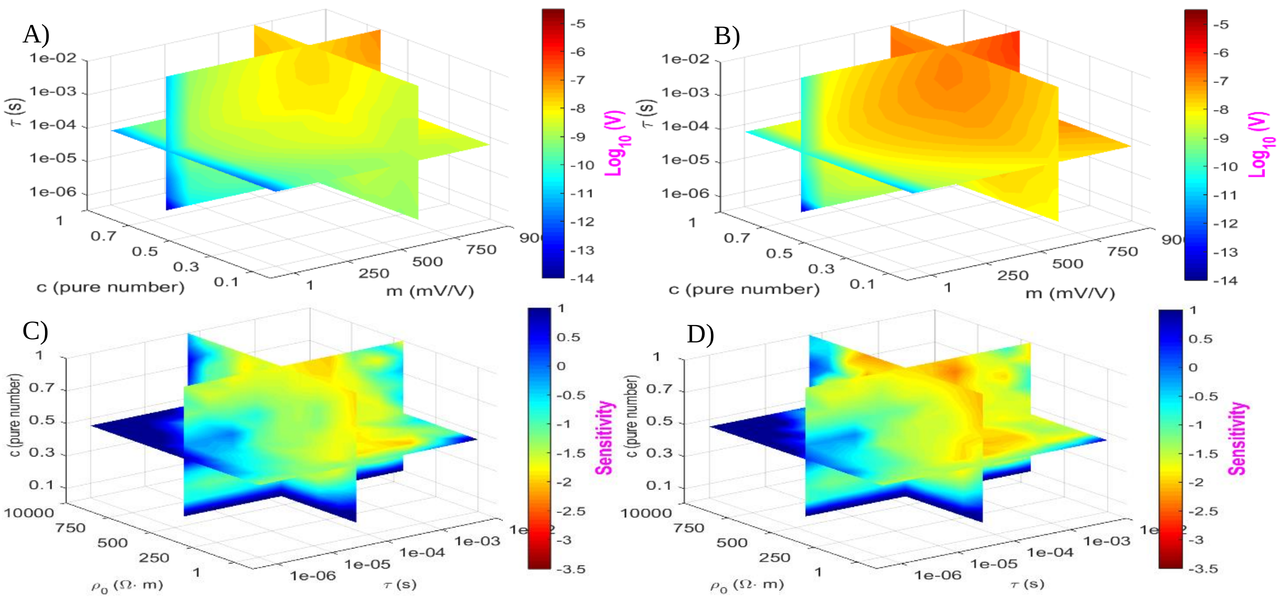

Figure 4: multidimensional plots showing the effect of system response (A= HeliTEM, B=VTEM) on AIP for homogeneous half spaces (ρ= 250 Ωm in these views). Areas in warm colours represent strong negative anomalies (Log 10 of sum of negative values). Effect of gates' widths (C= standard VTEM, D= VTEM with twice as many gates, half width) on sensitivity (linked to recoverability) of parameter m, for homogenous half spaces (m = 400 mV/V in these views). Red indicating higher sensitivity domains.

CONCLUSIONS

Detailed analysis of 10^5 FWD responses (different combinations of Cole Cole parameters and layering-layered earth approach) prove that measurable IP effects in AEM a) are more pervasive than historically acknowledged, b) affect models (both resistivity and chargeability) down to significant depths. At time they can produce rather unpredictable signatures. As a consequence, a) robust assessment of AEM data should routinely be concerned about possible presence of IP effects; this goes beyond presence of negatives, and b) robust inversion of AEM data that could contain even small amounts of IP effects should entail full IP modelling. The results presented herein offer a solid base for better understanding, recognition, processing, inversion and further interpretation of AEM data (both existing and yet to be acquired) affected by IP.

REFERENCES

Cole, K. S. & Cole, R. H. (1941), `Dispersion and absorption in dieletrcis', Journal of Chemical Physics 341(9), 341. 22

Flis, M. F., Newman, G. A. & Hohmann, G. W. (1989), `Induced polarization effects in time-domain electromagnetic measurements', Geophysics 54(4), 514{523. 17, 26, 29, 31

Hine, K. & Macnae, J. (2016), `Comparing induced polarization responses from airborne inductive and galvanic ground systems: Lewis Pond, New South Wales', Geophysics 81(6), B179{B188. 2, 17

Kang, S., Fournier, D., and Oldenburg, D., (2017). ”Inversion of airborne geophysics over the DO-27/DO-18 kimberlites — Part 3: Induced polarization.” Interpretation, 5(3), T327-T340.

Kaminsky, V. & Viezzoli, A. (2017), `Modeling induced polarization effects in helicopter time domain electromagnetic data: Field case studies', Geophysics 82(2), B49-B61. 2, 17, 38

Kirkegaard, C., and E. Auken, 2014, A parallel, scalable and memory efficient inversion code for very large scale airborne EM surveys, Geophysical Prospecting, 63, 495-507

Kratzer, T. & Macnae, J. (2012), `Induced polarization in airborne EM', Geophysics 77(5), E317-E327. 2, 17

Macnae, J. (2016a), `Quantifying Airborne Induced Polarization effects in helicopter time domain electromagnetics', Journal of Applied Geophysics 135, 495-502. 22

Macnae, J. (2016b) Fitting SPM and distributed Cole-Cole parameters to AEM data. SEG Technical Program Expanded Abstracts 2016: pp. 2190-2194.

Raich. A. P.. 1983. Negative transient voltage and magnetic field responses for a half-space with Cole-Cole impedance: Geophysics, 48. 790-791.

Smith, R. S. & Klein, J. (1996), `A special circumstance of airborne induced polarization measurements', Geophysics 61, 6-73. 2, 17

Viezzoli, A., Kaminsky, V. & Fiandaca, G. (2017), `Modeling induced polarization effects in helicopter time domain electromagnetic data: Synthetic case studies', Geophysics 82(2), E31-E50. 2, 17, 29, 38, 75