Characterizing the Critical Zone Using Borehole and Surface Nuclear Magnetic Resonance

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Understanding critical zone (CZ) structure below the first few meters of Earth’s surface is challenging and yet important to understand hydrologic and surface processes that influence life on Earth. Nuclear magnetic resonance (NMR) is an emerging geophysical tool that can quantify the volume of groundwater and pore-scale properties. Nuclear magnetic resonance has potential to aid in CZ studies, but it can be difficult to collect high-quality NMR data in weathered and fractured rock. We present data from seven surface NMR soundings and six borehole NMR profiles collected on a weathered and fractured granite in the Laramie Range, Wyoming. First, we show that it is possible to collect high-quality surface NMR data in a fractured rock. Second, we use the NMR data to delineate the weathering profile into three distinct zones—unsaturated saprolite, saturated saprolite, and fractured rock—and show that the surface NMR signal is dominated by saturated saprolite. Third, we show that lateral heterogeneity significantly reduces the surface NMR signal magnitude, which suggests that the boundary dividing saprolite and fractured rock is laterally heterogeneous. The NMR measurements, when combined with previously collected seismic refraction data, provide a unique opportunity to define the lateral heterogeneity of the boundary dividing saprolite and weathered bedrock in an eroding landscape underlain by crystalline rock.

Abbreviations: CZ, critical zone; NMR, nuclear magnetic resonance.

At Earth’s surface, rock is bombarded by water, battered by wind, and subject to fluctuations of temperature. These atmospheric forces drive chemical, physical, and biological processes that transform rock into soil (Schwartzman and Volk, 1989; Lebedeva and Brantley, 2013; Riebe et al., 2017), shape landscapes (Allen, 2008), and generate porosity (Brimhall and Dietrich, 1987; Graham et al., 2010; Navarre-Sitchler et al., 2015). The layer of Earth that experiences changes driven by interactions with the atmosphere is part of the critical zone (CZ), which extends from the treetops to unaltered bedrock (National Research Council, 2001; Brantley et al., 2006; Grant and Dietrich, 2017). The geochemical reactions and physical processes that occur in the CZ produce a subsurface structure that controls surface–groundwater interactions (Montgomery et al., 1997; Jencso et al., 2010; Voltz et al., 2013), the timing and delivery of runoff, the chemistry of rivers and streams (Anderson et al., 1997; Hood et al., 2006; Andermann et al., 2012), and the geometry of shallow groundwater aquifers, especially in crystalline rocks (Wright and Burgess, 1992; Dewandel et al., 2006; Chandra et al., 2012). In unweathered crystalline rocks, porosity is typically less than a few percentage points (Sousa et al., 2005; Novakova et al., 2012). As a result, groundwater will most likely be held in weathered material and bedrock fractures (Pavich, 1989; Caine and Tomusiak, 2003; Ayraud et al., 2008; Katsura et al., 2014).

Weathering profiles in crystalline environments are commonly divided into four layers: soil, saprolite, fractured rock, and unaltered bedrock (Pavich, 1989; Anderson et al., 2007, 2012; Befus et al., 2011). Saprolite is a material that has been significantly chemically altered but still retains the physical structure of the parent material (Lebedeva et al., 2007; Riebe and Granger, 2013; Langston et al., 2015). The fractured rock layer

Original Research

Core Ideas
- Unsaturated saprolite, saturated saprolite, and fractured rock have unique NMR responses.
- Surface NMR signals will be dominated by water in saturated saprolite.
- The heterogeneous nature of fractured rock results in low-amplitude surface NMR signals.
has the highest fracture density near the saprolite boundary and decreases away from this boundary (Wyms et al., 2004; Ayraud et al., 2008; Flinchum et al., 2018b). Unaltered bedrock occurs at a depth where the fracture density is low enough to prevent meteoric water from being circulated, limiting chemical reaction rates. The deeper layers of the CZ are inaccessible without drilling, geophysical methods, or road cuts and, as a result, the physical, hydrological, and chemical characteristics of the deep CZ are difficult to quantify, especially across large spatial scales.

Near-surface geophysical methods are advantageous for CZ characterization because they can image the subsurface across large spatial scales (e.g., Parsekian et al., 2015; Robinson et al., 2008). The CZ has been successfully imaged using seismic refraction (Gburek et al., 1999; Befus et al., 2011; Holbrook et al., 2014; St. Clair et al., 2015; Flinchum et al., 2018b), electrical resistivity (Chandra et al., 2004; Olona et al., 2010; McClymont et al., 2011; Leopold et al., 2013), and ground-penetrating radar (Grasmueck, 1996; Bradford et al., 2009; Orlando et al., 2016). However, the tradeoff for high spatial coverage is that the hydrological, geochemical, or physical properties of interest must be inferred from geophysical parameters, which is one reason why observations from drilling are used to aid in the interpretation of geophysical datasets (Gev et al., 1996; Beauvais et al., 2004; Katsura et al., 2014; Orlando et al., 2016; Flinchum et al., 2018b). Because the boundary dividing weathered and unweathered bedrock has been associated with a change in hydrologic properties (Maher, 2010; Rempe and Dietrich, 2014), nuclear magnetic resonance (NMR) may provide additional insights about the physical and hydrologic properties of this important CZ boundary.

Nuclear magnetic resonance is favorable for characterizing groundwater because the magnitude of the signal is dependent on the volume of groundwater and, under most geologic conditions, the signal characteristics can be related to the surface/pore volume ratio (Gallagher et al., 1988; Mohrke and Yaramanci, 2008; Keating and Falzone, 2013; Falzone and Keating, 2016a), which has been shown to be related to hydraulic conductivity (Timur, 1969; Kenyon, 1997; Walsh, 2008; Weller et al., 2010). The use of surface NMR to characterize fractured rock systems is uncommon due to (i) the low water content of unweathered crystalline rock (average matrix porosity less than ~5%; Begonha and Braga, 2002; Goodfellow et al., 2016), (ii) the presumed presence of magnetic gradients caused by Fe minerals commonly present in igneous rocks, which are expected to distort the surface NMR signal (e.g., Grunewald and Knight, 2011), and (iii) lateral heterogeneities of fracture networks, which break the common layered assumption used in surface NMR forward modeling (Legchenko et al., 2006; Müller-Petke et al., 2016). Previous surface NMR studies in crystalline rocks have yielded low signal amplitudes and thus low signal/noise ratio datasets (Wyms et al., 2004; Baltassat et al., 2005; Legchenko et al., 2006; Vouillamoz et al., 2014). As a result, the NMR signal characteristics of weathered granite are not well characterized.

This study utilized seven surface NMR soundings and six borehole NMR profiles collected in a weathered and fractured granite in the Laramie Range, Wyoming, to answer the following questions:

1. Can high-quality surface NMR data be acquired given the low water content of fractured rock aquifers?
2. Will the magnetic field gradients often associated with granite cause the relaxation times acquired by surface NMR systems to be artificially shorter?
3. What are the distinct NMR signal characteristics of the CZ?
4. What additional information can NMR provide about the saprolite and weathered bedrock interface?

