Dear Prof. Revil,

We first want to thank you for your constructive comments on our paper. We read the comments carefully and we have already done most of the revisions. Find our comments and new text below each point.

1- *Maybe remove " environmental purposes and" from the title.*

Thank you for your suggestion. Of course this will make the paper title more specific and concise. Now, it will be:

"*Spectral induced polarization measurements for predicting the hydraulic conductivity in sandy aquifers*"

2- *The abstract is very long. It should be condensed into a single paragraph and reduced by 20%.*

Regarding to your comment, the abstract was modified to be more condense in one paragraph and reduced by more than 20%. Please see the following:

*"**Abstract.** Field and laboratory spectral induced polarization (SIP) measurements are integrated to characterize the hydrogeological conditions at Schillerslage test site in Germany. The phase images are capable of monitoring thin peat layers within the sandy aquifers. However, the field results show limitations of decreasing resolution with depth. In comparison with the field inversion results, the SIP laboratory measurements show a certain shift in SIP response due to different compaction and sorting of the samples. The SIP data are analyzed to derive an empirical relationship for predicting the hydraulic conductivity (K). In particular, two significant but weak correlations between individual real resistivities (ρ') and relaxation times (τ), based on a Debye decomposition (DD) model, with measured K are found for the upper groundwater aquifer. The maximum relaxation time (τ_{max}) and logarithmically weighted average relaxation time (τ_{lw}) show a better relation with K values than the median value τ_{50}, however, the single relationships are weak. A combined power law relation between individual ρ' and τ with K is developed with an expression of $A \cdot (\rho')^B \cdot (\tau_{lw})^C$, where A, B and C are determined using a least-squares fit between the measured and predicted K. The suggested approach with the calculated coefficients of the first aquifer is applied for the second. Results show good correlation with the measured K indicating that the derived relationship is superior to single phase angle models as Börner or Slater models. "*

3- *The in phase resistivity is not a good predictor of anything because petrophysical models show that only the real (in phase) and quadrature (out of phase or quadrature) conductivities have a clear physical meaning (electromigration versus polarization). The real resistivity and the imaginary resistivity are composite of the in phase and quadrature conductivities, so there are a mix of electromigration and polarization processes.*

Based on your comments no.5 (see below), we refereed to that in the introduction. Accordingly, the inphase (real) resistivity is not applicable for predicting the hydraulic conductivity. This also was proved in our results and we attempted to derive the applied empirical relationship.

4- *Introduction: the relation between in phase conductivity and permeability was discussed and numerically investigated by the people of Schlumberger back in the 80s (Sen, Johnson and co-workers). I am surprise to see no reference to their work. See also along the same vein Bernabe and Revil (1995) that was the base for many subsequent works in this area.*

We added further four references at line 12, page 5317:

1- Bernabe, Y. and Revil, A.: Pore-scale heterogeneity, energy dissipation and the transport properties of rocks, Geophys. Res. Lett., 22(12),1529–1532, 1995.

2- Frohlich, R. K., Fisher, J. J., and Summerly, E.: Electric-hydraulic conductivity correlation in fractured crystalline bedrock: Central Landfill, Rhode Island, USA, J. Appl. Geophys., 35, 249–259, 1996.

3- Huntley, D.: Relations between permeability and electrical resistivity in granular aquifers, Ground Water, 24, 466–474, 1986.

4- Sen, P. N., Scala, C., and Cohen, M. H.: A self-similar model for sedimentary rocks with application to the dielectric constant of fused glass beads, Geophysics, 46, 781–795, 1981.

5- Regarding the paragraph page 5318, Revil and co-workers have recently argued that a very general model can be derived and unify all the dataset into a unified relationship. see revil et al. (2012), Revil (2013), Revil et al. (2013a, b). So I disagree with these comments ! Revil also found a unified relationship between the quadrature conductivity and surface conductivity (which follows some ideas developed by Borner). In the same papers, Revil and co-workers found unified relationships for the relationship between the quadrature conductivity, the CEC and the specific surface area.

