In-situ nuclear magnetic resonance detection of fracture-held water in variably saturated bedrock

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Summary

Many near-surface environments consist of variably weathered and fractured bedrock, where water can be dynamically stored in different pore environments. The fluxes and residence times of water strongly depend on the configuration of water in pore space and, in particular, the partitioning of water between fractures and the pores of the rock matrix. However, in-situ monitoring methods capable of discriminating between these two reservoirs are lacking. Here, we evaluate low-field borehole nuclear magnetic resonance (NMR) as a method for detecting water storage in fractures. We take advantage of a rising and falling groundwater table at two monitoring sites with instrumented boreholes (one in mudstone and the other in sandstone) to identify the NMR-derived relaxation time associated with the saturated (high water table) and unsaturated (low water table) states of the weathered bedrock. In both rock types, we observe a long relaxation time signal greater than 30 ms at saturation that diminishes or disappears as the bedrock desaturates. These long relaxation times are interpreted to be associated with saturated fractures and indicate that dynamic water storage at both sites occurs within fractures, supporting existing conceptual models. Our preliminary results illustrate the utility of NMR for partitioning between water storage in fractures and the rock matrix in complex weathered bedrock environments.

Introduction

In soil and weathered bedrock environments in the near surface, biogeochemical processes are strongly regulated by the configuration of water in pore space (Or et al., 2007). In bedrock environments, dynamically stored water may be partitioned between fractures and the rock matrix and the extent of this partitioning strongly influences fluid transport and chemical reaction. Low-field nuclear magnetic resonance (NMR) is a promising technique for identifying how water is distributed in fractured bedrock, because it responds directly to the volume and relative mobility of water in a porous media. Recently, the development of narrow diameter borehole NMR (Walsh et al., 2013) has advanced capabilities for in-situ monitoring of water content in the near-surface. Here, we investigate the NMR response to water content changes in weathered and fractured bedrock in response to a rising and falling seasonal groundwater table.

Theory

The NMR measurement of a water-saturated porous material records the signal produced by excited protons in water molecules as they relax to equilibrium after a perturbation in the presence of a background magnetic field. The initial amplitude of the recorded signal is directly proportional to the number of excited protons, and provides a direct measurement of volumetric water content. The decay of the signal is a result of proton dephasing mechanisms, and contains information about the pore-scale environment of the sampled material. To obtain information about the pore-scale environment, the NMR signal decay can be fit by a sum of decaying exponentials, each of which is characterized by a decay constant, the T_2 or transverse relaxation time (Coates et al., 1999). Each pore sampled by the NMR measurement corresponds to a different T_2 value. The net observed T_2 value is the sum of the individual T_2 components contributed by each sampled fluid-filled pore. Through inversion, the NMR signal is converted into a distribution of T_2 values.

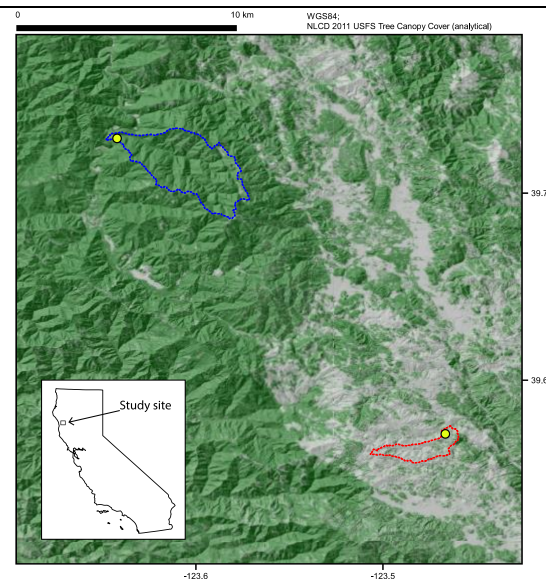

Figure 1. Study location. Yellow circles represent approximate borehole locations within study watersheds. Well 7 is located within the Elder Creek watershed (blue dashed line) and Well 503 is located within the Dry Creek watershed (red dashed line).

