Using time-lapse borehole NMR relaxation measurements to investigate the relationship between bedrock weathering and plant-available water storage

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November 24, 2022

Abstract

Time-lapse borehole nuclear magnetic resonance (bNMR) relaxation is a promising method for linking water content changes in the unsaturated region of the critical zone with pore-scale properties associated with bedrock weathering. The saturation-dependance of the NMR T2 distribution is strongly controlled by pore-scale material properties and can be linked to hydraulic properties (e.g. the water retention function and hydraulic conductivity). Here, we leverage NMR's sensitivity to pore-scale properties to investigate material controls on plant-available water storage dynamics in weathered bedrock via time-lapse bNMR relaxation measurements. To overcome slow logging speed and poor signal-to-noise (SNR) ratio typically associated with bNMR measurements in the unsaturated zone, we focus on the sum of echos (SE). We show that the advantage of using SE to characterize NMR relaxation, rather than using the full T2 distribution or the logarithmic mean of the distribution, is that it is easy to calculate, does not require inversion, has enhanced SNR, and is sensitive to both volumetric water content (VWC) and mean T2. This leads to high contrast in SE between time-lapse measurements relative to other metrics of NMR relaxation. At our hillslope study site associated with the Eel River CZO, VWC changes in weathered bedrock driven by deeply-rooted trees allow us to create "NMR characteristic curves" for different regions of the weathering profile. Analogous to a water retention function, the NMR characteristic curves describe NMR relaxation times of a material at a given VWC, and can be used to identify differences in pore-scale properties. We show that mean T2 times are typically shorter in bedrock that is more weathered for the same VWC, which is consistent with smaller pore-sizes and higher surface relaxivities associated with weathering products such as secondary clays and oxides. Our well logging indicates that changes in pore structure associated with bedrock weathering control plant-available water supply within the bedrock weathering profile. While these results illustrate the utility of bNMR, further studies that quantitatively link NMR measurements to flow properties via pore or empirical models will benefit mechanistic understanding of plant available water in the critical zone.

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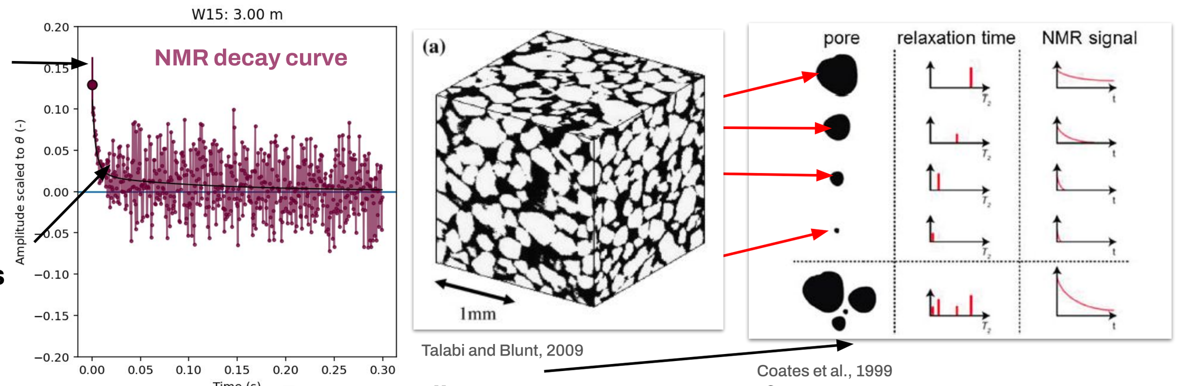
$$M(t)_{\text{pore dist.}} = \sum_i \mathbf{M}_i(0) \exp\left(\frac{-t}{T_{2i}}\right) \qquad \frac{1}{T_2} = \rho \frac{S}{V}$$

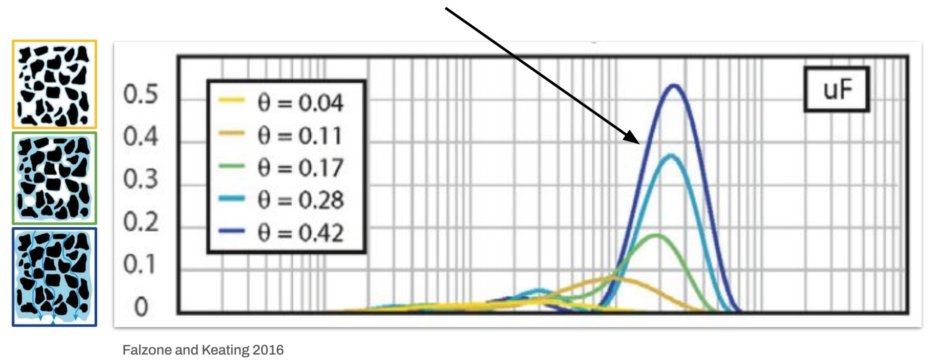
Initial amplitude is directly proportional to water content