Site Description

The study site is located in an unglaciated, weathered and fractured granite watershed in the Laramie Range, Wyoming (Fig. 1). The site is part of the Sherman batholith, which is composed of 1.4 Gyr granitic rocks (Frost et al., 1999). The area is characterized by gentle, undulating topography that stands out against the rugged peaks of the Rocky Mountains (Eggler et al., 1969; Bradley, 1987; Evanoff, 1990; Chapin and Kelley, 1997). The gentle topography is thought to be a result of deep weathering that occurred during the Eocene, when the climate was much warmer and wetter (Moore, 1960; Mears, 1993; Gregory and Chase, 1994). Outcrop is limited within our study area, but outcrops ~1 km northeast of the study show a clear fracture orientation that has a strike of approximately 50° (Fig. 1b; Novitsky et al., 2018). Underneath the ridge at our study site, the water table is between 12 and 13 m below the ground surface (Flinchum et al., 2018a). An ephemeral stream with numerous beaver ponds in the southern drainage peaks reach runoff between April and June. In the northern valley, the water table comes to the surface during peak runoff and then retreats to approximately 3 m below the surface.

The Sherman batholith hosts three distinct granites: the Lincoln, the Sherman, and porphyritic granite (Geist et al., 1989; Frost et al., 1999; Edwards and Frost, 2000). The Sherman granite is coarse grained and has the highest concentrations of Fe and K. The Lincoln granite is finer grained and has more quartz and plagioclase. The porphyritic granite is the darkest of the three varieties, contains large phenocrysts, often hosts mafic enclaves, and contains pyrrhotite (FeS). Although our study area is mapped uniformly as Sherman granite (Ver Ploeg and McLaughlin, 2010), all three granite types exist within the study area (Flinchum et al., 2018b). The study site also contains six boreholes drilled into the underlying bedrock (Fig. 1). Of the six, one (BW-4) is drilled into the porphyritic granite. This borehole is located near the center of a large magnetic anomaly in the eastern part of the study area (Fig. 1a).

An extensive seismic refraction study revealed that the boundary dividing saprolite and weathered bedrock broadly mimicked the topography and was thickest under the ridge and thinnest under the valleys. The fresh bedrock boundary was an inverted image of the topography and went as deep as 55 m below the ridge (Flinchum et al., 2018b). Geophysical porosity estimates showed
that the saprolite, fractured bedrock, and unaltered bedrock had porosities of $0.34 \pm 0.06$, $0.15 \pm 0.05$, and $0.03 \pm 0.02 \text{ m}^3 \text{ m}^{-3}$, respectively (Flinchum et al., 2018a).

We were able to achieve low noise conditions (1–3.2 nV) for all of the surface NMR soundings (Table 1). All of the surface NMR measurements were collected on top of a ridge that dips gently to the east at approximately $3^\circ$ (Fig. 1a). The ridge crest lies about 15 m above the valley floor to the east, and the ridge has an average width of $\sim 200$ m (Fig. 1). The hillslope was gentle enough to place flat loops on the ground, fulfilling the assumption of a flat loop required by the inversion codes.

**Methods**

**Nuclear Magnetic Resonance**

Nuclear magnetic resonance capitalizes on the fact that protons, when immersed in a magnetic field, possess a non-zero magnetic moment. In the Earth’s crust, the magnetic moment is produced by H protons in the groundwater. At equilibrium, the magnetic moment aligns itself with the direction of a background magnetic field and oscillates at a particular frequency called the Larmor frequency ($f_0$). The Larmor frequency is a function of the static magnetic field strength ($B_0$) and the proton gyromagnetic ratio ($\gamma = 0.2675 \times 10^9 \text{ s}^{-1} \text{ T}^{-1}$):

$$f_0 = \frac{\gamma}{2\pi} |B_0| \quad [1]$$

An NMR measurement is made by transmitting an excitation pulse at the Larmor frequency through a saturated material. The excitation pulse causes the precession of the magnetic moment around the central axis of the background magnetic field. Ideally, the excitation pulse tips the magnetic moment of the protons perpendicular to the background magnetic axis; this direction represents the farthest point from equilibrium. When the excitation pulse ends, the protons return to equilibrium in a process called relaxation. During relaxation, the protons produce a measurable resonating magnetic moment that decays exponentially (Bloch, 1946; Torrey, 1956; Brownstein and Tarr, 1979). The transverse relaxation time is described by the $T_2$ term and is expressed in units of time. The initial magnitude of the signal is directly proportional to the number of protons excited, which in near-surface exploration are assumed to come from the groundwater, and the rate of decay (i.e., the length of $T_2$) is related to the pore size. For a thorough review of NMR theory, see Behroozmand et al. (2015) and textbooks dedicated to the theory of NMR (Coates et al., 1999; Levitt, 2001; Dunn et al., 2002).

The transverse decay rate described by $T_2$ is a function of two distinct processes: the bulk relaxation and the surface relaxation (Brownstein and Tarr, 1979; Cohen and Mendelson, 1982; Grunewald and Knight, 2011). The surface relaxation is influenced...
by the surface relaxivity—an intrinsic property describing the material’s ability to intensify relaxation—and the surface/pore volume ratio of the pore space. This dependence is what relates the NMR decay to pore-scale properties. In general, materials with larger pore spaces have longer $T_2$ relaxation times (e.g., gravels), and materials with smaller pores have shorter $T_2$ relaxation times (e.g., clays). It is necessary to have an accurate estimate of the $T_2$ distribution (multi-exponential) or $T_2$ value (mono-exponential) to link the NMR measurement to the hydraulic conductivity and pore-scale properties.

In practice, accurately measuring the $T_2$ relaxation time can be difficult because there are three main challenges to overcome. The first is that the presence of magnetic gradients within a material cause the protons to oscillate at slightly different Larmor frequencies. The slight variations in Larmor frequencies caused by magnetic field heterogeneities or magnetic grains cause the protons to diphase during relaxation, creating a more rapid decay of the measurable signal, which is associated with the magnetic gradients, not material properties (Mitchell, 2010; Grunewald and Knight, 2011, 2012; Walbrecker et al., 2014).

The remaining two challenges are specific to surface NMR. Because surface NMR uses the same loop to transmit and to record the signal, there is a window of time after transmission where the instrument cannot record the response—referred to as the dead time. The dead time limits surface NMR’s ability to measure materials with short $T_2$ relaxation times or regions characterized by large magnetic gradients. Furthermore, surface NMR signals are small. A bandpass filter is often applied to increase signal/noise ratios, but the dead time increases as the width of the bandpass filter narrows. Lastly, surface NMR uses a single pulse and then records the relaxation—referred to as a free induction decay (FID) measurement. The free induction decay is the standard pulse sequence used in surface NMR because it is quick to collect, provides the best depth penetration, and produces reliable water content profiles (Grombacher et al., 2014a; Grombacher and Auken, 2018). An implicit assumption with the free induction decay measurement is that relaxation begins only after the transmitting pulse has ended, but with the longer pulses (20–40 ms) used in surface NMR measurements, relaxation occurs during the excitation pulse. If unaccounted for, the relaxation during the pulse can cause underestimation of the true water content (Walbrecker et al., 2009; Grombacher et al., 2017). We accounted for relaxation during the pulse by providing an additional 10 ms (half of the 20-ms pulse length) prior to the shutdown pulse, following the methods of Walbrecker et al. (2009). The method is equivalent to adding 10 ms to the effective dead time (Table 1).

