Hydrology and Earth System Sciences Discussions

Interactive comment on "Hydraulic properties at the North Sea island Borkum derived from joint inversion of magnetic resonance and electrical resistivity soundings" *by* T. Günther and M. Müller-Petke

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We like to thank the reviewer for the very profound comments that helped to improve the manuscript significantly.

General comment:

From my point of view the paper seems to be addressed to specialists is the mathematical apparatus concerning the geophysical data inversion, providing too many details

irrelevant for other kind of readers (Nevertheless, these details may be insufficient for the ones willing to take advantage of the new inversion approach proposed by the authors, as is becoming usual in our nowadays scientific publications system). In contrast it is a little short in providing the necessary information about some geophysical aspects, with the result that this interesting experiment may result in poor help for other people working in the hydrogeophysical methods.

The paper is intended to address hydrologists (the readers of HESS) taking advantage of the newly developed geophysical technique for characterizing aquifer structures. Therefore we tried to shorten the mathematics of the geophysical problem to the essentials and to give further references for reading. The geophysical contribution is a combination of different parts (block joint inversion, QT inversion) that have already been published. Possible applicants of the method would need an MRS expert to do the analysis anyway.

Specific comments:

Page 3, line 28-29: For calculation of surface NMR responses a resistivity model is needed that determines the magnetic fields in the subsurface. This paragraph is confusing. I think rocks resistivity has nothing to see with rocks magnetic susceptibility. The resistivity matrix or filter for MRS inversion is needed to calculate the electromagnetic field (either the excitation one or the one due to precession of magnetic moments of hydrogen protons), not the magnetic field, which can be understood as a natural magnetic field.

To be precise, we speak about the excitation field, which is (assuming negligible susceptibility) depending on resistivity. We will reformulate the text to avoid this confusion.

Page 4, line 4-5: "However, the instruments do often not deliver reliable phases". May be a short explanation of this sentence is needed; otherwise it is useless. One of the parameters provided by MRS measurements is the change of phase between the excitation electrical current and the one induced by the water signal, which depends on

the layers resistivity and then could be used to acquire the geoelectrical model of the underground.

Yes, further details would be necessary, but would definitely go beyond the scope and technical level of the paper. Therefore we will skip this sentence. Anyway, for the reviewers: Measured MRS-phases would be a single topic to be discussed in a paper. However there are only few paper using the phase information and all of which are published by Braun or Braun and Yaramanci (2008, 2009, 2010). They show that in principle phase information can be used for obtaining resistivity. All other publications do not use the MRS phase for inversion, however the measured complex signal is used for estimating the initial values, but for water content inversion only amplitudes are used, i.e. the sounding curve. Thus it is common procedure to use only amplitudes, e.g. none of the "standard software" available either delivered by Iris instruments or Vista Clara uses complex inversion. We just wanted to make clear why most people do not use phases.

Page 4, line 16: "There are a few papers dealing with retrieving hydraulic conductivity K from free induction decay (T2*) measurements in the field scale." Almost all the published papers dealing with this questions make also (or principally) use of longitudinal time T1*.

We agree, most papers indeed deal with T1 since it is more independent, e.g. on susceptibility variation. However two recent papers by Walbrecker et al. (2011a:off-resonance effects, 2011b: estimating T1) showed that commonly used schemes are not reliable in many cases both due to off-resonance excitation (which is often the case) and because measurement scheme and inversion routines are incomplete. Consequently we did not use T1 measurements and still tried to keep in mind that T2* is less reliable compared to T1 concerning hydraulic conductivities. Nevertheless T1 measurement and inversion can be the solution to T2* problems once appropriate schemes have proved to work. We will add a short comment on this to explain the problem to the reader.

Page 9: as deduced from Figure 1 you have used a reference coil (presumably connected by means of a diode box to the Tx-Rx coil) at a certain distance. It should be interesting providing some details about this question.

With the latest generation of MRS instrumentation providing multiple channels it is possible to directly connect several receiver channels and simultaneously record signals. Thus diode boxes are no longer used, instead transfer functions are calculated and a software-based noise cancellation is applied. This is state-of-the-art and described (e.g. by Walsh, 2008) according to the used GMR instrument. Unfortunately neither the paper nor the GMR software provides the theoretical basics of how this is done but principal schemes of how it is applied in the field. However we give further reading on the theory in a new reference of Müller-Petke (2011) that provides all the math details. Repeating this here is not of primary interest.

Page 11, line 1-2: "For joint inversion we chose a 5-layer model to account for the dry sand, the two aquifers, the aquitard and the conductive clay/salt-water zone where we do not expect an NMR signal." May be you should explain why you do not expect a signal from this layer.

We will add a short sentence on fast decaying signals arising from material such as clay which decays too fast to be detected by the actual MRS instrumentation.

Page 11-12: The determination of longitudinal and transversal relaxation times of the NMR signal is a corner stone of the MRS methodology, and the communication of all the experiences acquired is welcome by the MRS community. So it is important to know if all your comments about the influence of magnetic impurities on relaxation time are supported by magnetic susceptibility measurements of these rocks, or they are just speculative (and may lead to confusion). On page 11 line 24 you say: "From borehole logs we observed an increased susceptibility in the second aquifer. . . .. . .but cannot be proved without samples." What kind of logs are you talking about? You mean that you do not have measured susceptibility on rock samples?. Can your provide with

susceptibility values?. Why you did not measured T1*.