The decay rate is controlled by material properties

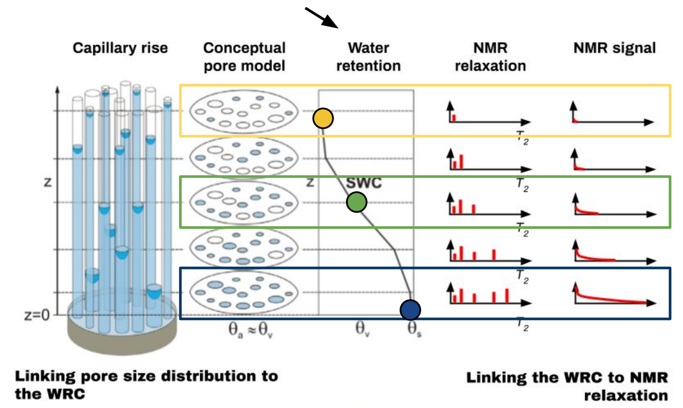


Porous media generate a spectrum of T2 times related to spectrum of pore sizes

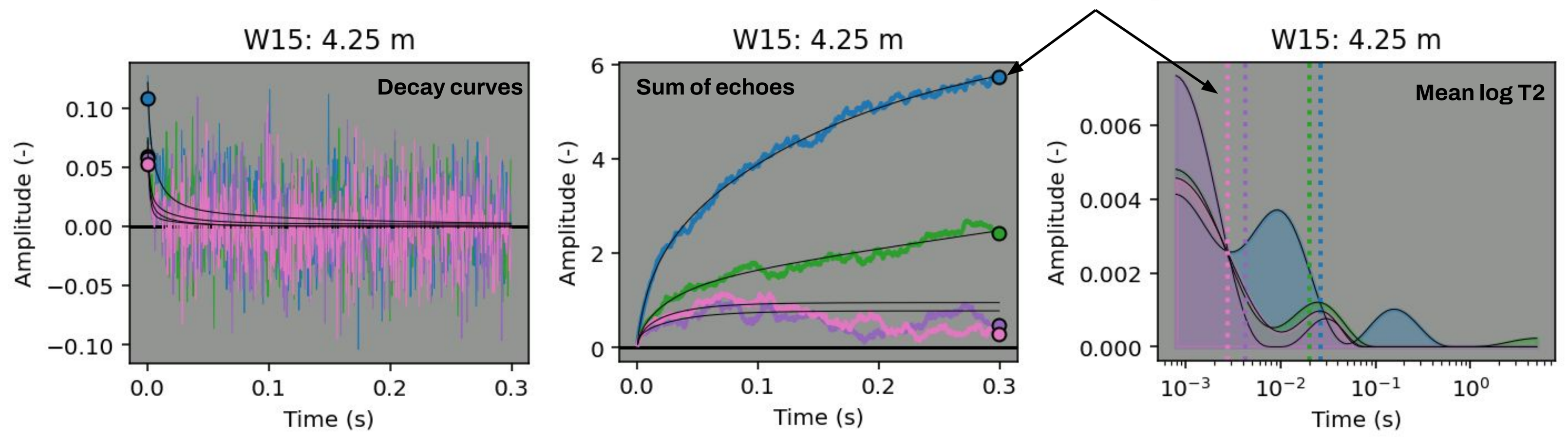
T2 distribution is saturation dependant



T2 saturation-dependance is related to water-retention



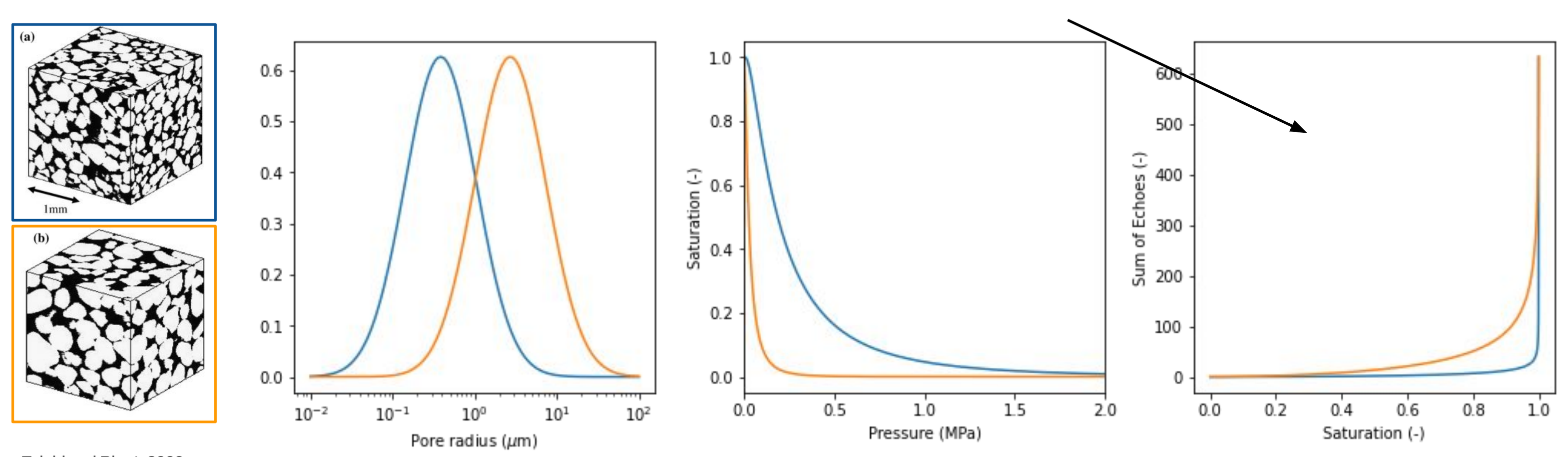
The full T2 spectrum can be characterized with a single value

