Hydrol. Earth Syst. Sci. Discuss., 11, C5692–C5694, 2014
www.hydrol-earth-syst-sci-discuss.net/11/C5692/2014/

Hydrology and
Earth System
Sciences
Open Access
Discussions

Interactive comment on "Understanding NMR relaxometry of partially water-saturated rocks"

by O. Mohnke et al.

Received and published: 15 December 2014

Responses to specific reviewer comments
Anonymous Referee #1

General

Figure 2b) With regard to the initial condition, where does the shift to slower relaxation times (96-89) in the beginning comes from?
We checked the data and discovered an error in our data plot processing, mixing up data entries from different samples of the study. We exchanged figure 2b with the correct T1 distribution results.

Figure 8, 9 and 11.
Where does the difference in the surface relaxivity parameter 10ˆ-5 m/s to 10ˆ-10 m/s comes from?
No difference, corrected the typo in units m vs us

Page 12698
Line 4 the NMR signal amplitude needs to be extrapolated to be proportional to porosity
Changed to 'initial signal amplitude'

Line 5-7 state that "[. . .] the relationship between pore size and NMR relaxation depends on pore shape [. . .]" whereas in the conclusions on page 12712 line 12 -14 "The NMR relaxation time depends on the surface-to-volume ratio (not on pore shape) [. . .]" is written. Please clarify, this seems contradictory.
We agree, and clarified this statement, to avoid confusion between NMR behavior at fully and partially saturation

Page 12705
Line 6 The whole paragraph needs to be more clear since the loss of phase coherence is a T2 issue and therefore not related to T1 as Eq. 8 states.
Clarified and removed reference to T2 phase coherence effects

Technical

Figures should be larger and printed in high resolution, they are hard to read in terms of font size and color

Figures image files are basically all in a good resolution, but seemingly were degraded during pdf conversion. We will possibly need check on that with HESS layouter

Figure 8b and c) decay time? T1 or T2?

Figure 10) decay time? T1 or T2?

Added 'longitudinal' magnetization in the respective captions in Fig 8, 9 and 10 to clarify (it is already referred to the NMR relaxation as T1)

Figure 8. Surface relaxivity has a wrong unit

Corrected

Figure 14) decay time? T1 or T2?

Corrected the plots to show T1 buildup signal behavior and corrected and clarified the caption

Figure 14. Amplitude of what? T1 or T2? Is this the extrapolated amplitude?

Clarified, that it is related to T1; Note, as we show simulated data we can directly calculate initial amplitude M0(t=0) similar to measured NMR data the integral of inverted T1 distributions yields the initial amplitude.

Page 12698

Line 25 delete "the"

Corrected

Page 12699

Line 6-9 the extrapolated signal amplitudes are proportional

Changed to 'initial signal amplitudes'

Page 12700

Line 22 insert blank between "and water"

Corrected

Page 12701

Line 25 air is not a fluid, I suggest to use the phrase "non-wetting phase" instead of Fluid

Changed to "non-wetting phase" (also changed the other occurrence on page12702, L2)

Page 12705

Line 11 I assume that you mean that the [. . .]molecules diffuse at the wall [. . .]- please clarify

Changed to "diffuse to at the pore walls"

S. Costabel (Referee)

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General comments:

The manuscript suggests the use of capillaries with triangular cross-sections for interpreting NMR relaxometry data of partially saturated rocks. Using this kind of pores, one accounts for remaining water menisci during de-saturation trapped by capillary forces in the corners of the triangle. After explaining the known properties of such pore systems regarding drainage/imbibition and the physical relationship between pore pressure and remaining water content, the NMR response of the water menisci is analytically derived and verified by numerical simulations. The NMR properties of single capillaries with triangular cross-section as well as a corresponding bundle of capillaries (pore size distribution) are analyzed and compared to usual circular capillaries. Unfortunately, the authors show only one real NMR data example (Rotliegend sandstone) to motivate the necessity of their study. Therefore, I am afraid that the relevance of this paper might be questioned by the community. However, I know from own experience with loose sediments that the phenomenon of occurring relaxation regimes for S<1 outside the original relaxation time distribution at S=1 can very often be observed, even with pure sand. I urgently suggest to show more own data or refer to literature with further data examples for motivation (e.g. Costabel, 2011; Bird et al., 2005; Jäger et al. 2009).

