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Interactive Comment

# Interactive comment on "Accelerated gravity testing of aquitard core permeability and implications at formation and regional scale" by W. A. Timms et al.

#### W. A. Timms et al.

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The authors would like to thank the two referees for their time and suggestions to improve our manuscript. As part of ongoing research, and in response to the the feedback that the referees have provided, we have completed additional centrifuge permeameter (CP) tests and evaluation of vertical hydraulic conductivity (Kv) data that is outlined below.

We propose revising and strengthening our manuscript on the basis of reviewer feedback and this additional work.





#### AR2 is X. Sanchez-Vila (9th April) and Referee #2 (11th April)

Response: The comment posted on 9th April was prior to both formal referee comments, although the text is the same. The authors therefore respond to these comments in the following section. We are fortunate that Professor Sanchez-Vila has provided his thoughtful feedback to detect weaknesses in our approach and to improve our manuscript. The opening review comments about "aquifer testing" are presumed be typographical errors, given the clear focus of the paper on aquitard testing. We are pleased to see that there is agreement about the need to properly characterize the hydraulic conductivity of aquitards, particularly at regional scale, and maintain that our manuscript is one step towards this objective. The following responses are presented systematically for each paragraph of referee #2 comments.

AR2 .... There is little to say regarding the part corresponding to the testing part....

Response: Whilst our manuscript does not aim to or claim to achieve characterisation of aquitards at a regional scale, the ability for rapid testing of large diameter drill cores of low permeability goes beyond previous ASTM approaches.

AR2 ... The geological setup and the sampling process are also relevant and should be included in any paper.

Response: We agree thank you.

AR2 .... Connectivity is therefore the issue. ....

Response: Yes, ultimately, the significance of vertical connectivity is a critical issue for scale of relevance to water resources. However, this is a grand challenge that is beyond the scope of this manuscript, requiring a significant effort with additional field data collection and suitable numerical modelling approaches.

AR2 ... There are 14 data points. Actually it is 3 + 5 + 6. Notice the great variability (except in CL). The variance is quite large in the NR and BF sites. So, if the variance is so large, it is difficult to assess how representative the values are.

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Response: We certainly accept the feedback from both reviewer #1 and #2 on the need to examine variance using a statistical approach and the limited number of data points. In the meantime, we have taken the opportunity to test an additional 4 samples from the CL site, between longer running reactive transport experiments in the centrifuge (for example Crane et al., 2015). This brings the total data to n = 18 for this study, including 9 from the CL site (new Kv data:  $2.2 \times 10$ -9,  $2.3 \times 10$ -9,  $2.70 \times 10$ -9,  $1.6 \times 10$ -9 m/s). It is proposed that Table 3 of our final revised manuscript include the details of these additional tests.

We would be pleased to revise this HESSD manuscript, referring to, and extending the statistical evaluation of the number of core tests that would be required for specific degrees of variance in permeability results. Statistical analysis was in progress because it was realised during early CP tests that this was indeed an important matter to follow up. A conference paper submitted in March 2015 was subsequently reviewed and accepted for publication (Timms and Anderson, in press).

In brief, our statistical analysis of the data followed basic small-sampling theory using the student t distribution, of which examples are provided by Gill et al. (2005). Upper and lower confidence intervals (UCI, LCI) were calculated from the apparent mean  $\pm$  t\_(n-1). s\_n /n^1/2, where sn is the standard deviation and t is the value of the student t distribution at the selected confidence limits (CL) of 90% and 99%. The confidence intervals were calculated for increasing number (n) of Kv data from each core.

Importantly, core samples for testing were randomly selected from the same lithostratigraphic formation. The clayey-silt cores were obtained from the upper 30 m of the alluvial sequence as described in Section 2. Although the alluvial sequence extends to over 100 m depth, we focused this study on sediments defined by a low net-to-gross ratio (Larue and Hovadik, 2006) of <0.4 that reflects that clay rich part of the sequence (Timms et al., 2011). We assumed a log-normal distribution of Kv within this formation, which as noted by (Fogg et al., 1998) might be justified within individual facies, but not over the full stratigraphic section. It was also assumed that the standard deviation

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of the samples tested is similar to the standard deviation of the total population of Kv results from the formation, which may only be known if a large number of samples are tested.

Applying this method to the Kv results for the CL site, a small uncertainty was calculated at a confidence limit of 99%. By increasing the number of samples, the confidence bounds for Kv were reduced from a range of  $4.8 \times 10^{-10}$  to  $2.4 \times 10^{-9}$  m/s (n=5) to a range of  $1.1 \times 10^{-9}$  to  $2.1 \times 10^{-9}$  m/s (n=9). Increasing the number of samples also decreased the standard deviation, although the geometric mean increased slightly (Table 1 is presented in the PDF supplement).

By comparison, the confidence interval calculated for Kv at the NR site with only 3 samples was more than an order of magnitude for Kv (at a confidence limit of 99%). However, by reducing the confidence interval to 90%, the range between the upper and lower confidence bounds for the NR site was similar to that for the BF site (Table 1).

In summary, this analysis demonstrates that Kv results for the CL and BF sites have been achieved with reasonable confidence, particularly for the CL site with N=9. However, additional sample testing for the NR site would be recommended to reduce the variability and improve the confidence in KÂňv.