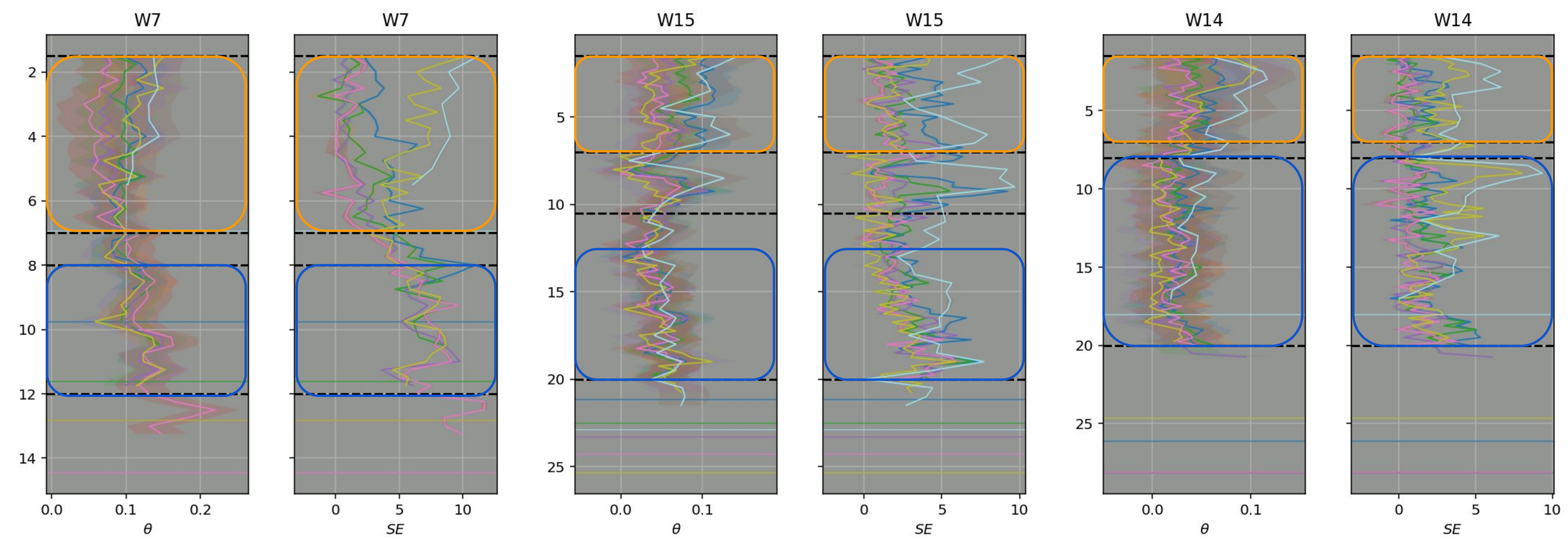


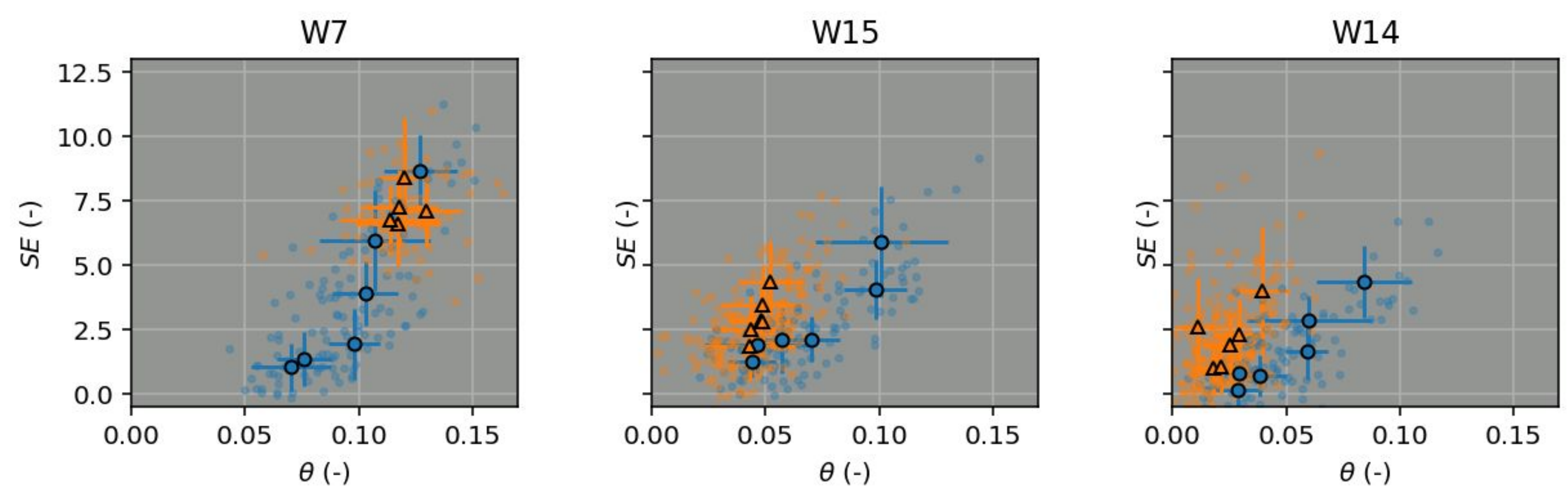
$$SE \propto \theta \cdot |T_2|$$

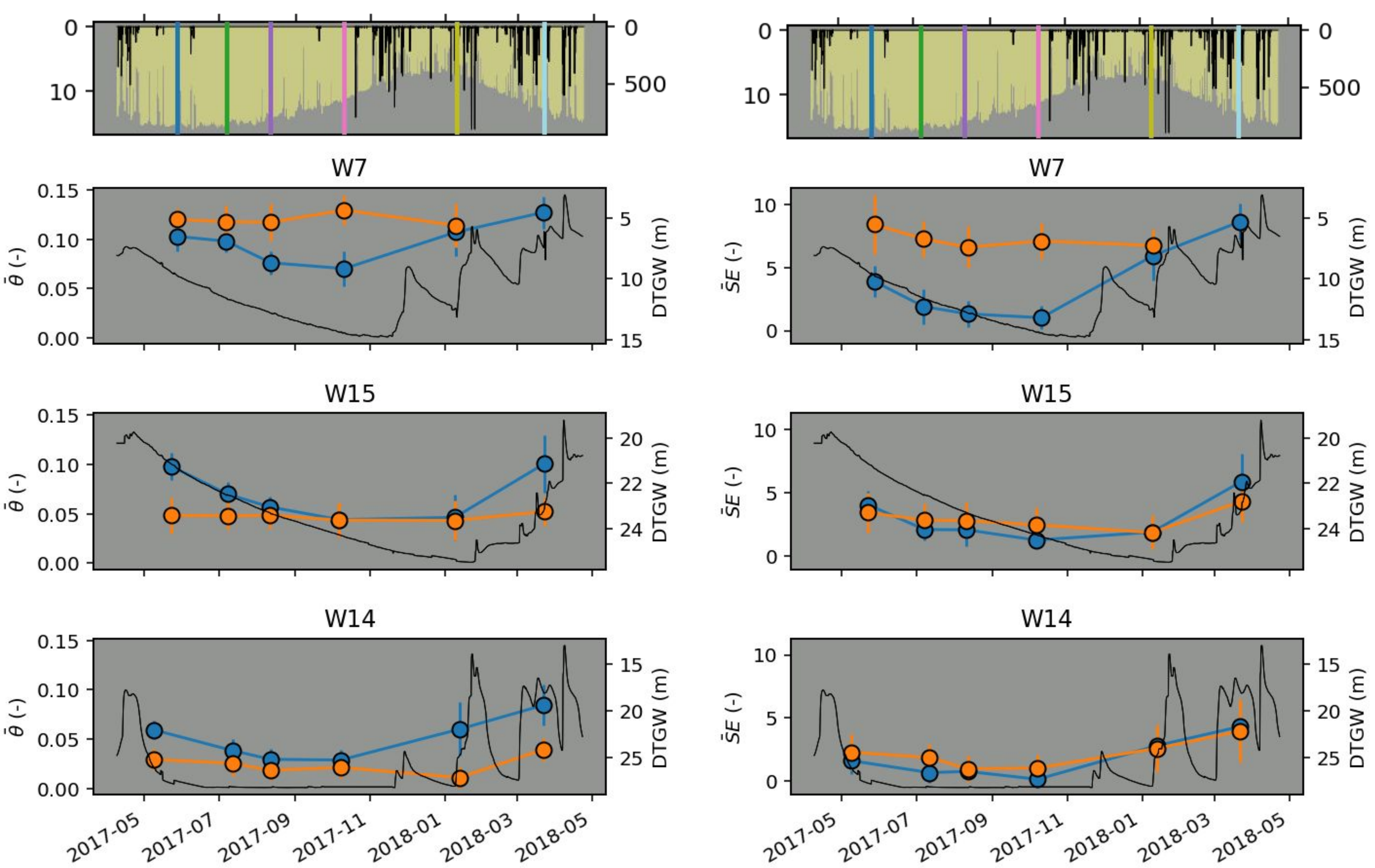
The sum of echoes has important advantages for characterizing NMR relaxation time in unsaturated conditions

NMR characteristic curves describe the relationship between T2 relaxation times as a function of water content and can be used to infer differences in material properties



