Application of time domain induced polarization to the mapping of lithotypes in a landfill site.

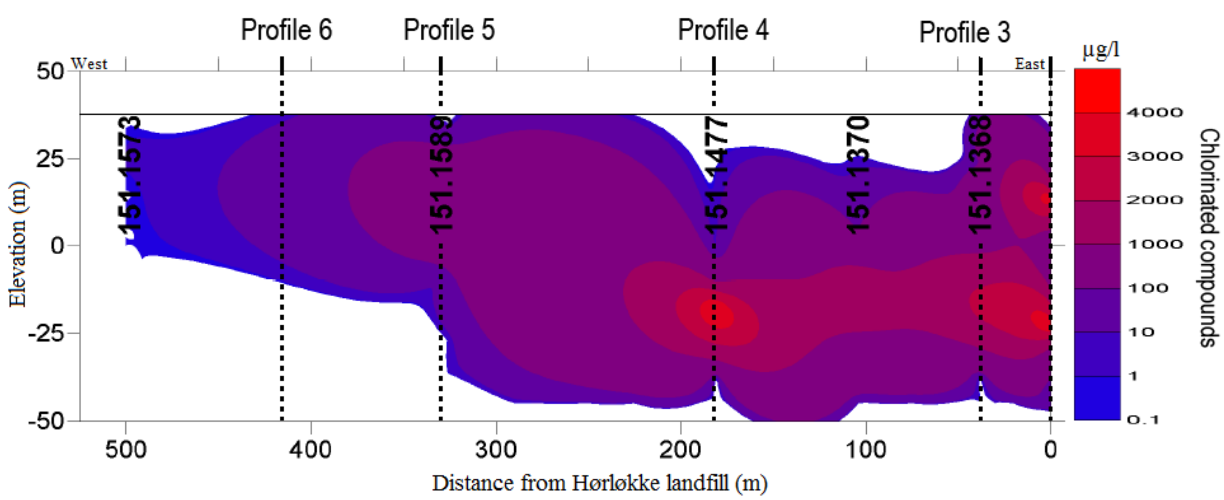
Reply to referees, by Gazoty et al., March 16th, 2012.

We thank the two reviewers for the careful reading of the manuscript, positive feedbacks, and support regarding this study. We have considered all their comments and try to improve the manuscript following their suggestions. In the following, we will answer in detail to all questions and issues raised by each reviewer.

A. Response to the Referee # 1, anonymous.

How was the contamination (page 987) characterized in the landfill itself and in the plume? By fluid sampling in the logged boreholes (page 990) and taking into account the log data?

A.G. et al.: After careful reading, we agree on the fact that more explanations could be brought to the plume description. As inferred from Referee #1, the contamination plume is characterized by water samples thanks to a numerous number of deep boreholes present within and outside the landfill area. These boreholes allowed the collection of water samples up to 60-70 m depth, and by interpolating these results, it was possible to precise the lateral extent of the plume as well as its depth. Thus, a map and a cross-section of the contamination plume could be made on the basis of boreholes where a significant content of chlorinated compounds was encountered (Sønderjyllands Amt, 2007). In order to improve and clarify the manuscript, we propose to add this explanation in page 987, line 13. A figure showing the inferred shape and extent of the plume could also be added in complement, just after Figure 1 (see below).



Cross-section of the contaminated plume. Concentration levels refer to the total sum of chlorinated compounds. Stippled lines show the locations where the profiles cross the plume and the different numbers refer to deep boreholes (Figure 1). Modified from Sønderjyllands Amt (2007).

Are landfills without impermeable layer underneath numerous? Is the one of Vojens representative in terms of geological and water management contexts?