Regarding to your comment and recent published papers, we have referred to such recent models in our paper. Consequently, we broke and modified the paragraph of page 5318. We added a new paragraph and references. Please see the following (two paragraphs):

"The hydrogeophysical research of the IP method has shown that SIP data can be correlated with physical properties of the pore space in non-metallic soils and rocks, such as the specific surface area (S_{por}) and K. There is a growing interest in the use of spectral induced polarization (SIP) for a wide range of environmental applications, in particular those focused on hydrogeological investigations. A clear link between hydrogeological properties and IP/SIP parameters has been empirically documented by various studies (e.g., Binley et al., 2005; Hördt et al., 2007). Binley et al (2010), Kruschwitz et al. (2010) and Titov et al. (2010) also point out that the detailed nature and origin of such linkages still lies ahead. Börner et al. (1996) Slater and Lesmes (2002) introduced models to estimate K from IP measurements. Both models require a direct link between the imaginary conductivity and K. Thus, the absence of such a relationship indicates that the imaginary conductivity is not related to the effective hydraulic length scale (e.g., Zisser et al., 2010b). Hence, these models seem to be of limited applicability."

"Recently, new models have been developed to describe the complex conductivity of saturated and unsaturated sands and clayey materials in the low frequency domain (Revil and Florsch, 2010; Revil, 2012; Revil et al., 2012a, Revil et al., 2013a). Revil et al. (2013a) presented a comparison between recently derived petrophysical models and a new set of petrophysical measurements including permeability, complex conductivity, and streaming potential data on saprolite core samples. They proved that the quadrature conductivity (i.e. polarization) is not controlled by the diffuse layer (the outer component of the electrical double layer) but more likely by the Stern layer (the inner layer of the electrical double layer). The surface conductivity is dominated by electromigration in the electrical diffuse layer coating the pore water/mineral interface. Revil (2013) indicated that the diffuse layer is not the main contributor to low-frequency polarization of clayey materials and also the Maxwell-Wagner polarization is not the dominating mechanism of polarization at intermediate frequencies. Accordingly, he presented an extremely simple unified model based on the low-frequency polarization of the Stern layer. This model is proposed for all sedimentary rocks, saturated and unsaturated clayey materials. It offers the possibility to predict the conductivity and permittivity (or alternatively the quadrature conductivity) as a function of frequency, clay content, and clay mineralogy. It also used to predict permeability from the critical frequency observed at low frequencies in the quadrature conductivity."

6- Equation 1: Ok for the ref of Vinegar and Waxman but these authors havce datasets that are not showing too much frequency dependence so they don't discuss too much this relationship (they use it mostly to define frequency bounds for the models).

7- Going from Eq. 1 to Eq. 2 is a bit risky as there is no formal proof that the characteristic length scale for polarization is the pore size (see an extensive discussion of this problem in Revil et al., 2012).

We agree and add the following sentences at line 9, page 5320:

"Revil & Florsch (2010) assumed that the Cole-Cole time constant, τ, can be related to the square of the grain diameter d as

$$\tau = \frac{d^2}{8D_i} \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (1)$$

Line 11: where D_i is the diffusion coefficient of species i in the Stern layer, which is temperature dependent and varies ~2 % per degree Kelvin.

Titov et al. (2010) showed the relationships between the modal pore throat diameter (R) in μm and the characteristic mean relaxation time, τ_m in s. A positive logarithmic dependence,
$$R = 16.8 ln\tau_m - 2.15 \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad (2)$$
was derived. Titov et al. (2010) suggested that the polarization of the sandstones is controlled with clay content. They also showed a good correlation between R and permeability k."

According to the above comments, the Eq. 2 will be replaced by the above equation.

8- For the reasons I mentioned above, it is not at all equivalent to use the components of the complex conductivity or the components of the complex resistivity. In the first case the in phase and quadrature conductivity have clear physical meaning, this is not the case in the second case. I think therefore that the approach used in the present paper is partly wrong. It would be much clearer to follow what other researchers have done so far: using the in phase and quadrature conductivities instead of the in –phase and quadrature resistivities (the latest are NOT the inverse of the formest, only the complex resistivity is the inverse of the complex conductivity).