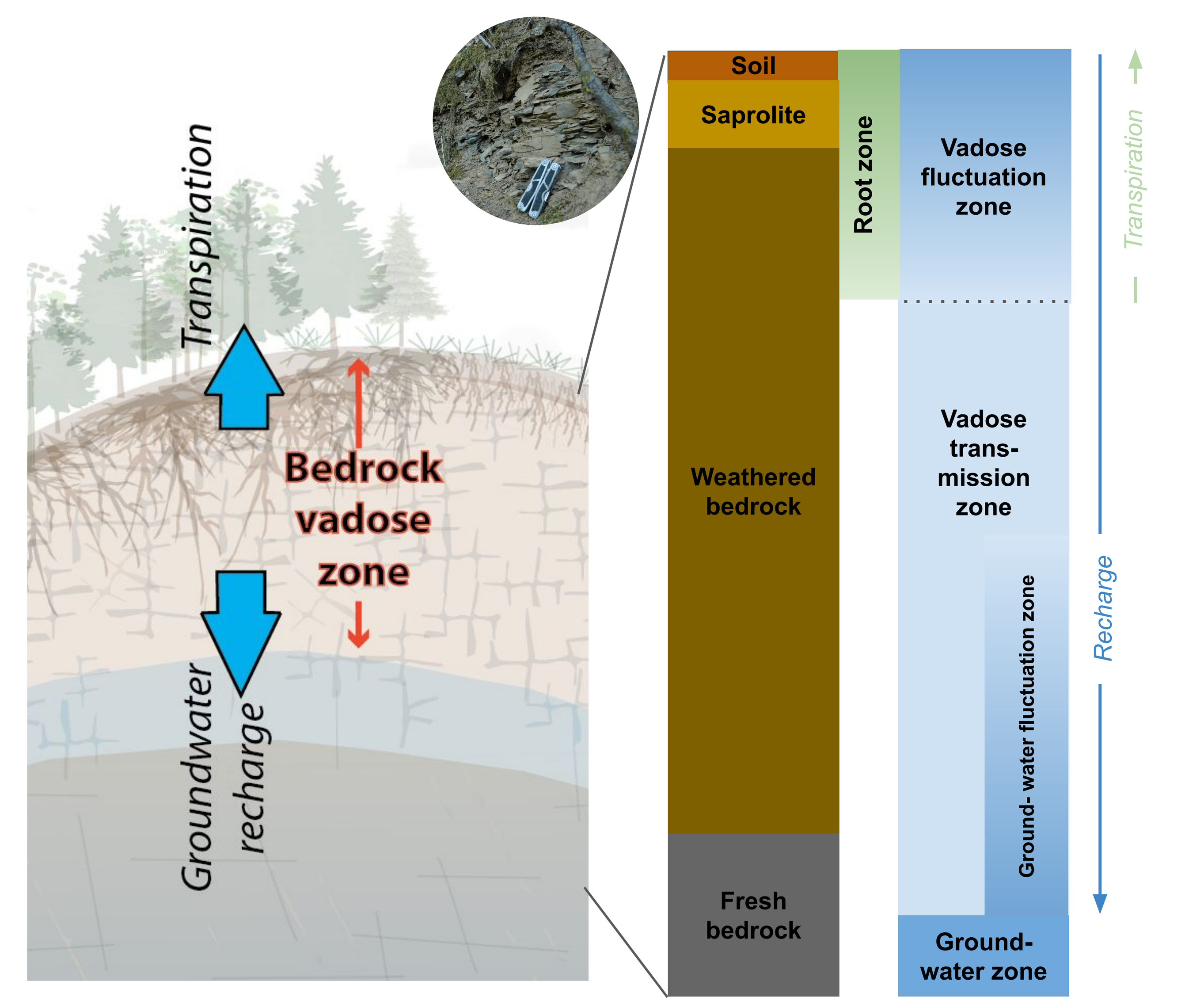






- Used repeat **borehole nuclear magnetic resonance** well logging to monitor **unsaturated water content changes** in highly weathered mud-rich bedrock within a hillslope in seasonally dry Northern California
- Unsaturated water storage in the upper 6 m of bedrock is seasonally dynamic (vadose fluctuation zone). Unsaturated storage in deeper bedrock is seasonally non-dynamic (vadose transmission zone).
- Goal is to interrogate this behavior via link between NMR relaxation and pore structure and water potential
- **Low signal to noise**, resulting from low water contents, precluded conventional inversion processing approach
- Opted for simple, convenient processing approach: the **sum of echoes**

- Sum of echoes has **improved contrast and precision** relative to other NMR products, making it