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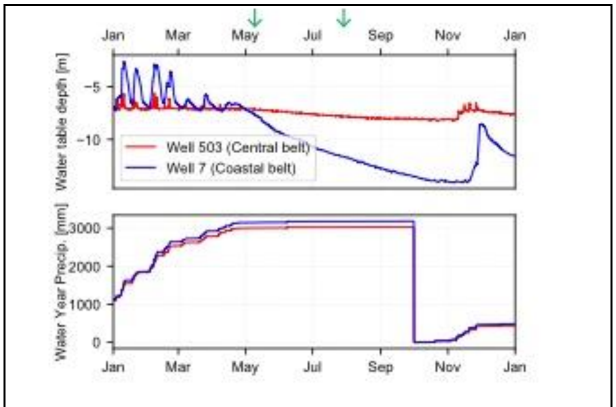

Figure 2. Groundwater levels (upper panel) and seasonal precipitation (lower panel) for Wells 503 and 7. Arrows mark survey dates.

Under the conditions where surface relaxation is the dominant T_2 decay mechanism, the T_2 distribution represents the pore-size distribution of the sampled material and the integral of the T_2 distribution reflects the total porosity (Coates et al., 1999). In unsaturated conditions, the integral of the T_2 distribution represents the total water content (WC).

Site Description and Methods

We conducted successive borehole NMR surveys in 3 inch diameter PVC-cased hydrological monitoring boreholes associated with the Eel River Critical Zone Observatory (Figure 1). Well 7 is located in a dense old-growth forest on a steep slope underlain by metamorphosed clay-rich turbidite deposits of the Franciscan Coastal Belt. Well 503 is located in a savanna-woodland on a ridge top within a sandstone block that is embedded within the clay-rich matrix of the Franciscan Central Belt mélange.

We use a portable borehole NMR system called the DART (Vista Clara, Inc.; Walsh et al., 2013) comprised of a battery-powered NMR control unit which remains at the surface, and a downhole 1.75 cm diameter probe. The sensitive volume of investigation of the tool is a 1-2 mm thick cylindrical shell with a vertical height of approximately 25 cm. We operate the system at two frequencies, approximately 426 kHz and 478 kHz, which correspond to a sensitive zone radius of approximately 7.6 and 6.7 cm, respectively. Only the fluid present within this thin shell affects the NMR measurement. The tool acquires NMR data using the Carr-Purcell-Meiboom-Gill (CPMG) sequence with an inter-echo spacing TE of 500 µs.

Data collection was optimized to effectively detect water in both large and small pores by using two CPMG stages which use a different polarization time (T_r). We recorded 28 stacks at 3 s T_r and 168 stacks at 0.15 s T_r. Because small water volumes generate small signals and more noise, fewer averages (36) were used for the long T_r record and more averages (500) were used for the short T_r record. To improve the signal to noise ratio further, the dual-T_r data is combined and the data from both frequencies is integrated.

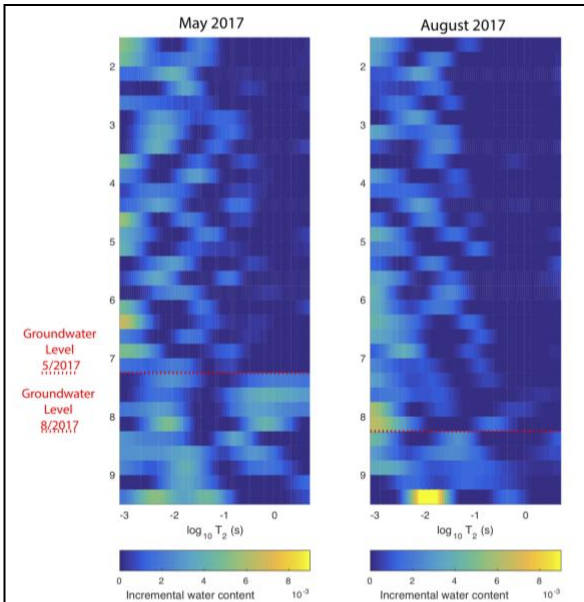

Figure 3. Depth profile of the NMR signal in the weathered sandstone well (503) in May and August surveys. The distribution of relaxation times is shown at each depth. Color corresponds to amplitude. Dashed red lines mark the groundwater level in the well at the time of the survey.