AR2 ...All the upscaling effort at the CL site is reduced to the paragraph in pg 2820, lines 1-6. The finding reported in pg 2821 regarding a very low K.....

Response: Yes Section 5.2 discussed the geological and regional context of the core permeability tests, although it was beyond the scope of the manuscript to focus on upscaling approaches. Implications of the core permeability tests at larger scale were discussed, noting the differences at regional model scale to the small scale data. We agree that it is not possible with the available information to know why there is a discrepancy, but consider that it is important to highlight the complexity of processes that could account for vertical connectivity.

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The current conceptual model on which the numerical models are based (simple layered aquitard overlying an aquifer) do not allow for spatial variability in connectivity mechanisms that could be important across a large valley alluvial fill sequence. Our statement "the clayey sediments in this region may lack preferential flow paths at some sites, and in other areas preferential flow may occur through features such as fractures and heterogeneity at a range of scales" is an explanation that is consistent with available field data from different parts of the sedimentary sequence. It is not surprising that would be multiple mechanisms for vertical connectivity (matrix flow, fracture flow, sedimentary heterogeneity) that would be important to varying degrees depending on the spatial scale and local setting.

AR2 The last discussion part is very interesting.....

Response: Yes, the final part of the discussion (Section 5.6) on implications of core scale measurements of aquitard properties speaks to an aim of this manuscript (and also reflects the title of our work). The paragraph from Section 5.6 that reviewer #2 reprints with the remark "this is precisely my point" indicates that we are taking a reasonable approach overall.

We agree that the permeability data reported in Table 3 is not spatially extensive, given that small scale samples from three drill sites cannot characterise regional aquitard connectivity. However, we would argue that we have taken a semi-quantitative approach by careful measurements of cores, and that an apparent inconsistency between these results and a regional numerical model is not a contradiction that should preclude publication. There are a number of possible explanations for the possible mismatch including data and model limitations (Section 5.4, p2821) and conceptual model surprises (Section 5.6, page 2823).

AR2 pg 2800 line 5 "....rapid and reliable".

Response: We agree to replace the term "reliable" with "reasonable" throughout the final revised manuscript. This would indicate that the results are considered to be an

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acceptable indication of aquitard permeability at the scale of testing, without extending the claim of "reliable" that implies a certain accuracy and precision of the results.

AR2 pg 2805 line 4 I find very strange to reference a figure in an introduction section.

Response: We agree to move the figure to Section 4.2 as suggested.

AR2 Equation 8 is mathematically incorrect.

Response: An error in d' and dr' has been corrected in Equations 8 and 9 thankyou.

AR2 pg 2816 line 19.

Response: Yes, this is referring to Figure 3. The transient behaviour and implications for structure of this clayey silt material is further investigated in a separate paper (Crane et al., 2015) that is currently under review. Any cracks in the material result in extremely rapid leakage of water under accelerated gravity and are readily detected. For implications of dual porosity flow mechanisms, readers are referred to this paper for details.

AR2 pg 2816 lines 23-25. Somewhat confusing....

Response: We proposed to rephrase this part of the final revised manuscript to clarify that the anomalous data is related to evaporative losses that occur over longer time periods of flow (ie. overnight versus 1 hour measurement intervals). The current expression in this section provides this explanation later in the paragraph.

AR2 pg 2818 I am sure the authors checked that the samples did not show at the end of test any impact from consolidation....

Response: We agree that there is an omission to correct in a revised manuscript. It is proposed to add the following statement on pg 2818: "A digital calliper was used during this study to determine core length, including spot checks after experimental runs, with no evidence of significant changes in core length due to consolidation of the samples."

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AR2 Table 3. Different g-levels used. Why? How were they selected?

Response: Maximum g-levels in Table 3 are the g-levels at which steady state flow was achieved during testing. The upper permissible g-level was designed to be less than the estimated in situ stress from the depth at which the core was obtained. This will be more clearly stated by revising Sections 4.2 and 5.2 of the manuscript. Further discussion of g-levels is provided in a following response to reviewer #1.

AR2 I do not see the relevance of figure 4.

Response: In regards to Figure 4, we maintain that this example of distribution of stresses and pore fluid pressure through the core sample is important to reliable tests of core materials. The concepts discussed in Section 5.2 refer to this figure, for example, "During centrifuge testing effective stress is maximum at the base of the free draining core, where fluid pressure is zero, and thus effective stress is equal to total stress under hydrostatic conditions (no flow)." We believe it would be more challenging to consider the implications of these non-linear relationships depending on radial position of the core, without the benefit of Figure 4.

AR2 Figure 6, it is questionable whether it should be included in the paper....

Response: The authors accept the opinion of reviewer #1 and #2 that Figure 6 is not essential to the text, and remove this from the revised manuscript. Our purpose in including Figure 6 was to provide some site context for the characterisation of core samples, showing the relative simplicity of the layered clay silt deposit that exhibits little lateral variation in resistivity (Page 2820, Lines 7-12).

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Please also note the supplement to this comment: http://www.hydrol-earth-syst-sci-discuss.net/12/C1891/2015/hessd-12-C1891-2015supplement.pdf

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