In this study, we used both borehole and surface NMR. There are two notable differences between the two measurements. The first is the volumes throughout which the measurements are conducted: borehole NMR measures localized volumes on the order of 10s of cubic centimeters in the shape of cylindrical shells around the borehole. In contrast, the volumes measured by surface NMR are on the order of 10s to 1000s of cubic meters depending on the loop geometry, pulse duration, and the underlying electrical conductivity structure. The second notable difference is that surface NMR measures the $T_2^*$ relaxation time, which includes the effects of magnetic variation, and borehole NMR measures $T_2^*$ relaxation time. The borehole NMR is able to measure $T_2^*$ because it carries onboard magnets to ensure a uniform magnetic field and utilizes a Carr–Purcell–Meiboom–Gill pulse sequence that compensates for the dephasing caused by magnetic gradients (Carr and Purcell, 1954; Melboom and Gill, 1958). The $T_2$ and $T_2^*$ relaxation times are related through the $T_{21H}$ relaxation time, which is used to quantify the effect of magnetic field heterogeneity. The relationship between $T_2$ and $T_2^*$ is

$$T_2^* = T_2 + T_{21H}^{-1}$$

where $T_{21H}^{-1}$ describes all of the dephasing effects caused by magnetic heterogeneities. Dephasing by magnetic heterogeneities complicates the relationship between the measured decay and pore-scale properties by masking the material’s true relaxation time. Theoretical studies have tried to quantify $T_{21H}$ (Grunewald and Knight, 2011, 2012), but without an independent measurement of $T_2$—usually a co-located downhole NMR measurement—$T_{21H}$ is difficult to calculate. In the absence of a borehole measurement, $T_{21H}$ can be estimated using the variation in the Earth’s

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Table 1. Geometric and noise information for the surface NMR soundings.

<table>
<thead>
<tr>
<th>Sounding (west to east)</th>
<th>Strike (from true north)</th>
<th>Stacks</th>
<th>Pulse moments</th>
<th>Noise floor</th>
<th>Max. amplitude</th>
<th>Effective dead time†</th>
<th>Max. water content</th>
<th>Depth</th>
<th>Signal/noise ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>S5</td>
<td>105</td>
<td>22</td>
<td>36</td>
<td>1.0</td>
<td>30</td>
<td>7.3</td>
<td>2.7</td>
<td>13.5</td>
<td>29</td>
</tr>
<tr>
<td>S6</td>
<td>92</td>
<td>22</td>
<td>36</td>
<td>1.1</td>
<td>35</td>
<td>7.2</td>
<td>2.3</td>
<td>17.5</td>
<td>25</td>
</tr>
<tr>
<td>S10</td>
<td>63</td>
<td>22</td>
<td>36</td>
<td>2.6</td>
<td>50</td>
<td>7.1</td>
<td>4.1</td>
<td>15.5</td>
<td>19</td>
</tr>
<tr>
<td>S7</td>
<td>34</td>
<td>22</td>
<td>36</td>
<td>1.1</td>
<td>60</td>
<td>7.2</td>
<td>4.7</td>
<td>15.0</td>
<td>54</td>
</tr>
<tr>
<td>S8</td>
<td>32</td>
<td>18</td>
<td>20</td>
<td>3.2</td>
<td>60</td>
<td>7.1</td>
<td>3.1</td>
<td>16.0</td>
<td>19</td>
</tr>
<tr>
<td>S11</td>
<td>96</td>
<td>16</td>
<td>36</td>
<td>0.8</td>
<td>35</td>
<td>7.6</td>
<td>2.7</td>
<td>20.5</td>
<td>44</td>
</tr>
<tr>
<td>S9</td>
<td>103</td>
<td>20</td>
<td>20</td>
<td>2.0</td>
<td>50</td>
<td>7.1</td>
<td>5.1</td>
<td>17.0</td>
<td>25</td>
</tr>
</tbody>
</table>

† Calculated by adding the instrument dead time and the additional time caused by bandpass filtering.
magnetic field across the loop (Chen et al., 2005; Müller et al., 2005; Grunewald and Knight, 2011):

\[ T_{21H}^{-1} \approx \frac{\gamma}{2\pi} \Delta B \]  

We collected surface NMR data with a Vista Clara GMR, which can record ambient noise on up to three channels (Walsh, 2008). The ambient recordings are used to cancel out background noise (Walsh, 2008). All of the surface NMR soundings in this study used 46-m-diameter figure-eight loops, a 20-ms excitation pulse, and two noise loops of approximately the same shape, size, and orientation (Fig. 2a). We stacked each pulse moment between 16 and 22 times (Table 1). We inverted the surface NMR data with a mono-exponential decay using MRSMatlab with a magnetic inclination of 67.4 (Mueller-Petke and Yaramanci, 2010; Müller-Petke et al., 2016). Before inverting each sounding, we applied a 500 Hz bandpass filter (centered at the Larmor frequency) to the noise-canceled data. The orientation of each loop was taken relative to true north and then adjusted to magnetic north using a declination of 8.8. To quantify uncertainty, a bootstrap algorithm built into MRSMatlab was used, where a random subset of data was extracted and inverted 150 times (Hertrich, 2008; Mueller-Petke and Yaramanci, 2010; Müller-Petke et al., 2016). The final results shown here are the average of all 150 inversions.

We acquired downhole NMR measurements in Boreholes BW-1, BW-2, BW-4, BW-5, BW-6, and BW-7 (Fig. 1) using a Javelin JP350 probe (Vista Clara NMR Geophysics; Walsh et al., 2013) in late August and early September 2016 (Table 2). The Javelin probe quantifies water content and \( T_2 \) relaxation times in four cylindrical shells of varying radii (14.0, 15.9, 17.8, and 19.7 cm). We collected the data at 0.5-m depth intervals. The downhole NMR measurement utilizes two recovery times \( (T_R) \):

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
\textbf{Borehole} & \textbf{Casing depth} & \textbf{Date NMR collected} & \textbf{Water depth} & \textbf{Date of water level} & \textbf{Method} \\
\hline
\hline
\end{tabular}
\caption{Key acquisition dates and measurements at the boreholes.}
\end{table}
the first is optimized for short relaxations ($T_2^* = 800 \text{ ms}$) and the second is optimized to capture long relaxations ($T_2^* = 4000 \text{ ms}$). The Javelin probe uses a Carr–Purcell–Meiboom–Gill pulse sequence with echo spacing of 700 $\mu$s. The average number of stacks for the short relaxations was 72, and the average number of stacks for the longer relaxations was 20.

To improve the signal/noise ratio, the Vista Clara software has the ability to apply a moving average filter to combine vertical measurements (Walsh et al., 2013). We inverted measurements by stacking the four different radii and five measurements vertically (2-m vertical average window). We selected this moving average filter because it increased the signal/noise ratio by a factor of three. We also processed 20 m of BW-6 and BW-4 without the spatial averaging filter due to sufficiently high signal/noise ratios to investigate the transition between saprolite and fractured rock. To help interpret the NMR measurements, we recorded water depths by hand or by a pressure transducer in all of the boreholes (Table 2).