Results

During drilling, intact rock samples recovered via standard penetration testing (mudstone well) and air-rotary coring (sandstone well) revealed pervasively fractured and weathered rock, with visible fractures present at a variety of scales. Fracture fill, aperture width, and roughness were highly variable at both sites. Many, but not all, fractures were oxide coated (likely Fe and Mn) and some fractures were filled with soil-like clay particles.

NMR surveys conducted in May (start of dry season) and August (mid-dry season) track the fall of the water table and represent relatively wet and dry vadose zone conditions, respectively. Seasonal groundwater level changes are driven by the seasonal Mediterranean precipitation at both sites (Figure 2), and groundwater levels are responsive at the storm timescale. Infiltrating rainfall during the wet season transits an ~8 m vadose zone comprised nearly entirely of weathered bedrock, with the exception of thin (<50 cm) soils at both sites.

The results of successive NMR surveys are shown in Figures 3- 6. Depth profiles of T_2 decay-time distributions May (left) and Aug (right) in the sandstone and mudstone wells are shown in Figures 3 and 4 respectively. The colors reflect the amplitude of the T_2 distribution and the location of the water level in the well at each survey is shown as a red dashed line. Large relaxation times (greater than 50 ms and up to 500) are observed within the groundwater saturated region during the May (wet) survey; however these larger relaxation times are not detected in the August (dry) survey when the water table receded. We interpret the loss of signal at the large relaxation times to reflect the depletion of water in fractures.

The T_2 decay-time distributions from discrete depths in the sandstone and mudstone well are shown in Figures 5 and 6 respectively. The depths shown were below the groundwater level at the time of the May survey (blue line), and were above the groundwater level at the time of the August survey (orange line). The T_2 distributions from these depths can therefore be considered to reflect saturated conditions in May and unsaturated conditions in August. We attribute the marked differences in the large (>100 ms) T_2 response measured during the different surveys to the draining of fractures with the lowering of the water table. The

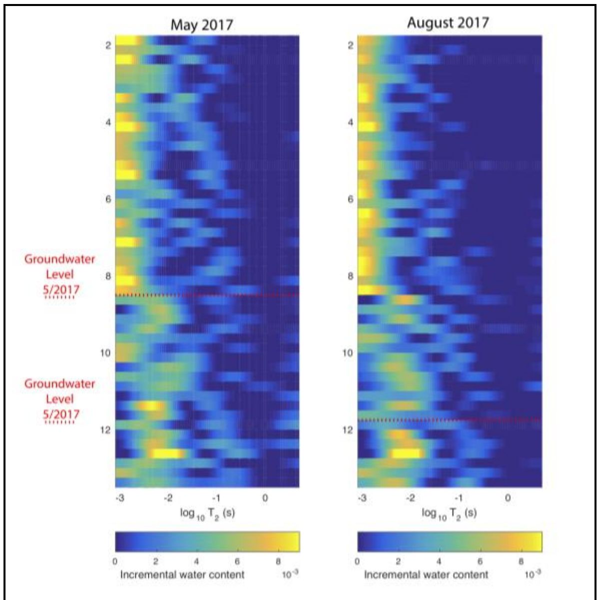

Figure 4. Depth profile of the NMR signal in the weathered mudstone well (7) in May and August surveys. The distribution of relaxation times is shown at each depth in the well, where color corresponds to amplitude. Dashed red lines mark the groundwater level in the well at the time of the survey.

difference between the T_2 associated with saturated and unsaturated states is more pronounced in the sandstone well (Figure 5) relative to the mudstone well (Figure 6) likely due to larger, more discrete fractures in the sandstone. Assuming that all T_2 changes between May and August greater than 100 ms were associated with fracture desaturation leads to an estimate of fracture porosity of approximately 7.5% in the sandstone well and 2.5% in the mudstone well.