According your comment, Eq. 5 will be rewritten to its correct format, where the relationship between K- σ' will depend on the physical and chemical properties of the mineral and pore fluids at the site and it will indicate whether σ_{el} or σ_{int} dominates measured σ'. On the other hand, the DC resistivity ($\sim\rho'$) was used to predict the hydraulic conductivity using a power law relation (e.g. Heigold e al 1997; Attwa et al., 2009; Attwa 2012).
$$K=a(\sigma')^b \qquad\qquad\qquad\qquad K=a(\rho')^b$$

In our measurements, we measured the complex resistivity. We observed that the inphase resistivity ($\sim|\rho|$) shows a positive linear log relation with K. Theoretically and regarding to the DC empirical relationships for unconsolidated sediments (e.g. Niwas and Singhal 1995; Yang et al., 1997; Attwa 2012), this reflects that the ρ_{el} dominates ρ'. Because K depends on different factors (e.g., porosity, pore space geometry), the dependence on such empirical relation only was not effective in our study.

9- Equation 6: the permeability model for a CPA is also described in Revil (2012) but the resulting equation is distinct than Eq. 6.
10- Equation 7 is correct only if there is a relationship between surface and quadrature conductivity. This subject has been discussed a lot in Revil (2012, 2013) who came with a relationship between these two parameters. It is unclear however if this relationship is universal or not.

Because we will use the Boerner model, which depend on Eq. 6, we prefer to show this equation which will be used below.

The equation 7 is not universal, but both Eqs. 6 and 7 were applied for wide hydrogeological investigations (e.g. Boerner et al (1996); Zisser (2005); Hoerdt et al (2006) and Hoerdt et al (2009).

11- Equation 10: A new unified model can be found in Revil et al. (2012), Revil (2013) and Revil et al. (2013a, b) that seems to work for all sedimentary rocks and that bypass the need for calibration or flush factors. Equation 11: it seems that a similar equation was discussed by Tong and co-workers.

Regarding to the comment no. 5, we referred to the unified model in the introduction.
Yes, Tong and Tao (2008) presented a multivariate relation using the complex resistivity to predict the k, but they used the porosity and the slope of the bilogarithmic plot of imaginary part versus frequency.

12- Much more data should be shown on the 33 core samples including tables of their properties, Cole Cole parameters, etc. and more figure of the data (especially in phase and quadrature conductivities, resistivity magnitude and phase are useless in terms of physical meanings as they mix electromigration and polarization processes).

Regarding to your comment, we concerned with the inphase- and quadrature components. We added new figures showing the physical properties of the collected samples and we will refer to that in the paper text under section 4.2 (page 14).
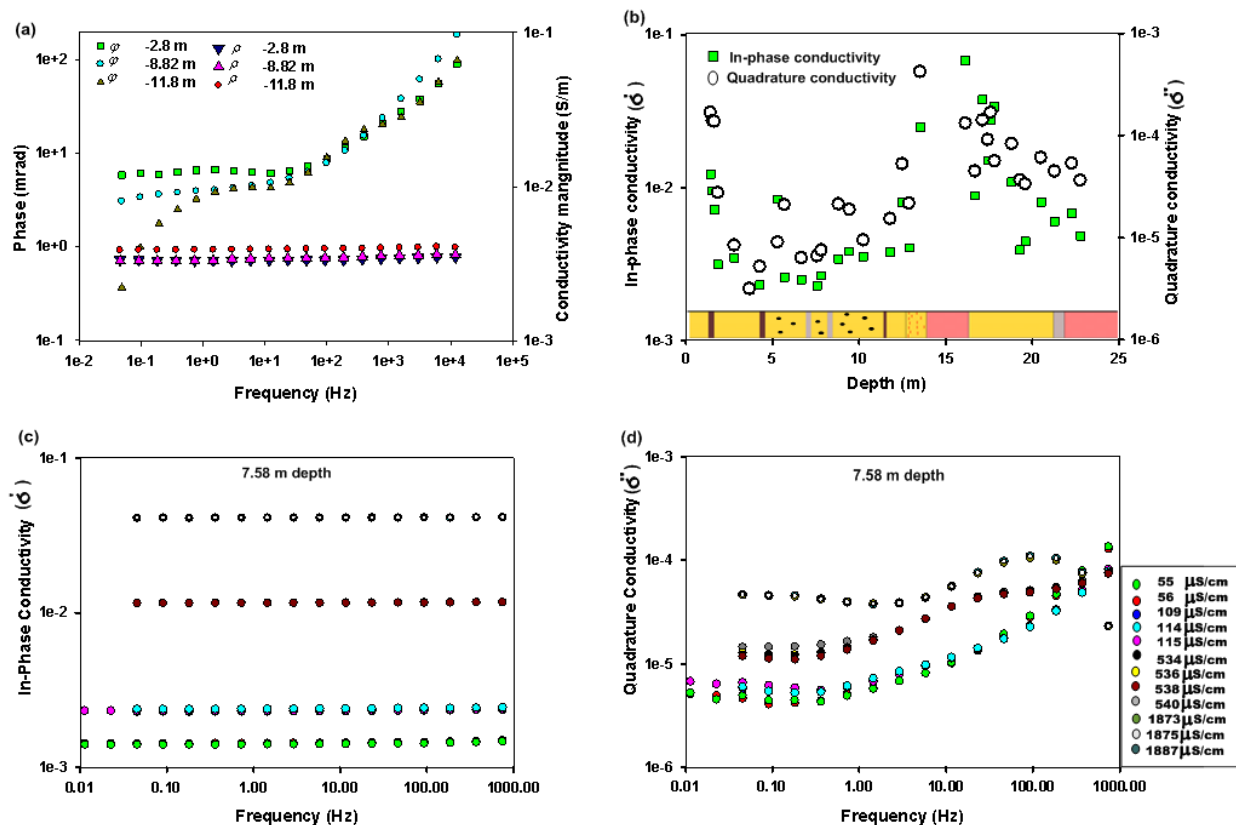