Magnetic Data
We collected magnetic data using a Geometrics G858 cesium vapor magnetometer. Data were well constrained within the study area (Fig. 1a). All measurements were diurnally corrected to the Boulder Geomagnetic Observatory, which is located $\sim 175 \text{ km}$ south of the study site. Prior to interpolation, we averaged data across a 5-m grid and then interpolated the magnetic field values to a 5- by 5-m grid using a continuous curvature with a spline-interpolation algorithm (Smith and Wessel, 1990) (Fig. 1a). For all seven surface NMR soundings, we calculated the Larmor frequency (Eq. [1]) by averaging magnetic field readings from the center of the circle in the figure eight as well as a reading from the intersection of each circle. The total field map integrates all vertical magnetic variations and illustrates how these changes vary spatially across our study area. The magnetic survey shows a 300-nT gradient that runs roughly west to east (Fig. 1). This change in the magnetic field would be associated with a change in the Larmor frequency of $\sim 10 \text{ Hz}$ (Fig. 1).

Results
Surface Nuclear Magnetic Resonance
Using a figure-eight loop and noise-loop configuration (Fig. 2a), we were able to achieve a high-quality signal and observe exponential decay across a swath of pulse moments (Fig. 2b–2e). Despite small signal amplitudes, all seven soundings showed signal/noise ratios $>18$ (the maximum amplitude divided by the average amplitude of the noise after 500 ms; Table 1). Across the span of approximately 500 m from west to east, the NMR soundings showed variability in both $T_2^*$ and water content (Fig. 3). The highest inverted water content was $0.05 \text{ m}^3 \text{ m}^{-3}$ (at S9; Fig. 3h), and the minimum inverted water content was $0.02 \text{ m}^3 \text{ m}^{-3}$ (at S6; Fig. 3c). In general, the inverted water contents increased from west to east. This increase in water content is visible not only in the inversion results but also in the amplitude of the signal (Fig. 3). In all of the surface soundings, the strongest signal occurred in pulse moments with values $<0.5 \log_{10}(A \text{ s})$, indicating a loss of water content with increasing depth (Fig. 3).

The $T_2^*$ values varied from west to east (Fig. 3). In Soundings S5 and S6, the $T_2^*$ curves are characterized by short relaxation times at all depths. The longer relaxation times in Soundings S10, S7, and S8 all occurred within a depth range between 11 and 18 m. The long relaxation times changed as the soundings moved east; the maximum $T_2^*$ values increased abruptly at S10, peaked at S7 to S8, and then decreased again at S9 (Fig. 3). The long $T_2^*$ relaxation times at S10 (247 ms), S7 (297 ms), S8 (366 ms), S11 (240 ms), and S9 (131 ms) are all consistent in shape and have a thickness of $\sim 7 \text{ m}$ (red dashed lines in Fig. 3). The two easternmost soundings (S9 and S11) have longer relaxation times than the two westernmost soundings but are shorter than those of Soundings S10, S7, and S8.

Borehole Nuclear Magnetic Resonance
We collected six downhole NMR profiles within the study area (Fig. 4). We refer here to the mean $T_2$ values ($T_{2\text{ML}}$), which are the mean values of the multi-exponential fit (white and gray lines in Fig. 4). This decision was made because we inverted the surface NMR data with a mono-exponential fit. Although the surface NMR data were high quality (Table 1), it has been argues that the signal/noise ratio should be $>60$ before applying multi-exponential analysis (Lubczynski and Roy, 2003; Boucher et al., 2011). Therefore, using $T_{2\text{ML}}$ does two things: it allows a more direct comparison between the surface and borehole NMR datasets, and it simplifies discussion. An assumption built into this decision is that the mono-exponential decays derived from the surface NMR are equivalent to the mean $T_{2\text{ML}}$ value.

Because of small signal amplitudes across the six boreholes, the inversions were run with the 2-m spatial average filter described above. The filter allowed us to have a reliable and robust comparison among all of the boreholes (Fig. 4) and data smoothed out the $T_{2\text{ML}}$ values (Fig. 4) but provided a threefold increase in the signal/noise ratio. This increased the reliability and the robustness of the inversions at the loss of some spatial resolution. Borehole BW-1 is not a complete profile because it was cased in steel to 16.5 m below the surface, so the top of the NMR profile shown in BW-1 (Fig. 4f) is from a Geoprobe hole 11 m west of BW-1. Water content for all boreholes ranged from $\sim 0.02$ to $\sim 0.34 \text{ m}^3 \text{ m}^{-3}$. In the four boreholes that penetrated $>30$ m (BW-5, BW-7, BW-6, and BW-4), the water contents below 30 m were $<0.08 \text{ m}^3 \text{ m}^{-3}$. In BW-5, there is a region between 10- and 17-m depth that showed longer $T_{2\text{ML}}$ relaxation times up to 293 ms. Boreholes BW-7 and BW-6, which lie $\sim 20$ m apart, have similar water contents and $T_2$ distributions, and both showed a large peak in water content and $T_2$ relaxation times around the 16-m depth (Fig. 4c and 4d). Other than BW-6 and BW-7, the $T_2$ distributions and water contents showed significant variation and do not have similar structure.

The most notable feature in the downhole NMR data is the high water contents and long $T_{2\text{ML}}$ values that occurred around...
Fig. 3. Surface nuclear magnetic resonance (NMR) results for all seven soundings in the study area, organized such that the westernmost sounding is at the top and the eastern sounding is at the bottom right corner: (a) a map showing the location of the center of each figure-eight loop; (b–h) for each sounding, the left profile is the water content as a function of depth, the middle plot is the $T_2^*$ distribution (linear scale), the two right color plots show the raw data (top) and the difference between the observed and modeled data (bottom) with gray lines showing the inversion results from the 150 models derived from bootstrapping (Müller-Petke et al., 2016) and black lines showing the average of the 150 runs: (b) S5, (c) S6, (d) S10, (e) S7, (f) S8, (g) S11, and (h) S9.
the 15-m depth in BW-6 and BW-7. This region of high water contents and long $T_{2\text{ML}}$ values is approximately 3 m thick and started at ~14-m depth and ended at ~17 m (Fig. 4c and 4d). A zone of high water content (0.24–0.27 m$^3$ m$^{-3}$) is seen at BW-6 and BW-7 about 4 m below the surface, despite being 9 to 10 m above the water table. These shallow high water contents (>0.15 m$^3$ m$^{-3}$) have short $T_{2\text{ML}}$ values (<7 ms; Fig. 4c and 4d). Boreholes BW-6 and BW-7 are within 20 m of each other, so similarities might be expected (Fig. 1). However, BW-1 is within 30 m of both BW-6 and BW-7 and is notably different because it is missing the high amplitude but low $T_{2\text{ML}}$ values above the water table. Unfortunately, because BW-1 was cased in steel, we do not know if the high water contents and long $T_{2\text{ML}}$ that exist at BW-6 and BW-7 also exist at BW-1. Borehole BW-4 is approximately 70 m away (less than the diameter of the long axis of the figure-eight loop) from BW-1 and has a completely different profile. Borehole BW-4 has much less water than BW-6 and BW-7 and has a region from 10- to 20-m depth with signs of long $T_2$ relaxation times. The lack of similarity between the $T_2$ distributions and water contents (except BW-6 and BW-7) across <100 m demonstrates the heterogeneous nature of fractured rock aquifers. This might be expected because fractured zones are not expected to be laterally continuous.