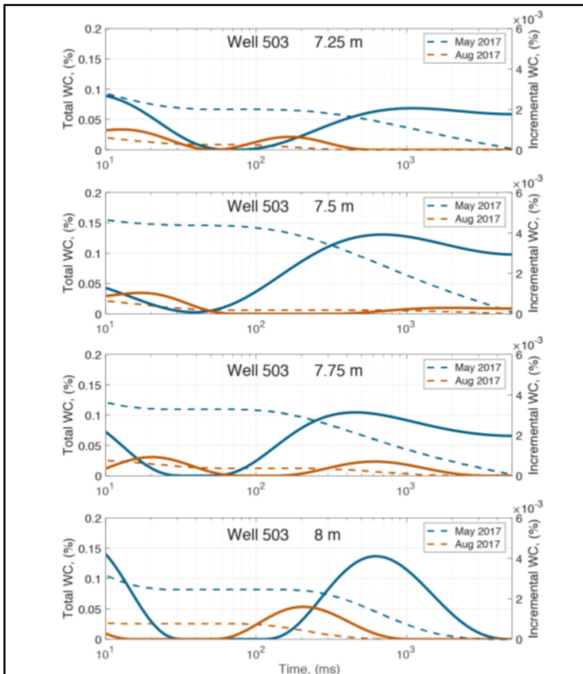

Figure 5. T_2 distributions for selected depths within the weathered sandstone well (503) are shown as solid lines. The depths shown were below the groundwater table in May and above the groundwater table in Aug. Dashed lines mark the cumulative water content for relaxation times greater than 10 ms.

Discussion

The extent to which seasonal groundwater is dynamically stored in interconnected fractures as opposed to the rock matrix influences physical transport mechanisms and chemical reactions occurring within seasonally dynamic groundwater. At the two study sites, it has been hypothesized that seasonally dynamic groundwater is largely isolated to fractures, such that the exchange of fluid between fracture and matrix reservoirs is minimal under high water table conditions (e.g. Kim et al., 2017, Rempe and Dietrich, 2018). This hypothesis is supported by the observation of pervasive fracturing, the rapid and large response of the water table to small rainfall events, and the high water contents of matrix rock chips extracted during drilling at low water table conditions. Together, these data suggest that the rock matrix largely remains saturated year-round and a network of highly connected fractures fill as groundwater levels rise.

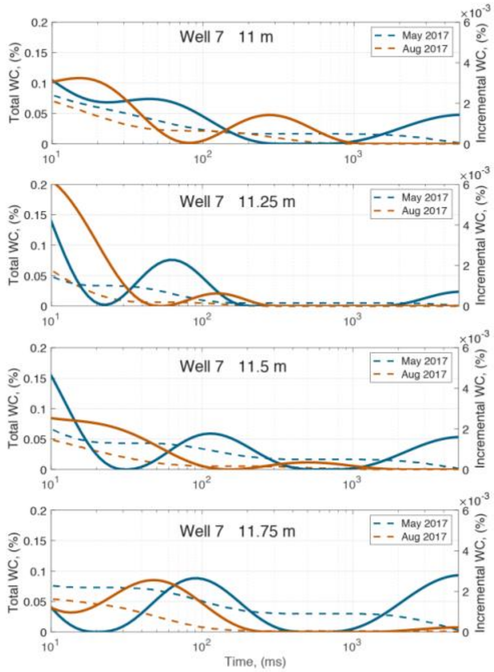

Figure 6. T_2 distributions for selected depths within the weathered mudstone well (7) are shown as solid lines. The depths shown were below the groundwater table in May and above the groundwater table in Aug. Dashed lines mark the cumulative water content for relaxation times greater than 10 ms.

Our NMR results demonstrate that large differences in high (>10 ms) T_2 relaxation times observed under saturated conditions are lost in unsaturated conditions. An empirical cutoff time of 33 ms is commonly used to distinguish bound fluid water content from mobile water content (Timur, 1969). The observed changes at T_2 greater than 100 ms (Figures 5 and 6) clearly fall within this range, such that reduction of high relaxation time signal is associated with mobile water. This is supported by the loss of this water over a 3-month time scale as groundwater levels dropped. Our observed T_2 distributions suggest that pore environments with relaxation times exceeding 1000 ms exist at both sites. These very high T_2 necessitate further investigation as they exceed expected values for porous media (Coates et al., 1999).