Fig. 6. (a) Exemplary of SIP response at three samples at different depths (2.8 m, 8.82 m and 11.8 m) and (b) in-phase and quadrature conductivities (at 1.5 Hz) at different depths. (c and d, respectively) In-phase and quadrature conductivities at different water salinities of the collected sample at 7.58 m depth.


13 What is missing is a good inversion of the formation factor from the lab data (which requires doing the conductivity measurements at least at two salinities to correct for surface conductivity) and also an investigation between the surface and quadrature conductivities.
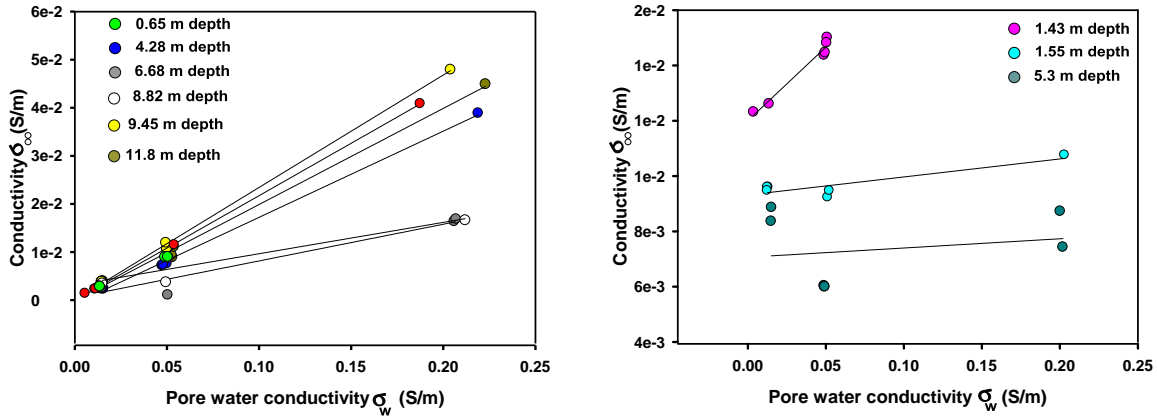
Regarding to your comment, the electrical conductivity data of some selected samples are shown in the above figure (left). It is clear that the formation factor of the samples ranges from 5-15, using $\sigma_\infty = 1/F_B(\sigma_w + \sigma_s^\infty)$. For peat layers, where the clay and silt sediments are dominant, the fitting between σ_w and the high frequency conductivity σ_∞ is different than other samples (figure, right).

