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"Hydrogeological characterisation of a glacially affected barrier island – the North Frisian Island of Föhr" by T. Burschil et al.

Author Comment to Referee #1 by Thomas Burschil et al.

We thank Referee #1 for the careful review and constructive comments. Below the authors comment (indicated by ***AC***) to the reviewer comments (indicated by **RC**).

General comment

RC: This paper contain some interesting studies, but the material seem to be rushed through before the interpretations and methodologies had reached a mature level. It contains a number of separate studies that individually have interesting ideas, but they are not linked very well together. Also, the conclusions are not supported sufficiently by the data.

Hence, I suggest a much clearer focus of the paper and extensive elaboration of the key elements before publication – Major revision.

The title indicates that a "hydrological characterization" is the aim, but as far as I read it, the contents point towards the two following separate issues:

1. Establishing of various petrophysical relationships, resistivity/lithology, velocity/lithology and resistivity/hydr. conductivity
2. The construction of a 3D geological model based on AEM data, seismic data and borehole data

None of the above aims at a "hydrological characterization" as far as I see it. If these two items are actively joined the paper would be significantly strengthened, but if not I suggest to focus the paper on one of the two (or both in two separate papers…).

***AC**: You are right, the title is misleading. We will choose as new title: "Compiling geophysical and geological information into a 3D model of the glacially affected island of Föhr". We also rethink the figures and text to make our goals and findings clearer. Results of developed relationships AND geophysical/geological interpretation leads to a better and mature interpretation and thus to a better 3D model.*

3D Geological model:

RC: Figure 3 shows a diagram of the 3D geological modeling flow, but I really miss some detailed information on how the geological modeling is done, more than a reference to what program was used:

- How are the closed bodies (e.g. Fig.2) modeled in a stratified environment?
- How are the resistivity data used? When setting up the empirical relationships the authors claim that they can improve the hydrological modeling, but yet they say nothing about how these results were actually used.
- How are the seismic data used?
- How are the empirical relationsships used?
- The presense of a glaciotectonic complex with thrust faulting is claimed but none of the data presented examples support this idea directly. Yet in the conclusions these findings are stated as "unique", even though in the text they are correctly stated as "indications". Personally, I think the interpretation is correct, but the wording needs to reflect the data support.

To understand the 3D modeling a detailed (profile) example is absolutely crucial. The current figure 3 is nothing more than a flow-diagram with very little information. Figures 9-11 individually hold some of the information needed, but they do not refer to the same profile and it is impossible to see how the different data types are combined to end up with a geological model.

In the example the use of the entire set of data should be presented ending up with a presentation of the layers in the final stratified model, so that the reader can follow what information was actually used from the various datasets and how big are the inconsistencies.

AC: *We will restructurate the figures and parts of the text to focus on the compiling process – we change our example profile to make geological structures more obvious. Therefore, always the same profile will be used.*

We decided not to show one single construction cross section, because the construction is an iterative process while using the same geophysical and geological results again and again. But we include a figure and change parts of section 3.5 to make the overall compilation more visible.

Fig.2 is an example of the cross sections from the analogue geological model which was the basis for the 3D-modelling in the project. The larger closed bodies have been included in the layers of the digital geological 3D-model. The layers are continuous throughout the modeled area. The thickness is reduced to zero in the parts where the unit was missing due to the information from the analogue model. The resistivity data have been imported into the 3D-model to identify the distribution of aquifers filled with fresh water on the one hand and to line out the areas where clay or/and saltwater is found on the other hand. For this a threshold of 50 ohmm was chosen.

Empirical petrophysical relationships:

This part of the paper actually contains interesting studies and the paper would have been significantly stronger if the findings had been used actively. Either these findings are included actively in the geological modeling or the paper need to be separated in two parts for clarity.

AC: *We used the information of the empirical petrophysical relationship to examine the geological setting from the resistivity data and for the structural interpretation.*

Specific comments

1. **RC**: Section 1: “In this paper we describe how the understanding of the local geological and hydrogeological situation is significantly improved by the geophysical surveys”. It is not clear to me after reading the paper how the model was actually improved, even though I am sure it is the case!

   AC*: We improved the understanding of the local geology by setting up a hydrogeological model which is consistent with our geophysical measurements. Layer boundaries within the model are no interpolations between boreholes anymore but they are founded by seismic horizons as well as taken by changes in SkyTEM resistivity. We will clarify that by a more detailed description of the modeling process.*

2. **RC**: Section 3.1: the penetration depth of the SkyTEm system is stated as 30-300 meter. What do you mean – does it vary between 30 and 300 (if yes, what controls it), or do you mean that the information can retried typically in that interval (if yes – does that mean that you cannot use the information from the top 30 meter of the models? To my knowledge SkyTEM collects useable data also for the top 10 meters)?

   AC*: We mean the maximal penetration depth, which depends on the present resistivity.*

3. **RC**: Section 3.5: Lacking a description of the lower element of figure 3 (3D views?).