The extent of saturation change in the matrix, however, remains ambiguous. We observe changes in the amplitude of the shorter (<10 ms) T_2 signal at the depths where the water table dropped (Figures 4 and 5), which suggest that saturation changes within the smaller pores of the rock matrix may also occur in this region. However, changes in saturation associated with smaller pores are subject to higher uncertainty due to the smaller NMR signal generated by such changes and limitations associated with the minimum echo time of the instrument. Additionally, quantitative interpretation of the NMR response to draining fractures and rock matrix remains challenging due to the complicating influence of variable saturation (Falzone and Keating, 2016), variable fracture structure and the possibility of multiple porosity diffusional coupling (Chi and Heidari, 2015), and the influence of paramagnetic species (Grunewald and Knight, 2009). Under these conditions, the NMR-derived T_2 distribution does not represent pore-size distribution. These complexities are all present in weathered bedrock environments in the near surface and complicate quantitative interpretation. Future work on petrophysical relationships between variably saturated fractures and NMR measurements in weathered bedrock conditions are needed.

The focus of this contribution is on the variably saturated zone (between the red lines in Figures 3 and 4), however, our data also show evidence of changing water content, and specifically changing mobile water content at high T_2 within the unsaturated zone. This suggests that NMR is useful for quantifying unsaturated storage of mobile water.

Conclusion

The dynamic storage of water, and in particular, the partitioning of water between fracture and matrix storage reservoirs, strongly influences biogeochemical processes and water residence times in the near surface. Here, we use successive low-field borehole NMR surveys at high and low saturation to identify the extent to which NMR signals reflect water storage in fractures. Our results reveal that the signal associated with long relaxation times, which reflect larger pores, diminishes as the fractured bedrock desaturates. These changes indicate that significant dynamic storage occurs in fractures in the weathered bedrock and that borehole NMR surveys are a useful tool for evaluating the in-situ configuration of water in complex heterogeneous media.

Acknowledgements

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REFERENCES

Chang, C. T. P., J. Qiao, S. Chen, and A. T. Watson, 1997, Fracture characterization with NMR spectroscopic techniques: Journal of Magnetic Resonance, **126**, 213–220.

Chi, L., and Z. Heidari, 2014, Quantifying the impact of natural fractures and pore structure on NMR measurements in multiple porosity systems. *In* IPTC 2014: International Petroleum Technology Conference.

Coates, G. R., L. Xiao, and M. G. Prammer, 1999, NMR logging: Principles and applications: Halliburton Energy Services Publication.

Falzone, S., and K. Keating, 2016, A laboratory study to determine the effect of pore size, surface relaxivity, and saturation on NMR T2 relaxation measurements: Near Surface Geophysics, **14**, 57–69.

Grunewald, E., and R. Knight, 2009, A laboratory study of NMR relaxation times and pore coupling in heterogeneous media: Geophysics, **74**, no. 6, E215–E221, https://doi.org/10.1190/1.3223712.

Kim, H., W. E. Dietrich, B. M. Thurnhoffer, J. K. B. Bishop, and I. Y. Fung, 2017, Controls on solute concentration discharge relationships revealed by simultaneous hydrochemistry observations of hillslope runoff and stream flow: The importance of critical zone structure: Water Resources Research, **53**, 1424–1443, https://doi.org/10.1002/2016WR019722.

Or, D., B. F. Smets, J. M. Wraith, A. Dechesne, and S. P. Friedman, 2007, Physical constraints affecting bacterial habitats and activity in unsaturated porous media—A review: Advances in Water Resources, **30**, 1505–1527, https://doi.org/10.1016/j.advwatres.2006.05.025.

Rempe, D. M., and W. E. Dietrich, 2018, Direct observations of rock moisture, a hidden component of the hydrologic cycle: Proceedings of the National Academy of Sciences, **115**, 2664–2669.

Timur, A., 1969, Pulsed nuclear magnetic resonance studies of porosity, movable fluid, and permeability of sandstones: Journal of Petroleum Technology, **21**, 775–786.

Walsh, D., P. Turner, E. Grunewald, H. Zhang, J. J. Butler, E. Reboulet, S. Knobbe, T. Christy, J. W. Lane, C. D. Johnson, and T. Munday, 2013, A small diameter NMR logging tool for groundwater investigations: Ground Water, **51**, 914–926, https://doi.org/10.1111/gwat.12024.

10.1190/segam2018-2998484.1