Generally, T2* is influenced by magnetic susceptibility changes as shown by, e.g., Keating (2008). Since we could not yet measure T1 (see comments above) we have to deal with changes in T2* not only due to pore size changes but also due to magnetic gradients. We want to draw the attention of the readers to this point when using T2*. A borehole susceptibility log shows an increase, but the absolute values (i.e. the calibration of the tool) could not be used. We do not have samples measured in the lab. Consequently you are right that is slightly speculative but we think it is important for the reader to know about this problem. However since we do not want to present an uncalibrated susceptibilty log and confuse readers about speculative measurements we will delete the sentence about the log. We will discuss T2* decay times more generally to make clear what can influence decay time, and tell the reader in the context of Borkum what we think is plausible here.

Page 15, line 7: you refer to a large amount of stacks in your MRS measurements. On table 2, for SKD sounding you have used 32 stacks. This is really a very low number of stacks in the general MRS world wide experience. It would be very interesting if you add some figures showing some field results: e(t), E0(q), noise (q), phase (q), etc.

This sentence stacks refers to the old generation of instruments. Using noise cancellation by reference loops significantly decreases the needed stack numbers, sometimes only 16 stacks are carried out and SDK is of very low noise. We do not use sounding curves for inversion but the complete data set of FID signals over time and pulse moments. This scheme is described in detail and compared to others in Müller-Petke and Yaramanci (2010). The sounding curve is the first column in Figs. 3 to 6 (d). Therefore we do not see do add redundant (E0) or not used (phase) information. However we will add some more text on noise levels and how it affects the results.

Technical corrections:

We will consider all suggestions for technical corrections.

Page 5, line 6: write u= Kw instead of u=K f

OK

Page 5, line 12: I suggest changing "(calculation of B fields and.." for (calculation of magnetic field intensity B and.

text refinement (see above)

Page 9, line 1: "MRS soundings" is a redundancy. Say MRS or MR soundings instead.

OK

Page 9, line 7. mind sounding PO5 is not labelled at Figure 1.

YES, and the others as well (in the online version). We will redraw all Figures to improve readability.

Page 9, line 12: "Magnetic field was about 49.3 μT.." Geomagnetic field was about 49300 nT. (I suggest using nT, more usual within the geophysical world).

OK

Page 9, line 17: .."with small instrument dead times". Please, quantify "small".

With instrument dead times below 40 ms.

Page 9, line 19: pulse moment is usually expressed in A ms. I think it is better to be consistent in the use of units. If you are talking about a pulse length of 40 ms (and not of 0.040 s), why not to say 7000 Ams?

In older publications Ams was indeed used. We prefer As, since it is direct SI, and 7 As reads better than 7000 A ms. Units are part of physical properties and can thus be multiplied.

Page 10, line 1: please, quantify "a very good noise level".

It was already stated in the manuscript: Overall a very good noise level was observed,

decreasing from about 40 nV (CL2) over 20 nV (OD33/P05) down to 5 nV (SKD).

Page 10, line 16: say "resistivity inversion models.." instead of "resistivity inversion.."

OK

Page 10, line 19: I do not understand what you mean by surrounding in the sentence "It is followed by a silt-sand-clay layer surrounding the Holoceene base".

OK

Page 10, line 21: ". . .sand and clay at about 50 m." of depth?

OK, inserted "depth"

Page 12, line 21 About the title "3.3 Soundings OD33: hydraulic calibration". You say nothing about calibration in this paragraph.

added "for calibration purposes (see section 4.1)", deleted s in Soundings

Page 15, line 14: "However, the latter. . ." The latter what? Please, modify this sentence.

We will reformulate the sentence.

Page 17, line 1-3: maybe there is something wrong in the figures. Transmissivity should be 9.86x10-4 m2/s, and calibration factor becomes 1.01x10-6 (for porosity in

The calibration factor Cs (not Ck) from eq. (6) includes units and Phi and K go in with units (1 and s). The reference Mohnke Yaramanci (2008) will be added.

Page 18, line 25 number of unknowns

OK

Page 19, line 1: "(iii) Noise Cancellation techniques improved the data quality of MRS significantly." Please, provide some information about the noise cancellation techniques you have used.

We add a reference on noice cancellation (see above).

Page 19, line 2: "The data presented have very good S/N ratio". Please, give some figures of S/N.

S/N is difficult to specify globally, but it can be easily be calculated using E(q,t)/dE. Since the error is considered constant and used for the weighting an absolute number makes more sense.

For decay time you should use ms for consistency with other figures and Table 3

OK

Figure 1: - Indicate units and system of coordinates - VES, borehole and HEM marks are not visible - MRS PO5 is not labelled.
Figure 2: depth number in the lithological column are not visible
Figure 3, 4, 5 and 6: - add units for porosity (

We redraw all Figures, remove the mentioned errors and improve readability.

Table 1: add units to water content [

We will use

Table 2: could you add a column with the Signal/Noise, and other one with the maximum E0 values?

We add a column with noise level and maximum E0 (for S/N see above).

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