The relation between the surface conductivity and the quadrature conductivity are shown the figure attached below.

These results encourage us to apply your recent models (2013) in our next research. In our paper, we concentrated in other approaches and consequently the use of the formation factor is out of our study now. We will consider that in the next research.
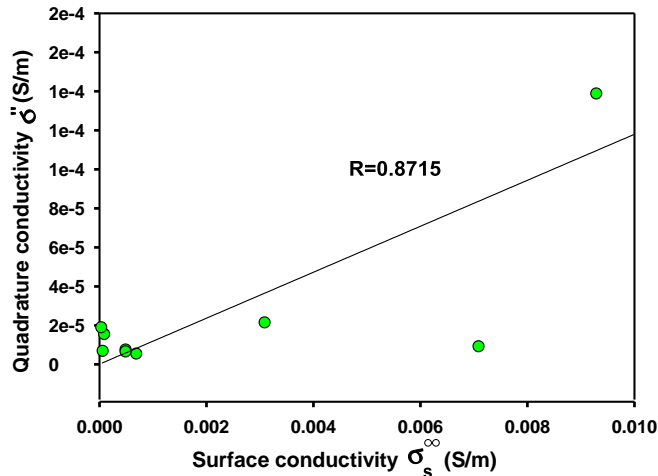
14- Page 5331, again much more discussion on the literature discussing the relationship between the characteristic relaxation time and the pore size should be given, see for example the discussion in Revil et al. (2012, 2013a, b) and Revil (2013). As the permeability depends on the formation factor, this parameter should be carefully evaluated too. The approach is a bit half-baked.

Yes, regarding to your last literatures and discussions, further details and discussions would be necessary for our paper. Accordingly, we will add more discussion about the relation between relaxation time and pore size. Please see the following paragraph which will be added in the paper text (page 5331):

"In general, the relaxation time τ is the time required to establish a stationary ionic distribution in the Stern layer coating a grain of diameter d under the action of a static electrical field (Revil and Florsch, 2010). The relation between the relaxation time with the square of the grain size is represented in Eq. 1, which was confirmed by by Titov

et al. (2002) and Leroy et al. (2008). Revil and Florsch, (2010) presented a model indicating that the permeability depends linearly on relaxation time. Revil (2012) developed a new robust model named POLARIS describing the complex conductivity of shaly poorly sorted sand. He showed that the permeability can be predicted inside 1 order of magnitude using the formation factor F and the quadrature conductivity. Revil et al. (2013b) have developed a simple polarization model accounting for the dependence of the in-phase and quadrature conductivities on the porosity, cation exchange capacity (or specific surface area of the material), and salinity of the pore water for simple supporting electrolytes like NaCl in isothermal conditions. They showed a linear relationship between the main relaxation time and the pore throat size for clan sand and clayey sand sample. Revil (2013) predicted the permeability for various clean sands and clayey sands and sandstones using a low-frequency relaxation time τ and the formation factor F. Accordingly, these studies indicate that there is a linear relation between the relaxation time and the pore size characteristics and the permeability of the materials."

15- Discussion: is the IP effect of roots the same of the root alive or dead. In a recent paper, Revil and Co-workers models the effect of biological cells upon IP (Revil, A., E. Atekwana, C. Zhang, A. Jardani, and S. Smith, A new model for the spectral induced polarization signature of bacterial growth in porous media, Water Resour. Res., 48, W09545, doi:10.1029/2012WR011965, 2012). They found that dead cells do not produce high IP effects.

First, we observed high IP response for the peat layer in the field data. On the contrast, we observed a low IP response in the lab data. This can be attributed to the geological environment of the peat layer, where the silt, sandy clay are dominants. We observed this high response of this lays all over the area using field IP data (Attwa and Guenther, 2012). Second, Zenitti et al (2010) attributed the high IP response of the peat layer to many factors: tree species, root orientation and the nature of earth fill material. Accordingly, the high IP response is expected. In addition, we will consider these factors in our next research. Regarding to your comment, we will also refer to your results and model in the discussion section (6), page 5333.