A.G. et al.: From our experience, all the landfills we have investigated so far in Denmark, which were active before the 80's do not have any isolation system underneath. More generally, landfills without impermeable layers as clay or artificial liners (uncontrolled landfills) are very common in Denmark and worldwide. In the western part of Southern Denmark, there are approximately 500 landfills, and most of them are located on permeable sand. In the literature, some similar cases can be found (e.g. Christophersen et al., 2001), and general descriptions provided by Kjeldsen et al. (1998a), Kjeldsen et al. (1998b) and Christensen et al. (1993) report a large number of groundwater contaminations caused by landfills with insufficient leachate collection system or by old dumps with no measures to prevent leachate from entering the groundwater. In 2002, Poulsen et al. explained how significant efforts have been dedicated for the development of improved landfill designs towards membrane isolation systems for protection the landfills surroundings.

In terms of water management context, as drinking water in Denmark is entirely based on groundwater, the Hørløkke case is not unusual – many landfills are located in areas where the groundwater is utilized for water supply (see Christensen et al., 2001).

B. Response to the Referee # 2, Jean-Cristophe Gourry.

No analysis on contaminant concentrations - No discussion on plume localization: in the abstract, introduction, and at fig.11, authors mention a contaminant plume (drawn on fig 11 sketch) but we don't know how this plume was found (what kind of anomaly is created by the plume?).

A.G. et al.: We partially answered this question in Part A, thanks to Referee 1. We agreed to include the explanations above mentioned as well as a figure showing the extent of the plume West from the landfill with the concentration levels of chlorinated compounds. In the manuscript, we specified that the plume yielded to high concentrations of hydrocarbons, iron and inorganic compounds, as well as a small amount of percolating chlorinated compounds, within the landfill (P 987 lines 15-18). Within the plume, the contamination is composed of a high concentration of volatile chlorinated compounds and inorganic parameters (potassium, sodium, calcium, chloride, etc.). Furthermore, the chemical analysis revealed that the chlorinated compounds found from the boreholes are trichloromethane, 1, 1, 1-trichloroethane, trichloroethylene, Cis-1, 2-dichloroethylene and 1,1-dichloroethane.

I suggest to calculate and represent the normalized chargeability (see Lesmes and Frye, 2001) when working in high conductive environment.

A.G. et al.: We agree with the referee that it actually makes sense to compute the normalized chargeability according to Lesmes and Frye (2001) when working in high conductive environment. In our context, however, because the resistivity magnitude is rather high (see