- Deep, non-dynamic unsaturated water storage is associated with longer relaxation times than shallow, dynamic storage, for the same water content
- In the deepest wells, evidence that the sum of echoes is sensitive to groundwater recharge in the transmission zone



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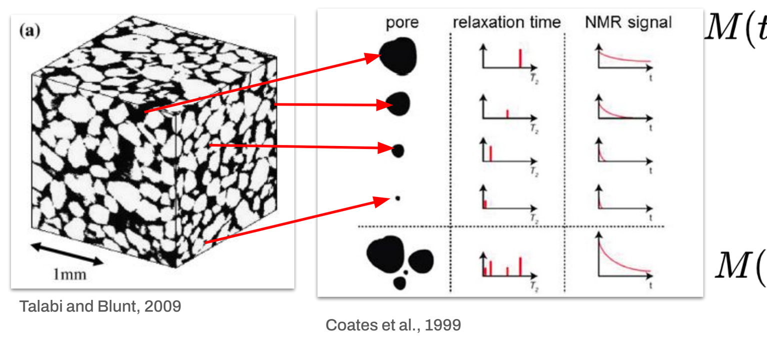
Acknowledgements

This work was supported by the Keck Foundation, the National Science Foundation (EAR 1331904 for the Eel River Critical Zone Observatory), and the University of California Reserve System. Special thanks to Jesse Hahm, Kelsey Crutchfield-Peters, Amy De Luna, Miranda Wiebe, and the Critical Zone Observatory Network for their continued support in the field. Your sore legs are appreciated.



$$M(t)_{\text{single pore}} = \mathbf{M}(0)\exp\left(\frac{-t}{T_2}\right)$$

$$M(t)_{\text{pore dist.}} = \sum_i \mathbf{M}_i(0)\exp\left(\frac{-t}{T_{2i}}\right)$$