   ***AC**: We will replace this schematic modeling overview by a detailed description, illustrated by a construction example.*

4. **RC**: Section 3.5: "In a next step the SkyTEM and seismic data are added to the model" Fine, but I really miss information on how these models are added to the building of the geological model.

   ***AC:** We included the geophysical data into the modeling program, than used the information to adjust the layers in the construction cross sections. We will delineate this process in the paper.*

5. **RC**: Section 3.5: It is not clear to me whether the layers are globally present and continuous throughout the area, which seem quite contradicting to the conceptual model of Figure 2 having both incised valleys and thrust structures that are impossible to model in a layer model. The authors claim in the discussion section that the structures are "very complex and cannot be included in detail in a groundwater model". I disagree. The groundwater model should be able to handle the complexity level described by SkyTEM and seismics, but the problem might be that the geological modeling tool cannot handle the required complexity, or the time required (man-power) to build the model is not available.

   ***AC**: In the digital geological model the layers are globally present and continuous throughout the area, in which the thickness of the different layers was reduced to zero in that parts where the analogue model indicates that the unit does locally not exist.*

   The aim of the digital geological 3D-model was to reproduce the hydrogeological structure of the modeled area as the base for the groundwater model. The groundwater model was built up to show how the hydrogeological system of the island will react to the impacts of the predicted climate changes. The model should be regarded as a "trend model" and, due to the lack of detailed data in many parts of the island, not as a model including every complex local detail.

   Due to the very heterogeneous database with a lot of information in the southern areas around the waterworks and very sparse data in the northern marshland, it was not considered to be meaningful to build up a geological model representing all complex details only found in some parts of the modeled area. Nevertheless, e.g., the complex structures of the aquifers in the deeper parts of the island have been mapped, using the SkyTEM data and seismic data in combination with borehole data. The results of this mapping show a significant pattern of glacial thrust structures which gave indications for the construction of the geological model in the northern part of the island where these data are not existing (due to saltwater saturated sediments).

6. **RC**: Section 4.1: Rubin and Hubbard, 2005 seems to be superfluous as the two other references are specific sub-references to the Rubin and Hubbard book.

   ***AC:** Thanks for that comment, we remove this reference here.*

7. **RC**: Section 4.1.1: It is claimed that these relationships are made to improve the interpretation of the SkyTEM survey, but I did not find any information on how these findings were actually used.

   ***AC**: We used the correlation of resistivity and lithology, shown in Fig. 5, to characterize lithological units, e.g. sand, till and clay, in the SkyTEM resistivity volume. The boundaries of the units were the basis to adjust our model. We think, hence we have the data available, it is worth to evaluate the data and not only take values from textbooks.*

8. **RC**: Section 4.1.1: “Overlapping resistivity values for sandy and clayey material are in the range of 50– 100ohmm. This can lead to interpretation problems”. Well, did it cause problems, and how did you handle it?

   AC: *We handled these problems by using not only SkyTEM resistivity to characterize boundaries, but also seismic and borehole results.*

9. **RC**: Section 4.1.1: “If the drilling is not in the immediate vicinity of a SkyTEM flightline, projected datapoints were used” It is unclear what this means. One nearest sounding (possibly of low quality?) or some average of a group of soundings within some radius? Also, it is unclear how this comparison is made – or at least it was unclear to me. Some sampling of the logs must take place and will also define the number of data points in the probability functions (“multiplicity”) of figure 5. A few pages ahead a sampling of 1 m is mentioned, but it is unclear whether this refers backwards as well (and should of course then be mentioned there…).

   AC*: We used the 1D model of the nearest SkyTEM sounding, even if it is of low quality. The inversion (LCI respectively SCI) of the entire dataset uses constraints between the soundings, so that the inversion has also an averaging effect on the data. The use of several models within a certain radius would by possible but creates other questions. Should there be a weighting of the model due to their distance to the borehole? Models along a flightline should have just small variations due to the inversion. This would over-represent a flightline with many soundings compared to a flightline with less data. For that we decided to use just the nearest 1D inversion model.*

10. **RC**: What is “Y3” referring to in the text following figure 5?

    AC*: Y3 is our internal name for this version of the improved SkyTEM inversion, but it is not important within the paper. We changed that.*

11. **RC**: Section 4.1.1: “If low resistivity layers are embedded in the fine layered ground electrical anisotropy leads to reduced resistivity value for current flow parallel to the layering, while for current flow perpendicular to the layering an increased resistivity is measured.” I do not believe that this is the explanation. To my knowledge (correct me if I am wrong) electrical downhole tools measure the horizontal resistivity as well (the so-called paradox of anisotropy), which means that they should reveal equal values (rho_Horiz). Another explanation is therefore required if these data should be used.

    AC: *For my (RK) understanding the reason for the paradox of anisotropy (a higher resistivity is measured in the direction of the fine layering than perpendicular to it) is in the fact that the injected current is channeled in the highly conducting layers leading to a high current density and so to a high potential difference dU which is measured. This leads to a high apparent resistivity roh = k x dU/dI. Here we need galvanic coupling to the ground to inject the current and to measure the voltage.*

    For SkyTEM data, we measure the magnetic field of the induced eddy currents in the good conducting layers. In this case the high current density leads to a high secondary magnetic field, and the data inversion gives a highly conducting or low resistivity layer.