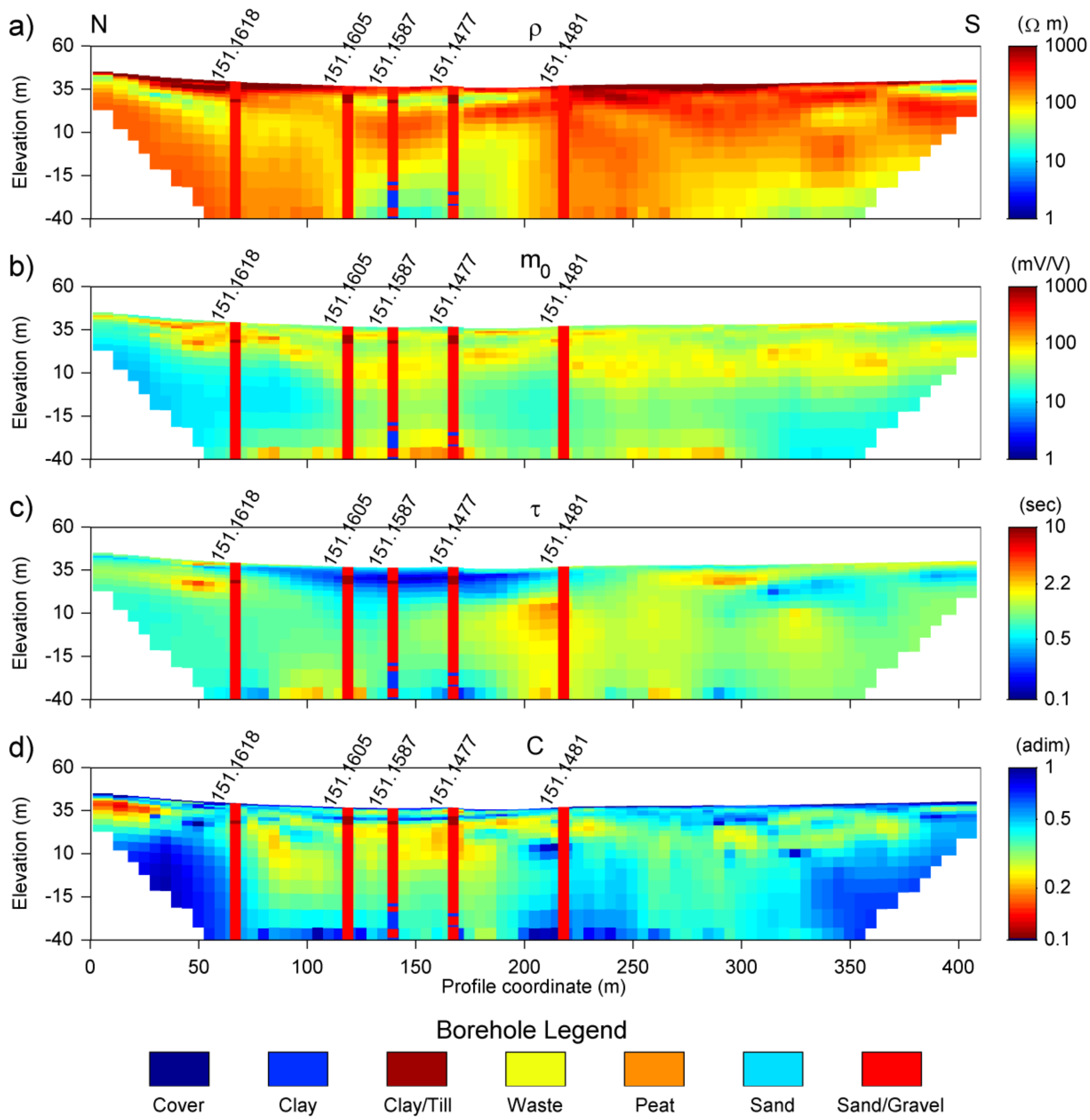
Figure 8 and Figure 9b, where the mean resistivity is around 100 Ω m), it is reasonable to keep the parameter M0 in mV/V. Moreover, it is seen from Figure 9a that M0 and gamma log shows a perfect agreement between each-other, which reinforces our choice of M0 instead of normalized chargeability.

There is an introduction on Cole-Cole model in time domain, multi-windows IP measurements, also a chapter on inversion of DC-IP data (pp989-990). But finally there is just an analysis of M0 chargeability (is it calculated after inversion of chargeability curves?). Give more explanations why tau and c are not relevant.

Nevertheless, I have seen recent communications from the same authors explaining that tau and c improve lithology discrimination, data interpretation (e.g. at the Second International Workshop on Induced Polarization). – If tau and c add no information, maybe the Cole-Cole model is not appropriate. Make a discussion.

A.G. et al.: Actually the M0 parameter is one of the direct output from the inversion, where the four Cole-Cole parameters are retrieved for each layer; these Cole-Cole parameters are the resistivity (Ohm m), the chargeability M0 (mV/V) which is the chargeability taken at time t=0, tau (s), and c (dimensionless). It is true that the manuscript only shows results for the M0 parameter, because it is the only one for which a straightforward correlation with the lithology, the waste content and borehole information can be made. Indeed, M0 tells you how polarizable the medium is, and whether there is a signature in chargeability or not. Parameters tau and c are also relevant and provide significant information at the pore scale, and can be linked somehow with hydrogeological parameters as hydraulic conductivity, but their use involves a further modeling and analysis, which is beyond the scope of this study.

We propose anyway to replace the current Figure 8 by the figure below, where parameters tau and C have been added. From this figure, it seems that high C fits with the clay layer, in agreement with borehole information (borehole numbers 151.1605, 151.1587). The parameter tau shows some general trends, such as a small magnitude within 50-200 m laterally, where the stream is located, and an increase of magnitude with depth beyond 20 m. In the Hørløkke case study, we do not have enough information to link these trends with petrophysical properties, whereas the interpretation of M0 in terms of landfill location and lithological discrimination is straightforward. The observed lateral variations of Tau are probably not related to an unsuitable model, and would most likely appear with another model such as the Davidson-Cole one. The sensitivity analysis shows that the main features are reliable, but can not be more interpreted at this state of knowledge.