**Discussion**

**Addressing the Challenges of Surface NMR in a Fractured Environment: $T_{2\text{IH}}$ Calculation**

In crystalline rock, the common assumption that $T_2^*$ is directly related to pore-scale properties (i.e., $T_2^* \approx T_2$) may not be valid because of the presence of Fe oxides (Legchenko et al., 2002; Grunewald and Knight, 2012; Walsh et al., 2014). Iron(III) in Fe oxides like hematite and goethite can reduce $T_2$ relaxation times...
Along the long axis of the figure-eight loop, $S_{11}$ had a well-
quantified by the inhomogeneity term is quantified by the $T_{21H}$ term (Eq. [2]).
Furthermore, if a material has a high magnetic susceptibility, the relationship between $T_2^*$ and pore size diminishes because the $T_2^*$ decay becomes dominated by the dephasing and not by the pore-scale properties.
We compared the $T_2^*$ values from a surface NMR sounding with $T_2^*$ values measured from the downhole NMR to determine if the relaxation times we observed were caused by pore-scale properties and not induced by magnetic heterogeneities. We compared the maximum mean $T_{2ML}$ value from BW-6 on the vertically averaged data (348 ms at 15 m) and unfiltered data (773 ms at 15 m), and the maximum $T_2^*$ value from S11 (238 ms at 14 m) and S9 (132 ms at 17 m). Sounding S11 had the figure-eight loop centered on BW-6, while S9 was centered on BW-1 approximately 20 m to the east. We selected these values because we assumed that they were originating from the same subsurface feature. We calculated the range of $T_{21H}$ values using Eq. [2]. We found that $T_{21H}$ ranged between 159 and 750 ms. If $T_{21H}$ is on the lower end of the spectrum, our measured $T_2^*$ values are probably underestimated, especially for materials with long $T_2^*$ relaxation times. On the other hand, if $T_{21H}$ is on the upper end of our range, the maximum $T_2^*$ values of $\sim$770 ms (in the unfiltered case) would be only slightly affected. In reality, the true value of $T_{21H}$ is probably somewhere in the middle of our estimated range. Our data suggest that the magnetic field heterogeneities have the potential to impact our observed $T_2^*$ values, but given that S11 was centered on BW-6 and that the 2-m vertical averaged NMR data are more robust and imitate a slightly upscaled measurement, we believe that $T_{21H}$ is closer to the values on the upper end of our range. Therefore, the $T_2^*$ values derived from surface NMR can be used to quantify the NMR response of the weathering profile.

In cases without a coincidental borehole NMR profile, $T_{21H}$ can be estimated using the change in the magnetic field magnitude (Müller et al., 2005; Grunewald and Knight, 2011). Along the long axis of the figure-eight loop, S11 had a well-constrained change of 32 nT (Fig. 1). This change in the total field would lead to an approximate $T_{21H}$ value of 733 ms (Eq. [3]) which is on the high end of our estimated range. Thus, the change in magnetic field across the diameter of the loop is a good approximation for the $T_{21H}$ term in the absence of a borehole NMR profile. In fractured rock environments, having a high-resolution magnetic map to estimate $T_{21H}$ is beneficial.

To better understand the origin of the decays measured by the surface NMR, we utilized forward modeling from the MRS Matlab package (Mueller-Petke and Yaramanci, 2010; Müller-Petke et al., 2016). To generate a forward model, we extracted the $T_{2ML}$ values and water contents from borehole NMR logs in BW-6 (Fig. 4d). We vertically averaged the 0.5-m-interval water contents and mean $T_{2ML}$ values to produce a layered model that has a water content and $T_2$ value every meter in depth (Fig. 5a and 5b). We simulated the subsurface response using the loop geometry and pulse moment scheme from S11 and added 10 nV of random Gaussian noise (well above our observed 3.2 nV noise floor). We inverted the subsurface response using the same inversion parameters used on the field data (we show only the average of the 150 inversions for clarity; Fig. 5c and 5d).

The results indicate that the surface inversion reproduces the region of long $T_2$ relaxation times (>200 ms) between a depth range of 11 and 18 m (Fig. 5c). Furthermore, the $T_2$ value was correctly retrieved. The water content profiles lack the region of high water contents (>0.2 m$^3$ m$^{-3}$) above 10 m (Fig. 5b and 5d) because the mean $T_2^*$ relaxation times from BW-6 were too short (<7 ms) to be imaged by the effective 7.6-ms dead time of the surface NMR (Table 1). Other than the large amplitude of water missing above the 10-m depth, the inversion of the modeled data resolves the maximum water content and location of the thin, 3-m-thick $T_2^*$ relaxation time feature (Fig. 5c and 5d). This forward modeling exercise suggests, at least in the region between the 11- and 18-m
depths, that the surface NMR loop geometry, pulse sequence, and inversion parameters can recover the water contents and $T_2^*$ values observed at the borehole—assuming that the structures observed in the borehole NMR are laterally continuous under the loop.

Understanding the Source of the NMR Signal: Saprolite or Fractured Rock?

Due to the lack of high-quality NMR data in fractured crystalline rock environments, the NMR signal characteristics of weathering profiles in crystalline rocks are not well understood. Here we address two questions:

1. What are the relaxation times of saprolite and fractured rock?
2. Will low water contents and the surface NMR instrument dead time limit the ability of surface NMR to successfully quantify water content and pore characteristics in the weathering profile?

Conceptually, saprolite is expected to have high porosity but will only produce an NMR response if there is water in the pore space. For our site, the saprolite porosity has been measured on laboratory samples up to depths of 9 m and ranges between 0.28 and 0.4 m$^3$ m$^{-3}$ (Flinchum et al., 2018a). The weathered bedrock is expected to have water in fractures that could be either open or filled with weathering products, and these fractures would be bound by a rock matrix with significantly lower porosity than the saprolite. Previous studies showed that the matrix porosity of granite ranges between 0.01 and 0.13 m$^3$ m$^{-3}$ (Begonha and Braga, 2002; Sousa et al., 2005; Novakova et al., 2012; Goodfellow et al., 2016).

At BW-6 and BW-4, due to high water contents, we were able to invert the region around the casing contents without the spatial average filter to produce detailed observations of the NMR signal in the region dividing the saprolite and fractured bedrock (Fig. 6 and 7). There are three key observations to highlight from the unfiltered profile at BW-6:

1. The $T_{2\text{ML}}$ relaxation times above the water table were short (<7 ms; Fig. 6a).
2. Approximately 1 m below the measured water level (~14 m), there was a large increase in the $T_{2\text{ML}}$ values between 14.5 and 17 m (Fig. 6a). The $T_{2\text{ML}}$ relaxation time increased to a maximum of 773 ms (when the vertical average filter was applied, this value averaged 348 ms). The water content in this region also increased to a maximum of 0.34 m$^3$ m$^{-3}$ (Fig. 6b).
3. From 17 to 27 m, both water content and $T_{2\text{ML}}$ dropped to an average of 0.04 m$^3$ m$^{-3}$ and 45 ± 37 ms (Fig. 6b and 6a).