    This is our explanation (maybe we are wrong) for the lower resistivities (compared to the borehole data) measured by the SkyTEM survey. It would be interesting to compare long normale data with data from induction logs (that we don’t have).

12. **RC**: Section 4.1.1: I would like a quality assessment of the FEL compared to the 64” log as it seems that one is miscalibrated.

AC: *Borehole resistivities shown in Fig. 5 are a statistical evaluation of resistivity logs of 18 drillings. The logging was carried out by an experienced contractor. Even if at single logging the equipment was miscalibrated this should not change the result.*

13. **RC**: Section 4.1.2: It is not clear to me how the comparison between hydr. conductivity and resistivity is made. The figure presents 9 different K-values, but it is not clear to me what 9 different lithologies these values refer to.

    AC*: We include a table with lithology, petrographical classification and hydraulic conductivity as well as the origin of that table.*

Lithology		Petrographical classification	Hydraulic conductivity k_f [m/s]
T		1	1×10^{-9}
T,u / U,t	Clay	2	1×10^{-8}
U	Silt	3	3×10^{-7}
T/U, fs		4	3×10^{-6}
U, t, s, g	Till	5	5×10^{-6}
U, s,g		6	1×10^{-5}
fS, u		7	3×10^{-5}
f-gS,u		8	5×10^{-5}
fS	Fine sand	9	1×10^{-4}
f-mS		10	2×10^{-4}
mS		11	5×10^{-4}
f-gS		12	3×10^{-4}
f-gS, g		13	5×10^{-4}
m-gS		14	7×10^{-4}
m-gS, g		15	7×10^{-4}
gS	Coarse sand	16	1×10^{-3}
G,s		17	5×10^{-4}
G	Gravel	18	5×10^{-2}

14. **RC**: Section 4.1.2: The actual setup making the comparison is not clear to me: “The so obtained resistivity values were mean averaged for each petrographic unit (Table 2 and Fig. 7). Only resistivity data averaged over at least 50 samples (vertical spacing of samples is 1 m) were used for this comparison. For the clayey material not all variations are included as is seen in Fig. 4 (left panel) where variations in the till are shown in the gamma ray and resistivity logs.” Please write more clearly what you actually did.

    AC*: We correlated resistivity values from logs and projected SkyTEM soundings with petrographical designation for all available boreholes. For each petrographical unit with more than 50 samples (vertical spacing of values is 1m) averaged values were generated and for the empirical relationship.*

15. **RC**: Section 4.2: “To integrate these sand bodies as aquifers in the model, their spatial extension was derived from the resistivity data. How was this done? Searching for resistivities above some threshold or fully manual estimation?

    AC*: In a first step the resistivity data were plotted in the model, using 50 ohmm as the threshold value to define the spatial distribution of aquifers/sand bodies containing fresh water. The resistivity data in combination with seismic and bore hole data delivered*

indications for the construction of the geological model also in the northern part of the island where the resistivity data strongly are influenced by the saltwater.

16. **RC**: Figure 11: The left panel of fig. 11 is quite poor in terms of getting any information across and it contains much information not described in the text. (Colors, panels, black thin line, etc.).

    ***AC**: We changed Fig. 11 to a good resolution with readable labels. The all final figures will be provided in a proper resolution for this online journal.*

17. **RC**: Section 5: "Concerning the resistivity, a clear discrimination between sand and till (Fig. 5) is possible using borehole data (long normal 64'', FEL). Using SkyTEM data, some overlapping of resistivities for sand and clay occur. A possible reason is that the SkyTEM results had to be projected to the borehole locations (interpolation between flightlines) resulting in reduced resistivity resolution."
    I do not agree that a clear discrimination is seen with the logs as huge overlaps is actually present. When doing volume averages over thin layers the SkyTEM will of course get many "misinterpretations" due to the limited capability of seeing thin layers. This is much more important than the interpolation. Also, I think it is very important to mention the everpresent limitations and inaccuracies of the borehole data, which is not mentioned at all!

    ***AC:** We will elaborate this paragraph and mention limitations and inaccuracies.*

18. **RC**: Section 6: "The extent of the freshwater occurrence is determined as well as the freshwater/saltwater boundary and the extent of glaciotectonic structures" This might be true, but I see no evidence of that in the paper itself.

    ***AC:** Via resistivity thresholds the extent of the freshwater body can be estimated from the resistivity volume or depth slices. Within the low resistivities, indicating saltwater intrusions (e.g. in the northern Marsch area), the structure of the glaciotectonic complex is not obvious anymore but an indication can be estimated. We emphasize these facts in section 4.2 and will change Fig. 8.*

19. **RC**: Section 6: "The structural interpretation is improved by rock identification. Not clear to me what you mean here.

    ***AC**: Structures detected in geophysical data are separated as different units and they were identified by their petrophysical properties.*