Thoughts on layered inversions

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SUMMARY

The earth is composed of layers of rock of different lithology, with sharp boundaries between them, so surely it is better to use layered AEM models than smooth models? However, this idealised cartoon model is complicated by the fact that most electrical conductance is through pore water of varying salinity rather than through the rock matrix, and by factors, such as weathering gradients, which will induce gradients in physical properties. This paper discussed experiences with trying to use layered, rather than smooth, inversions of AEM data.

Key words: Airborne electromagnetics, layered-earth model, inversion

INTRODUCTION

Most airborne electromagnetic (AEM) inversions are smooth 1D inversions, stitched into a section under the flight line. Individual decay curves are inverted for a conductivity distribution which is smooth in the depth direction (Farquharson & Oldenburg, 1993; Christensen, Reid, & Halkjær, 2009; Brodie, 2016), sometimes including lateral constraints between adjacent soundings. These conductivity sections are then interpreted, typically by choosing some conductivity threshold to represent a geological or groundwater feature of interest.

However, we know that the earth is not smooth. A glance at a geophysical borehole log will show that there is variation in physical properties at all scales. In particular, there are often sharp boundaries between different lithological units. If different units have differing porosity, then we could expect them to have different electrical conductivity, especially in the sedimentary environments conducive to modelling using 1D codes. The question is, can we use our knowledge that the earth is composed of layers to improve inversion results?

This talk looks at inversion using a layered model, where the layers are intended to represent geological units. An advantage is that the model is parameterised in terms of depths to geological layer boundaries, which are quantities that we are actually interested in, rather than having to draw lines on a coloured section. Another advantage is that, if the earth's conductivity really is layered, then we ought to get a better result.

In order to assess this approach, there are a few questions that need to be addressed:

1. What is the consequence of a model with the wrong number of layers?
2. In most earth materials, the electrical conductivity is through water in the pore spaces, rather than through the rock matrix, which means that water content and salinity strongly affect the electrical conductivity. So, to what extent do conductivity changes parallel geology, rather than possibly cross-cutting groundwater differences?
3. How does the water table affect the conductivity structure? We know that rocks remain conductive when partially saturated, and Archie's law, along with modifications to account for clays, gives us an indication of the relationship between saturation and conductivity. So, there should be a drop-off in conductivity above the water table, but what does it look like?
4. Many geological processes probably result in gradients in physical properties, rather than sharp changes between homogeneous units. Examples are chemical weathering processes in the regolith, and upward-fining or -coarsening sequences in sedimentary rocks, both of which could well result in electrical conductivity gradients. To what extend can these be detected in AEM data? And how useful is some kind of average property?

This talk is an attempt to make a start in addressing some of these questions.

MODELLING AND INVERSION

Forward modelling has been done using the freely-available AMIRA P223 code Airbeo (Raiche et al. 2007), which computes the response of a 1D layered earth. The code is capable of including induced polarisation effects as well as simple induction. For 2- and 3-D situations, an approximate forward model computes the 1D response due to the earth directly beneath each sounding point.

Inversion has been done using bespoke python algorithms, mostly built around the scipy optimization least-squares code. The inversions are 2D or 3D, and include lateral constraints in the form of distance-based prior covariances between model parameters (see, e.g. Tarantola, 1987). Generally, the covariances are between parameters of the same class, such as between thicknesses or conductivities of a given layer, with zero prior covariance between classes. I have (mostly) chosen to model conductivities using an exponential covariance,

$$C_M\left(m_1, m_2\right) = \sigma_1\sigma_2 \exp\left(-\frac{D\left(\mathbf{r}_1, \mathbf{r}_2\right)}{L}\right).$$

Here m_1 and m_2 represent, for example, the conductivity of a given layer at two points, σ_k and $\mathbf{r}_k$ are the conductivity of and location of point k, D(. , .) is a distance, and L is the correlation scale length. Large values of L imply large correlation lengths, which would be appropriate for well-mixed sediments in a channel, for example. I have modelled thicknesses using a

Gaussian functional form (where the argument to the exponential is squared).

DO LAYERED MODELS WORK?

An example that gives some confidence to the idea of modelling AEM using geological layers is shown in `Figure 3`. A very dense grid of boreholes was mapped, and geology characterised as being in one of four categories: alluvium/colluvium, channel sediments, saprolite, and basement. Each of these units was assumed to have a homogeneous conductivity. Water table depth information was also available, and the water table was modelled as splitting whatever layer it passed though into wet (conductive) and dry (resistive) sub-layers. An inversion was done for the layer conductivities, with the layer thicknesses and water table depths fixed at values interpolated from borehole measurements (King and Gonzalez-Alvarez, 2018). Although this is a dramatic over-simplification – we know that the saprolite conductivity will vary internally with degree of weathering, and the water table effect is more complicated than a simple extra boundary, for example – the fit to the data is remarkably good. A second-pass inversion, this time allowing conductivities of the different layers to vary from fid to fid, produced convincing results. `Figure 1` shows an example where a 3D region has been inverted, this time holding the conductivities fixed at the values determined from the line inversion, but allowing thicknesses to vary.