"Revil et al (2012b), developed a quantitative model to investigate the frequency domain induced polarization response of suspensions of bacteria and bacteria growth in porous media. They showed that the induced polarization of bacteria (α polarization) is related to the properties of the electrical double layer of the bacteria. The high IP effect can be attributed to the surface of the bacteria, which is highly charged due to the presence of various structures (fibrillar surface protein, capsular polysaccharide, lipopolysaccharide) extending away from the membrane into the pore water solution. Consequently, the dead cells (i.e. organic material) will show low IP effects."

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16) Regarding the correlation between Spor and the quadrature conductivity: the authors missed a part of the recent literature in which a universal function was found between the specific surface area or the CEC and the quadrature conductivity (Revil, 2013, Revil et al., 2013a, b).

Because we submitted this paper before publishing your paper, we applied the universe approach after Weller et al., 2010, which showed the relation between the specific surface area and quadrature conductivity. This universe relation can be applied for all unconsolidated sandy samples (clean sand and clayey sand). We will consider the recent approach (Revil, 2013, Revil et al., 2013a, b) in our next research, especially in your approach the coefficient values depend on the nature of sand material (i.e., clean sand and sandstone or clayey sand). In addition, we will refer to such universe function at the end of conclusion (outlook).

17- For the reasons exposed above I disagree with the statement " Our laboratory measurements indicate that for inhomogeneous sandy aquifers the direct relation between K and tau is not applicable" Recently developed models (assumed to be universal by their authors) are not tested so I don't think this statement is valid or at least it is not demonstrated to be invalid. As a big part of the recent literature is missing here, I consider the conclusions as not correct. I think the authors should pay attention to these models rather than ignore them, and they should tests them. They should allow others to see their dataset and if psosible testing these relationships.

We agree. After referring to your recent models in 2013 of using formation factor and relaxation time, it is not correct to write this general statement. Accordingly, we will rewrite this sentence to be more deterministic to our results and

the approaches we used: *"Our laboratory measurements of inhomogeneous sandy aquifers show a weak relationship between the measured hydraulic conductivity and the maximum, median and weighted average relaxation time. Independently of soil….."* Line 28 (page 5334)


18- There are many places where English needs to be correct. e.g., the last sentence of the abstract " A further, an application of this approach on 2-D SIP data is recommended." is not clear to me.

The authors have their paper read and corrected the grammatical errors.
Ex. The last sentence of the conclusion will be:
"The present approach offers the possibility to use the field data to monitor hydrogeological parameters using the SIP components. Further work including lab measurements is required to study the spectral behavior of the peat layer. In addition, application of recent universe models (e.g. Revil, 2013) for calculating the specific surface area and the permeability using the formation factors are desirable in comparison with the approaches we used in this paper. Taking these points into account can improve the accuracy of predicting the hydraulic conductivity measurements."

19-The map of Germany in the insert should be simplified and should be readable. This is presently not the case.
We insert a new map and improve readability.
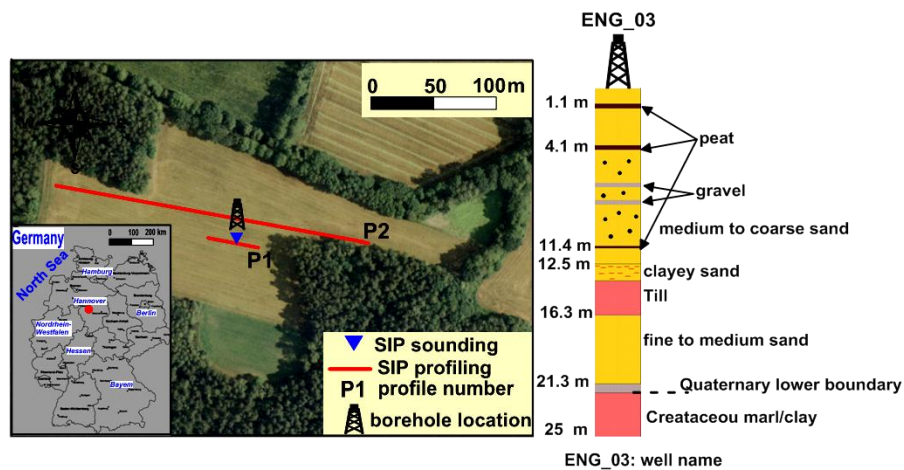
20- Figure 2: It should to show the resistivity and phase but the parameters that have a physical meaning are the in phase and quadrature conductivities. Figure 3: put a title to the figure before starting in the caption with "a)". Figure 4: please label the z axis properly.

