

Interactive comment on “Understanding NMR relaxometry of partially water-saturated rocks” by O. Mohnke et al.

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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

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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).

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

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-filled pores at different matric potentials by stray field nuclear magnetic resonance. *European Journal of Soil Science*, 56:135143.

Costabel, S.: Nuclear magnetic resonance on laboratory and field scale for estimat-

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ing hydraulic parameters in the vadose zone, PhD thesis, Berlin University of Technology, 2011. (opus4.kobv.de/opus4-tuberlin/files/3173/costabel_stephan.pdf)

Jaeger, F., Bowe, S., van As, H., and Schaumann, G. E. (2009). Evaluation of ^1H NMR relaxometry for the assessment of pore size distribution in soil samples. *European Journal of Soil Science*, 60:1052 – 1064.

Specific comments:

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

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

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).

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.

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

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).

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P 12709 L5: Fig.11 has no subplot “a”.

P 12709 L9: Include “partially saturated” before “system of pores”

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.

P 12710 L 8 ff: In addition to my concerns 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 T_{bulk} and surface relaxivity. Why did you choose the T_2 relaxation here in contrast to the T_1 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?

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

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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.

P 12711 L 12: On the statement “. . .triangular pores strongly influence . . . hydraulic properties”. Tuller and Or (2001) derived the hydraulic conductivities for different cross-sections 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.

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.

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?

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