From the borehole observations at BW-6, we divided the weathering profile into three distinct regions: unsaturated saprolite, saturated saprolite, and fractured bedrock (Fig. 6c). The uppermost region, unsaturated saprolite, is characterized by short relaxation times ($T_{2\text{ML}}$ ~7 ms) and extends from the surface to the water table at ~14 m. No images of the borehole exist in...
The long Geoprobe in the summer of 2016 are composed of a matrix of feld-the measured water table and the casing depth (times in the vadose zone are thought to be caused by a preference for filling the smallest pores first, which usually have shorter relaxation times (Walsh et al., 2014). Furthermore, the relaxation times can change as a function of saturation and have been shown to exhibit hysteretic behavior (Falzone and Keating, 2016a, 2016b).

The second region, saturated saprolite, is thin and lies between the measured water table and the casing depth (~14–17 m; Fig. 6c). The long $T_{2\text{ML}}$ relaxation times between the 14- and 17-m depths are indicative of materials with large pores and high hydraulic conductivity (Timur, 1969; Kenyon, 1997; Walsh, 2008; Weller et al., 2010). We interpret the region between ~14 and 17 m as saturated saprolite instead of a large fracture zone for three reasons. First, the maximum water content measured by the borehole NMR (0.34 m$^3$ m$^{-3}$) is consistent with the average measured porosity of saprolite (0.34 ± 0.06 m$^3$ m$^{-3}$) based on 25 measurements collected along the ridge in the study area (Flinchum et al., 2018a, 2018b). Second, it occurs just above the casing depth (Fig. 6a), which would have been the depth at which the drillers intersected a solid interface and is assumed to be the top of fractured bedrock. Third, the $T_{2\text{ML}}$ relaxation times are much longer and the water contents much higher than those observed below the casing at BW-4, which is located in pervasively fractured rock (Fig. 7d).

The final unit derived from NMR was fractured rock. Below the casing at BW-6, we observed a drop in $T_{2\text{ML}}$ and low water contents (~0.04 m$^3$ m$^{-3}$) that have localized zones of increased water content that qualitatively appear to be associated with visible fractures in the borehole wall (Fig. 6b and 6d). At BW-4, we see an increase in $T_{2\text{ML}}$ below the casing, probably because the saprolite above the casing is unsaturated. Water contents are higher in BW-4 than in BW-6, which is not surprising given the visible difference in fractures observed in the optical televiewer logs (Fig. 6d vs. 7d). At BW-6, where the borehole wall is relatively unfractured, maximum water contents are on par with porosities reported for weathered granite (Begonha and Braga, 2002; Sousa et al., 2005; Novakova et al., 2012; Goodfellow et al., 2016). Therefore, the fractured rock region will, in general, be defined by low water contents (<0.04 m$^3$ m$^{-3}$) and relaxation times of approximately 40 ms. In regions where the fracture density is high, such as isolated or vertical fracture zones, we might expect higher water contents and longer $T_{2}$ relaxation times. We expected the response of the fractured rock to vary significantly depending on the abundance, aperture, and whether or not the fracture is filled with a weathered material (Nakashima and Kikuchi, 2007; Ren et al., 2018).

The detailed downhole observations at BW-6 and BW-4 can help inform the interpretation of the surface NMR data. First, water content in the unsaturated saprolite, even if it is >0.1 m$^3$ m$^{-3}$, will not be measured by surface NMR because of the low porosity of unfractured bedrock. The saturated saprolite, which is characterized by high water contents (>0.3 m$^3$ m$^{-3}$) and long $T_{2}$ relaxation times (>200 ms), is an ideal target for surface NMR. Despite the region of saturated saprolite being thin (~3 m), our forward modeling suggests that the loop geometry and pulse sequence used by the surface NMR can resolve this thin layer—under the critical assumption that the structure observed at BW-6 is laterally continuous below the loop (Fig. 5). The $T_{2\text{r}}$ values derived from surface NMR are consistent with those reported (between 150 and 300 ms) for the saprolite or fissured layer (they did not differentiate) by Vouillamoz et al. (2014). Third, water in fractured bedrock will be difficult to quantify with surface NMR because of the low porosity of unfractured bedrock.
combined with the heterogeneous nature of fracture zones. We hypothesize that the surface NMR response in weathering granite terrains will be dominated by saturated saprolite.

**Addressing the Challenges of Surface NMR in a Fractured Environment: Low Water Contents**

One of the most puzzling observations that emerged from this unique dataset was the large discrepancy between measured water contents by borehole NMR (\(>0.25\) m\(^3\) m\(^{-3}\) in BW-6 and BW-7) and surface NMR (\(<0.05\) m\(^3\) m\(^{-3}\) in all soundings). We hypothesize that the low water contents are caused by the compartmentalization of water in the fractured rock and the overlying weathered material—specifically saprolite. Compartmentalization occurs in fractured rock systems because the matrix porosity is low (average matrix porosities greater than \(<5\%\) (Begonha and Braga, 2002; Goodfellow et al., 2016). As a result, groundwater will be confined to fractures or held in the higher porosity saprolite. Compartmentalization is tied to the landscape’s evolution and can be difficult to predict on large spatial scales. Furthermore, high porosities can occur in localized regions; an example is the visible fractures observed in BW-4 (Fig. 7d). Moreover, the porosity can be unevenly distributed; the example is the visible difference in fracture density between BW-4 and BW-6, when these sites are only 70 m apart. That is less than the distance that spans the long axis of our figure-eight loops (92 m; Fig. 2). Clearly, the fracture density will not be uniform underneath our loops.

The issue with compartmentalization is that it makes porosity scale dependent. This is critical because of the vastly different scales across which the surface and borehole NMR measurements were taken. At the borehole scale, large porosities can easily be achieved if the sample volume is on the order of a couple of cubic centimeters. But as the sample volume scales up—to a few thousand cubic meters—the porosity will change as a function of the fracture density. Although the excited volumes of surface NMR are nonlinear and hard to quantify, they are large. It is possible that the 46-m-diameter loops used in this study could excite water within structures that were observed in the NMR logs in BW-6 and BW-4. Thus, to explore the idea that groundwater is compartmentalized, we must look at the data in the context of the CZ.

Our study site has been targeted by many geophysical experiments and the CZ structure is well characterized at the hillslope scale (Hayes, 2016; Novitsky et al., 2018; Flinchum et al., 2018a, 2018b; Wang et al., 2019; Keifer et al., 2019). An important boundary in the CZ is the one that divides saprolite and weathered bedrock. At our site, this boundary has been mapped in three dimensions using seismic refraction data and casing depths of six boreholes, along with depths from seven Geoprobe boreholes (13 data points; Flinchum et al., 2018a, 2018b). Through this analysis, Flinchum et al. (2018b) determined that the transition from saprolite to fractured rock coincided with a refraction velocity of \(1.1 \pm 0.2\) km s\(^{-1}\). They argued that the \(1.1\) km s\(^{-1}\) velocity contour, when extracted from a volume of seismic velocities generated by ordinary kriging of 30 seismic refraction profiles, mapped the general location of the saprolite–weathered bedrock boundary (Fig. 8a). Furthermore, this boundary lacked a strong velocity contrast and was therefore interpreted as a vertically heterogeneous or gradational boundary (Fig. 8; Flinchum et al., 2018a, 2018b).