For the all field data (1D and 2D) we prefer to show the inversion results of the phase shift and magnitude, especially we will compare the inversion results of both 1D and 2D inversion results in Fig. 7 in comparison with the borehole to show the limitations of both inversion results. For Fig. 4 , we have already labeled *Z* axis.
We added a title to both Fig. 3 and Fig.4 before starting the caption: *"The 2D IP inversion results of P1 profile (for location see Fig. 1. (a) The complex resistivity magnitude………………"*

21- Figure 5: did you saturated the core samples under vacuum?

No.


22- Figure 6: I would like to see much more data condensed in few figures together and showing the in phase and quadrature conductivities. At this point the manuscript requires to display much more data including some tables.

We did (please see Fig. 7, attached above).

23- What is the reproducibility of the data?

Technically, the data are very accurate. But it is hard to say what happens over time electrochemically.

24- Figure 7: hard to read!
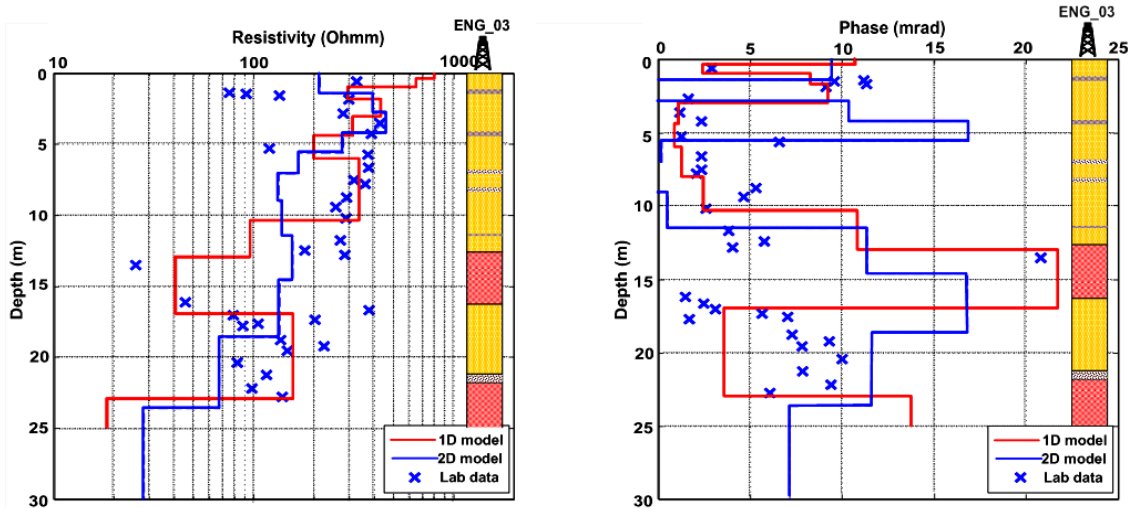
25- Again plotting K versus the in phase resistivity or quadrature resistivity is meaningless as these parameters are composite of electromigration and polarization processes. I regret that the authors did not try a more in depth analysis of their lab data with existing models.

We modified fig.8. The imaginary conductivities, which will be used to apply the single phase angle mode (Slater model) were plotted versus K. Because our relation depends on the real resistivity values and the relaxation time, we prefer to show that there is a weak relation between the DC resistivity and the K values, which reflects that the dependence on DC empirical relation only was not effective in our study.
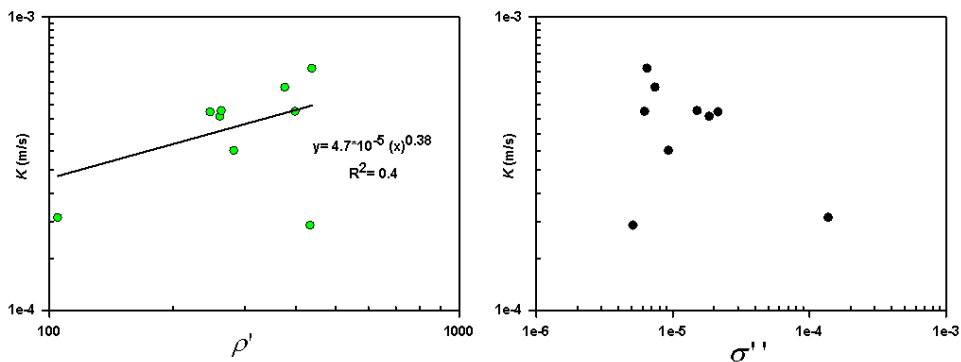
26- Figure 11: It would be good, if possible, to put some error bars.