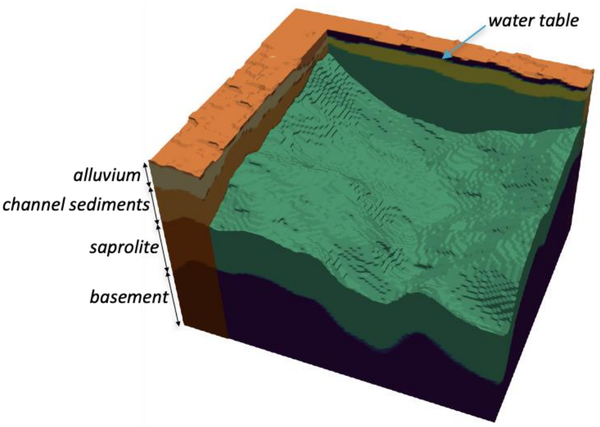

Figure 1. 3D example of homogeneous-layer inversion. Here layer conductivities were held fixed, and thicknesses were allowed to vary.

WHAT CAN WE IMAGE?

Figure 2 compares two inversions of the same decay: a smooth model, and a layered model where the depths have been fixed according to those in a nearby borehole. While the models are very different, the fit to the data is almost identical. This shows how little we can determine using AEM data alone. It makes much more sense to use AEM inversions as a kind of hypothesis test: a hypothesised geological can be parameterised in terms of its unknowns, say, the thicknesses of a fixed number of layers, and an attempt can be made to fit the data. If data cannot be fitted, then the hypothesis should be rejected.

In the context of this talk, this large ambiguity means that, if (and only if) the layers can be characterised as homogeneous, or nearly so, then a meaningful inversion for layer thicknesses can be done, and the layered model is useful. If individual geological layers have conductivities that vary internally as much as they do between layers, then the approach is doomed to failure.

An interesting point to note regarding this example, is that the layered model requires the addition of a water-table effect (splitting the shallowest layer into two) in order to fit the data. The smooth model also shows an increase in resistivity at the surface. This also illustrates that, although the water table might be more complex than a simple split into wet and dry, that simple split might be the best we can image with most AEM systems.

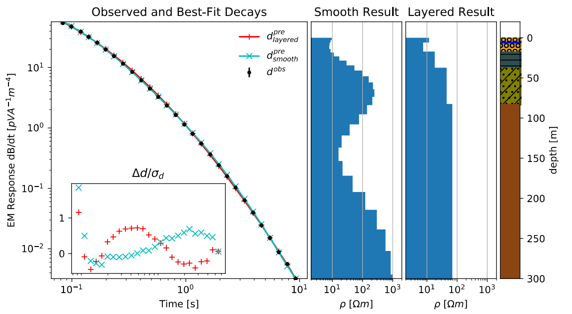

Figure 2. Comparing smooth and layered inversions. The layered-inversion boundary depths were constrained by a nearby borehole. Large model differences can nonetheless have small differences in data fit. (a) Observed and predicted data. The inset shows residuals scaled by data errors. (b) and (c) Smooth and layered model resistivities vs depth. (d) Nearby borehole log used to constrain depths.

CONCLUSIONS

In many cases that I have looked at, modelling the earth as a set of near-homogeneous layers, and including the water table as a "layer splitter", is able to successfully fit AEM data. Where layer depths are known at a single sounding, layer conductivities determined at that sounding can be used to determine thicknesses away from that point. However, the inherent ambiguity of AEM inversion means that this can only be done if the layer conductivities can be constrained to be close to homogeneous.

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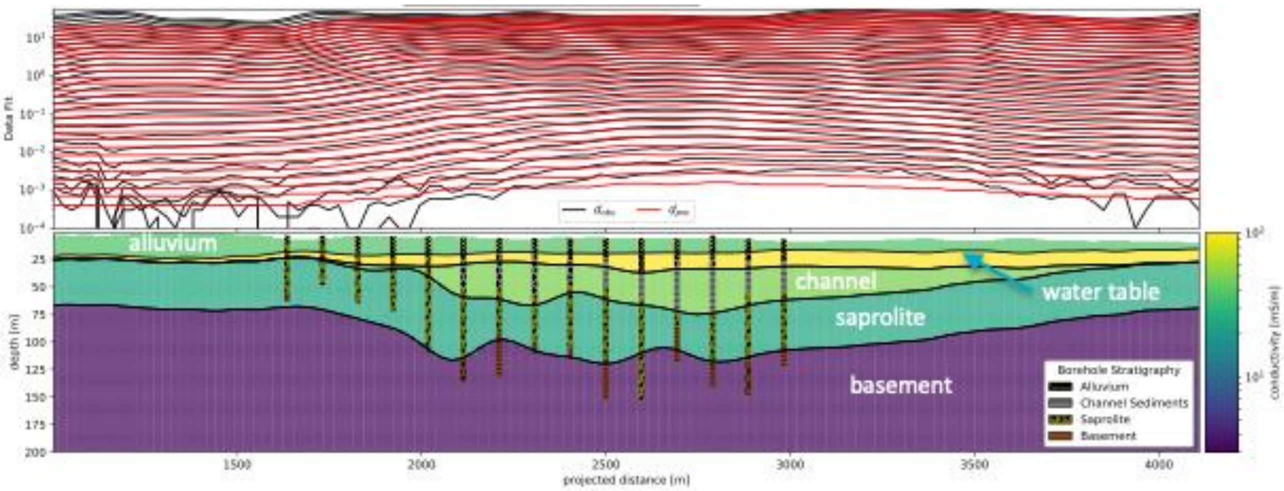

Figure 3. An inversion for homogeneous layer conductivities, where layer thicknesses are fixed at values interpolated between dense borehole measurements. The water table, whose depth is also fixed from borehole measurements, is modelled as splitting a layer into wet (conductive) and dry (resistive) sub-layers. Boreholes are oblique to the flight line. The fit is remarkably good, considering how simple the model is.