We added additional references (also, see comments below)

I suggest to accept the paper after major revisions.

The step from single pore to pore size distribution must be explained, analyzed and discussed more in detail. I would be glad to see a figure similar to Fig. 1 (de-saturation for the bundle of circular capillaries)
also for the distribution of triangles.

Included figure with desaturated triangular pore size distributions and added discussion in text

Furthermore, the critical role of hysteresis and
its representation in the simulated NMR data is not worked out adequately, although the authors mention this in the Summary/Conclusions section as key feature of their approach (P 12711 L 17).

We added additional figures and included a paragraph to better illustrate and clarify the observed hysteresis behavior.

I doubt that hysteresis effects can be observed unambiguously using NMR relaxometry.

Agreed, possibly a very challenging experiment to demonstrate. Other complementary data, a priori information/assumptions and/or model constraints would be required. However, the main focus here is on introducing and promoting a basic model towards improving the understanding of NMR behavior on partially saturated rocks or soil.

However, I believe that the key feature of triangular
pore spaces is the exact description of the physical relationship between remaining water content, pore pressure and permeability/hydraulic conductivity (e.g. Tuller and Or, 2001).

Using this relationship for interpreting NMR data would be a clear benefit and this manuscript has the potential to show the way how this can be done.

Best regards, Stephan Costabel

Additional references:

Costabel, S.: Nuclear magnetic resonance on laboratory and ïnˇA¸eld scale for estimating hydraulic parameters in the vadose zone, PhD thesis, Berlin University of Technology, 2011. (opus4.kobv.de/opus4-tuberlin/files/3173/costabel_stephan.pdf)
Added above reference and additional comments regarding in the text (see below)

Bird, N. R. A., Preston, A. R., Randall, E. W., Whalley, W. R., and Whitmore, A. P.(2005). Measurement of the size distribution of water-ïnˇA¸lled pores at diïnˇAˇ erent matric potentials by stray ïnˇA¸eld nuclear magnetic resonance. European Journal of Soil Science, 56:135143.
Jaeger, F., Bowe, S., van As, H., and Schaumann, G. E. (2009). Evaluation of 1 H NMR relaxometry for the assessment of pore size distribution in soil samples. European Journal of Soil Science, 60:1052 – 1064.
Added above references

Specific comments:

P 12699 L 20: Include (2006) after citing Al-Mahrooqi et al.
corrected

P 12700 L 22: Include a space after “and”
corrected

P 12700 L 26: Costabel (2011) analytically derived the NMR response of a single water meniscus for the first time (for an arbitrary opening angle and for the fast diffusion regime, Costabel, 2011, Pages 33 – 38). It would be fair to cite this work, even if it is (only?!) a part of the PhD thesis and not published as a peer reviewed paper. Costabel (2011) analyzed the relationship between mean relaxation time (= single angular pore system) and saturation degree (Costabel, 2011, Pages 33 – 41). He also concluded that, when considering capillaries with angular cross-sections, new relaxation regimes will occur during de-saturation that might exceed the relaxation time distribution at S=1 towards smaller relaxation times (Costabel, 2011, Page 61).
Agreed, this goes without any questions! We have cited this work accordingly.

P 12701 L 2: I could not figure out what you mean by “. . . the simulated signals are tested using synthetic pore size distributions.” Do you really test the simulated signals? As I understand, you simulate signals based on synthetic pore size distributions.
We clarified the sentence

P 12701 L 20: “. . . gravity forces are weak.” Actually, these are neglected.