Stacking errors of the measurement are not reasonable in the sense of how well the data should be explained by a model.

27- Figure 12 is the kind of useless plot if you consider recent developments in IP: the relationship between K and Tau involves also the formation factor (Revil et al, 2013) and therefore for samples of different porosities, it is obvious that K would not correlate with Tau alone. It obvious that you have spent quite a time doing the lab work and working on the field data interpretation. It is a bit sad that there is only a small effort that has been devoted to the data analysis regarding existing petrophysics.

Thanks for sending me your recent papers. Of course we will **consider your recent models in our next paper.** Actually, we submitted our paper before publishing your recent papers and, accordingly, we also regret that we can't apply your interesting universe model. In our paper we focused on the other approaches which show the direct relationship between tau and K (e.g. Zisser et al., 2010; Weller et al., 2011). We tried to combine the real resistivity and the tau to improve these relations, which was achieved under the area investigated. Of course your recent approaches will improve the prediction of K and confirm our results, that the tau alone is not effective.

We hope that we have explained all comments and the paper now becomes clearer. Again, we are greatly indebted to you for these comments and revisions.
M. Attwa and T. Guenther, 05/2013

New references:

1- Bernabe, Y. and Revil, A.: Pore-scale heterogeneity, energy dissipation and the transport properties of rocks, Geophys. Res. Lett., 22(12),1529–1532, 1995.

2- Frohlich, R. K., Fisher, J. J., and Summerly, E.: Electric-hydraulic conductivity correlation in fractured crystalline bedrock: Central Landfill, Rhode Island, USA, J. Appl. Geophys., 35, 249–259, 1996.

3- Huntley, D.: Relations between permeability and electrical resistivity in granular aquifers, Ground Water, 24, 466–474, 1986.

4- Sen, P. N., Scala, C., and Cohen, M. H.: A self-similar model for sedimentary rocks with application to the dielectric constant of fused glass beads, Geophysics, 46, 781–795, 1981.

5- Revil, A.: Spectral induced polarization of shaly sands: Influence of the electrical double layer, Water Resour. Res., 48, W02517, doi:10.1029/2011WR011260, 2012.

6- Revil, A.: Effective conductivity and permittivity of unsaturated porous materials in the frequency range 1 mHz–1GHz, Water Resour. Res., 49, doi:10.1029/2012WR012700, 2013.

7- Revil, A., Atekwana, E., Zhang, C., Jardani, A., and Smith, S.: A new model for the spectral induced polarization signature of bacterial growth in porous media, Water Resour. Res., 48, W09545, doi:10.1029/2012WR011965, 2012.

8- Revil, A., Eppehimer J. D., Skold, M., Karaoulis, M., Godinez L., and M. Prasad: Low-frequency complex conductivity of sandy and clayey materials, J. of Colloid and Interface Science, 398, 193-209, 2013b.

9- Revil, A., Koch, K., and Holliger, K.: Is it the grain size or the characteristic pore size that controls the induced polarization relaxation time of clean sands and sandstones?, Water Resour. Res., 48, W05602, doi:10.1029/2011WR011561, 2012a.

10- Revil, A., Skold, M., Hubbard, S. S., Wu, Y., Watson, D. B., and Karaoulis, M.: Petrophysical properties of saprolite from the Oak Ridge Integrated Field Research Challenge site, Tennessee, Geophysics, 78(1), D21-D40, doi: 10.1190/geo2012-0176.1, 2013a.