The water contents and \(T_2^*\) distributions from the surface NMR appear to be related to the underlying CZ structure imaged by the seismic refraction data. Comparing the \(T_2^*\) relaxation times on the ridge to the depth of the seismically inferred saprolite–weathered bedrock boundary along a two-dimensional profile down the ridge (Fig. 8b), we observed that the region of long \(T_2^*\) relaxation times occurred near the bottom of the seismically inferred boundary’s region of uncertainty (Fig. 8b). Here, the uncertainty is defined by extracting the contours \(1.1 \pm 0.2\) km s\(^{-1}\). Long relaxation times are absent at S5 but can be observed in S10, S7 and S8, and S11 (Fig. 8b). The water contents also increase from west to east down the ridge (Fig. 8c). The water table measured by hand and reported by Flinchum et al. (2018a) is associated with increased water content observed in six of the seven soundings (Fig. 8c). Although the maximum water contents are small, surface NMR does predict the location of the water table, consistent with other studies in fractured rock aquifers (Wyns et al., 2004; Baltassat et al., 2005; Legchenko et al., 2006; Vouillamoz et al., 2014).

Forward modeling, discussed above, showed that the loop geometry and pulse moment sequence used during surface NMR acquisition could successfully invert for the structure observed in the borehole under the critical assumption of layers with lateral continuity under the loop. The MRSMAtlab one-dimensional forward modeling package is not built for compartmentalized regions of groundwater; it assumes a layered model (Mueller-Petke and Yaramanci 2010; Müller-Petke et al., 2016). Both the seismically interpreted interface (Fig. 8a) and borehole NMR data (Fig. 4) show lateral heterogeneity at the scale of our surface loops, suggesting that a layered model is not appropriate. To improve surface NMR in fractured rock environments, it will be critical for modeling software to model isolated three-dimensional structures under the loops.

To explain the discrepancy in water contents, we must look at where the water is—specifically where the water level intersects the boundary dividing the saprolite (a viable NMR target when saturated) and fracture-dominated weathered bedrock. The seismically inferred boundary extends below the water table east of S7 and S8 (Fig. 8), which would increase the chances of encountering saturated saprolite. Thus, east of S7 and S8, the presence of saturated saprolite would explain our observations of an increase in water content down the ridge (Fig. 3). In contrast, to the west of S7 and S8, the seismically interpreted boundary is entirely above the water table. This would decrease the chances of encountering saturated saprolite, which would result in low water contents and the missing long \(T_2^*\) decays—consistent with our surface NMR observations (Fig. 3).

Discontinuous regions of saturated saprolite could also explain the additional thickness of the \(T_2^*\) profiles in the surface
compared with the borehole NMR profiles (~7 m in the surface NMR vs. ~3 m at BW-6; Fig. 5c). One explanation is that a weathered fracture that is filled with saprolite is sitting below the water table. The saprolite at our site is seismically anisotropic, and the most anisotropic regions correspond to regions of thick saprolite, which implies that inherited bedrock fractures may control saprolite development (Novitsky et al., 2018). Therefore, regions of saturated saprolite could be controlled by the underlying fractures and compartmentalize the groundwater. We postulate that the saturated saprolite makes up only a small part of the large volume excited by the surface NMR measurement because of lateral heterogeneities. The results would be a sounding with low water contents and long relaxation times associated with saprolite (between 150 and 300 ms), which is consistent with our observations. Because the inversion is fitting layers, if the fracture had any kind of dip underneath the loop, the \( T_2^* \) profile would be thickened.

If the lower water contents are caused by water in saturated saprolite, we can use the seven surface NMR soundings to qualitatively map regions of saturated saprolite on the ridge in our study area. Our analysis assumes that the volume excited by the NMR measurement is exciting the volume directly under the figure-eight loop. We did not attempt two-dimensional inversions due to the small signals and nonuniform spacing between our soundings. Instead, we used the overlapping area of each figure-eight loop as a proxy (Table 3), where the area of each sounding is 3324 m².

The similarity between S7 and S8 is expected due to the high percentage of overlap (Table 3). Similarities between S9 and S11 are also expected, but they do show slightly different structure in the water content profile, which might be explained by the overlapping area being only ~54% (Table 3). The inverted results at S5 and S6 are different from those at S7, S8, and S10 (Fig. 3). Based on the similarities between S7, S8, and S10, particularly the 7-m thickness of the \( T_2^* \) anomaly between the 10- and 20-m depths (Fig. 3), we believe that we are imaging the same subsurface feature and that this feature must lie within the overlap of these three soundings but not within the S6 loop. We interpret this structure as a zone of saturated saprolite (Fig. 9a). Sounding S11 does not share any overlap with S7 and only 5.6% with S8 (Table 3). Due to this lack of overlap, we interpret the saturated zone to extend west into the region where S11 and S9 overlap (~54% overlap; Table 3). This region must also pass through both BW-6 and BW-7 (Fig. 9a), where we know saturated saprolite exists from the borehole NMR soundings. Due to the steel casing, it is difficult to rule out if this saturated zone extends through BW-1, but we do know that at BW-4 there is a lack of saturated saprolite (Fig. 7).

The interpreted saturated zone is also located above a large depression in the seismically estimated boundary (Fig. 8a). This depression is also present in independent seismic investigations (Wang et al., 2019; Keifer et al., 2019). In cross-sectional view, the water table is much closer to the interpreted seismic
boundary (Fig. 8c). Based on overlap, the surface NMR provided a rough estimate of where the saturated saprolite exists, but we could not invert for the exact shape. Based on the average strike of fractures of the outcrops in the northeast of the study area (050 ± 7°; Fig. 1b) and the presence of seismic anisotropy in the saprolite with roughly the same strike as the outcrop (Novitsky et al., 2018), we interpret this saturated region to have a similar strike as the large fractures observed in the outcrop to the northeast (Fig. 1b).

Although we explain the difference in water contents between the surface and borehole NMR in the context of lateral heterogeneity and water compartmentalization in the CZ, this is probably not the only explanation. Understanding the causes behind this unique observation requires more research and more carefully designed experiments. Our goal was to understand how water was distributed in the CZ, not to explain this surprising discrepancy. Nonetheless, the discrepancy is not a modeling error or caused by low-quality data. The observations presented here open the door to interesting questions related to NMR in fractured rock systems. For example, how significant is relaxation during pulse in decreasing the surface NMR water contents? How sensitive is the surface NMR measurement to lateral heterogeneity? Could a series of surface NMR measurements be used to “triangulate” lateral heterogeneities? Furthermore, the figure-eight loop was instrumental in adequately lowering noise levels to measure the low-amplitude signals. This raises another important question related to surface NMR in fractured environments: How does orientation of the figure-eight loop change the measured response? (Flinchum et al., 2018a, 2018b; Fig. 8a).

Table 3. Percentage of the overlapping area among all seven soundings.