Added comments in the text

P 12705 L 11 - 14: I suggest to include the term “fast diffusion” anywhere in this sentence.
P 12708 L 4: The term “fast diffusion” is referred to here for the first time without any further explanation. Please introduce it first (e.g. at P 12705 L 11-14).
C5735
Introduced fast diffusion term in 12705, L11ff

P 12709 L5: Fig.11 has no subplot “a”.
Deleted the reference to Fig.11a
P 12709 L9: Include “partially saturated” before “system of pores”
Corrected

P 12709 L 18 to P 12710 L 7: I do not understand the necessity of combining the analyses of the drainage/imbibition behavior of the angular pore system and the NMR response of that system in this passage. The focus jumps from Fig. 14 to Fig. 13, then back to 14 and back again to 13, before Fig. 14 is analyzed in detail, which is quite confusing. Finally, no effects of hysteresis can be observed in the simulated NMR data in Fig.14. Indeed, I would not expect that any drainage/imbibition behavior can be made visible using these NMR simulations. Therefore, I suggest to compare and discuss the hysteresis effects of the pore systems earlier, e.g. after introducing the de-saturation behavior of the single pores in Fig. 4 and Fig. 5. Here, in section 2.3 you should focus the discussion on the NMR responses at partial saturation only. If you do not agree, please explain more in detail how the hysteresis effects influence the NMR data and discuss how this influence can possibly be used in future interpretation schemes. I expect that there is a natural ambiguity between drainage and imbibition that cannot be resolved by NMR relaxometry.
We added additional figures and rearranged paragraphs so for a more consistent read without jumping to better address these items (also, see our response above)

P 12710 L 8 ff: In addition to my ncerns above, some important details on the simulations in Fig.14 are missing. What are the properties of the underlying pore size distributions for the three cases?
What are the values for Tbulk and surface relaxivity.
Why did you choose the T2 relaxation here in contrast to the T1 simulations in Fig. 8 and 9? Possibly, this information should be introduced together with Fig.12, but Fig.12 is not mentioned in the text at all. Seems to be a lognormal distribution: what are the values for the mean and the standard deviation?
Parameters for pore size distribution were included and changed the figures to be consistent with the previous discussion of NMR T1 relaxation. Also, the order of figures was adjusted accordingly.

P 12710 L 25: Regarding the assumption of pore size distributions based on triangular capillaries, there is a principle problem occurring during de-saturation. The pore system is considered to be a bundle of triangular capillaries and each capillary has its individual size, but all are similar in shape. After the snap-off, the contribution of each capillary to the NMR relaxation behavior is identical, even if they are originally different

in size. This is because the de-saturation is controlled by the pressure, which determines the curvature of the arc meniscus. Following the concept of reduced geometry all de-saturated triangles with their remaining water in the corners look the same. Consequently, at some point during de-saturation, i.e., if the air has entered all capillaries of the pore system, only one single relaxation time is left for the case of the equilateral triangles (Fig. 14b) or three relaxation times for the case of the right-angled triangles (Fig. 14c). Strictly speaking, the assumption of a relaxation time distribution is no longer valid at this point. This is a conceptual problem and must be discussed at the end of this section.
Agreed, we are aware of this inherent behavior of a single (or n) corner related discrete decay times. Seemingly, becoming somewhat 'professionally blinkered' of this 'obvious' behavior we did not include this particular point in our initial discussion. We have thankfully taken up on that comment and added a figure and discussion of this behaviour.
This feature is of course not captured in the typical inverse modeling approach for NMR lab/log data we used here. We also tried to address this accordingly in discussion and conclusion It is intended to implementing this concept an adapted future inversion scheme mentioned as part of our outlook.

P 12711 L 17 – 19: A discussion is missing on how the hysteresis behavior is encoded in the NMR data. This is not obvious from Fig. 14. Please see also my comment on P 12709 L 18 to P 12710 L 7.
Include NMR related hysteresis plots in a consolidated figure (Fig. 15)

P 12711 L 12: On the statement ". . .triangular pores strongly influence . . . hydraulic properties". Tuller and Or (2001) derived the hydraulic conductivities for different crosssections of capillaries, also for the equilateral triangle. What relationship between shape/size of the triangle and saturated hydraulic conductivity must be expected? Such information would strengthen your statement a lot.
We added a paragraph and discussed this relationship

P 12711 L 22 - 25: You should explain in detail what benefits are expected of such an inversion scheme compared to the classical approach of using circular capillaries. What are the shortcomings of existing approaches for partial saturation if the remaining water menisci remain unconsidered?
We tried to point out and list possible benefits, e.g. NMR inversion on partially saturated rocks when estimating surface relaxivity or predicting relative permeability from laboratory or borehole data