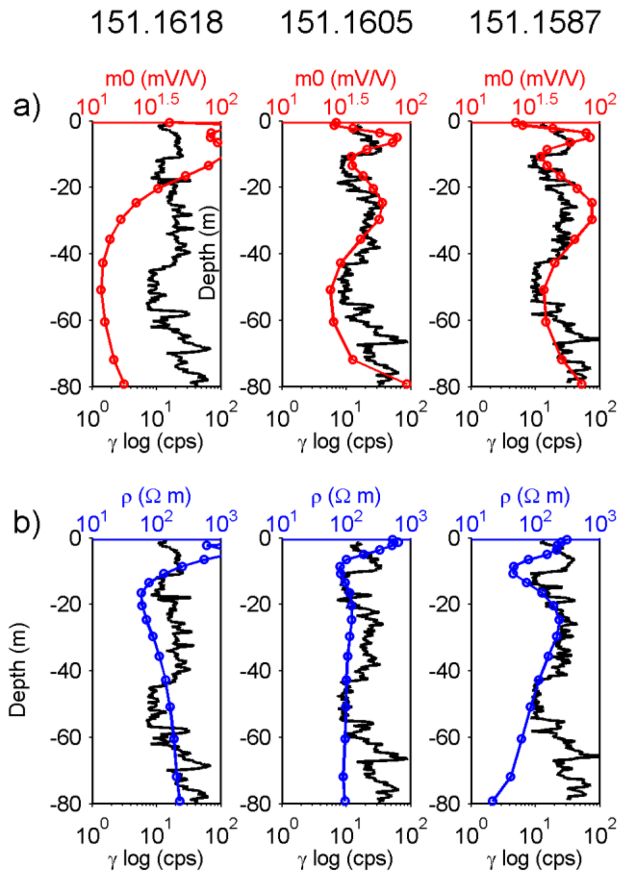
Inverted sections for Profile 4 (see map in Fig. 1) with superimposed boreholes. (a) Resistivity section. (b) Chargeability M0. (c) Tau parameter. (d) C parameter.

You have to reformulate the sentence lines 19-21 where you explain that physical models such as Leroy and Titov models can be compared to empirical models such as Cole-Cole models. Leroy or Titov try to give physical explanations of IP phenomenon's, where Cole-Cole model is useful for classifying IP measurements based on their parameters (tau, M0, c and rho).

<u>A.G. et al.</u>: We agree on the fact that the phrasing is confusing, because all models are implicitly compared and enumerated as if they were of the same nature. We propose to change the phrasing as follow: "Numerous models exist for describing the complex resistivity response of rocks and soils. These models can be classified into two, the microscopic models, e.g. based on the so-called Electrical Double Layer (Leroy et al., 2008), throat models (Titov et al. 2002), or the empirical models, among which the Cole-Cole model (Cole and Cole, 1941), the Davidson-Cole model (Davidson and Cole, 1950) or Constant-Phase-Angle (CPA) model (Van Voorhis et al. 1973). The Cole-Cole model is the most popular for field application, and it is used by Pelton et al. (1978) to describe complex resistivity, etc."

I didn't understand why loggings from 151-1477 well are so noisy. If you have no confidence with this logging, don't show it!

<u>A.G. et al.</u>: As mentioned in the manuscript, we know that borehole 151-1477 was not drilled in the same conditions as other boreholes ("gamma log experiment carried out many years after the drilling, with the casing inside"), this is why we do not have any confidence in it. We agree with the Referee that showing loggings from 151-1477 will add some confusion, this is why we chose to remove it from the study and from Figure 9 (see below) where it initially appeared.



Gamma logs (black) in comparison with 1-D models extracted from surface measurements.
(a) Chargeability *M*0. **(b)** Resistivity.

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