<table>
<thead>
<tr>
<th>Sounding</th>
<th>S5</th>
<th>S6</th>
<th>S10</th>
<th>S7</th>
<th>S8</th>
<th>S11</th>
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<tr>
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<tr>
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<tr>
<td>S8</td>
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<td>26.9</td>
<td>67</td>
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<td></td>
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<tr>
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<td></td>
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<td></td>
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<tr>
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<td>53.8</td>
<td>100</td>
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Fig. 9. (a) Map showing the figure-eight loops, with the regions where they overlap (Table 2) shaded in gray, a hachured region marking the area where we think there is saturated saprolite, which is the source of the signal for the surface nuclear magnetic resonance (NMR), and the yellow line is the same as the black line in Fig. 8a; and (b) profile of this region, with an average thickness of 8.4 ± 2.6 m, where the shaded gray area represents the possible range where the saprolite–weathered bedrock boundary could occur, as constrained by seismic velocities (Fig. 8a), the black vertical lines represent the locations of Boreholes BW-6 and BW-4 (the thickest part of this line represents casing), the dotted blue line shows the modeled water table (Flinchum et al., 2018a), consistent with surface NMR measurements, the shaded blue areas show regions where the water table is above the lower seismically interpreted saprolite and weathered bedrock boundary, and the hachured rectangle corresponds to the same saturated zone in (a).

Chemical processes. Therefore, being able to quantify or even differentiate between these two types of boundaries across landscape scales is a major goal of CZ imaging. Here, we merge the information from surface NMR, borehole NMR, and seismic refraction to create a conceptual model of the deep CZ at our site (Fig. 10). At borehole NMR locations where the casing depth is deeper than the water table (BW-5, BW-6, and BW-7; Fig. 4), we observed a drop in water content near or below the casing. Because the casing is below the water table at these locations, this drop in water content probably represents a decrease in porosity. At BW-5, the porosity decreased from 0.12 to 0.03 m³ m⁻³ across a range of 4 m (Fig. 4a). At BW-6, where the spatial average filter was removed, the porosity dropped from 0.34 to 0.05 m³ m⁻³ from depths of 15.6 to 18.1 m (Fig. 6b); BW-7 was similar to BW-6. Furthermore, the borehole NMR data showed a shift of the pore structure from longer to shorter relaxation times, suggesting a drop in hydraulic conductivity near this boundary. The exception is BW-4, where saturated saprolite does not exist, and higher water contents (~0.12 m³ m⁻³) and longer T₂ML relaxation times exist for 20 m below the casing. The most visibly fractured borehole in optical televiewer logs was BW-4 (Fig. 7d) (also see Fig. 7 in Flinchum et al., 2018b). Although we lack geochemical data, the link between

✨ Insights about the Saprolite–Fractured Bedrock Boundary

The saprolite–weathered bedrock boundary is commonly described in two forms: corestones of downward increasing size until the material transitions into fractured rock (Berry and Ruxton, 1959; Jones, 1985; Fletcher and Brantley, 2010; Buss et al., 2013) or a zone throughout which the fracture density rapidly decreases (Anderson et al., 2002; Wyns et al., 2004; Ayraud et al., 2008). The physical structure of the transition region dividing fractured rock and saprolite is shaped by various physical and chemical processes.
porosity and chemical weathering is well known, as higher porosity is associated with more weathered materials (Brimhall and Dietrich, 1987; Bazilevskaya et al., 2015; Navarre-Sitchler et al., 2015; Hollbrook et al., 2019). Therefore, we speculate that the decrease in porosity at our geophysically interpreted saprolite−weathered bedrock boundary could be associated with a chemical reaction front.

The small signal amplitudes recorded by surface NMR data, combined with the measured high porosity of saprolite, the high water contents measured at BW-6 and BW-7, and the forward modeling all suggest that the surface NMR is measuring water only in the saturated saprolite. The fact that we observed changes in the signal magnitude along 300 m of the ridgeline suggests that regions of saturated saprolite change laterally. The water table is well constrained by hand-measured depths (Table 2) and by the surface NMR and is relatively flat (Fig. 8c). A likely scenario is that the boundary dividing saprolite and weathered bedrock dips above and below the water table and that the geophysical reconstruction smoothed out these heterogeneities. As discussed above, we interpreted a saturated zone that spans from S7 and S8 through BW-6 and BW-7 (Fig. 9). This is consistent with a large depression in the seismic surface (Fig. 8a) and has a strike consistent with the fast direction identified through seismic anisotropy (Novitsky et al., 2018) and the outcrop to the northeast (Fig. 1b). This region is also where the water table is closest to the seismically interpreted saprolite−weathered bedrock boundary (Fig. 9b).

The borehole NMR data suggest a 2- to 3-m transition zone from saprolite to weathered bedrock. In contrast, the lack of a strong seismic reflection or refraction and the varying low water contents measured by the surface NMR suggest a less defined or more gradual transition or, alternatively, a well-defined boundary that has enough spatial heterogeneity to scatter the seismic wave field, which undulates on the order of 10s of meters (Fig. 10). The surface NMR data suggest that we are imaging localized pockets of saturated saprolite, and it has been argued that fracture zones are associated with thicker saprolite at our site (Novitsky et al., 2018). One possibility is that the seismic refraction boundary is providing an average location of the weathered bedrock−saprolite boundary but smoothing local vertical and lateral heterogeneity (Fig. 10), but this heterogeneity, especially when a section dips below the water table, is probably what the surface NMR is measuring. Thus, the combined geophysical approach allows us to construct a detailed conceptual model for the CZ at our site (Fig. 10).

Conclusions

The biggest challenge when working with surface NMR data in fractured rock environments is the low water contents. Despite low water contents, we can collect high-quality surface NMR data in weathered and fractured rock environments if careful attention is paid to noise-canceling loops and stacking. Because these data were acquired in a granite, we expected to deal with significantly shortened relaxation times caused by magnetic field gradients. Using two surface NMR soundings and a borehole profile, we calculated a range of values for T$_{2IH}$ (159–750 ms). Although this range is large, our data suggest that most relaxation times observed in the weathering profile will not be significantly affected and that the common assumption that T$_2^*$ = T$_2$ is reasonable at this site. Furthermore, the high end of our calculated T$_{2IH}$ is on par with an estimate using the measured magnetic gradient. Thus, in the absence of a borehole NMR sounding, a magnetic map can be used to approximate T$_{2IH}$.

In a weathered and fractured granite, we show that unsaturated saprolite has short relaxation times (<7 ms) and potentially high water contents (>0.1 m$^3$ m$^{-3}$). Due to instrument dead time, water in the unsaturated zone was not imaged by the surface NMR. Saturated saprolite was characterized by high water contents (>0.3 m$^3$ m$^{-3}$) and T$_2$ relaxation times between 150 and 770 ms. Finally, the fractured bedrock was characterized by lower water contents (<0.05 m$^3$ m$^{-3}$) and short T$_2$ relaxation times (~40 ms). Saturated saprolite is a viable target for surface NMR studies.

We observed significantly lower water contents in the surface NMR data than the borehole data. Although more work is needed to fully understand this discrepancy, we postulate that it is related to the scale of the measurements and the compartmentalization of groundwater—specifically in the form of localized regions of...
saturated saprolite. Working within this framework, we used the overlap of our seven surface loops to define a region of saturated saprolite. We show that surface and borehole NMR have the potential to help define the boundary dividing saprolite and fractured rock as long as regions above and below this boundary are saturated. Existing seismic data provided an overall picture of CZ structure but were limited to mapping the boundary dividing saprolite and fractured rock with some uncertainty (Fig. 8). The unique abilities of NMR data provided valuable insights about how water interacts with this important CZ boundary.

Acknowledgments

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