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Drilling Within the Critical Zone

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ABSTRACT

The critical zone (CZ), extending from the vegetation canopy to the base of weathered material or depth of groundwater, hosts coupled hydrologic, geochemical, and biological interactions that regulate soil health, water resources, and ecosystem sustainability. The subsurface CZ can extend tens to hundreds of metres below the surface and is largely inaccessible, except in happenstance exposures from quarries or road cuts through mountain hillsides. Drilling and subsequent borehole sampling, monitoring, and imaging reveal the importance of the deep subsurface for CZ evolution and function. However, drilling can be labour-intensive, requires expensive, specialised equipment, and can only be done where the equipment can be deployed, limiting the number and placement of boreholes. Despite these challenges, drilling provides invaluable insights into deep CZ processes. To empower the next generation of CZ scientists to employ drilling and downhole techniques, this review synthesises emerging research objectives and methods commonly used during CZ drilling campaigns over the last 30 years. We focus on three CZ research themes: (1) physical and chemical weathering, (2) water storage and partitioning, and (3) solute, microbial, and gas dynamics. For each theme, we evaluate drilling techniques, sampling strategies, downhole logging approaches, long-term monitoring, and analytical methods that collectively enable diverse hypothesis-testing. We conclude by providing a vision for the future of drilling within the CZ, with a focus on novel drilling techniques aimed at recovering saprolitic material as well as borehole designs that can monitor and sample the vadose zone. Additionally, we emphasise that near-surface geophysics and data-model integration efforts are needed to expand borehole observations to the landscape scales necessary to advance CZ science and inform ecosystem and water resource management.

1 | The Importance of Drilling for Critical Zone Science

The critical zone brims with complex interactions between physical, chemical, hydrologic, and biologic processes that are required to sustain life (Chorover et al. 2007; Naylor et al. 2023). Central goals of critical zone science are to understand, quantify, and predict the interrelationship between the Earth's surface and subsurface to inform sustainable land and water management (Singha et al. 2024). Over the past three decades, research has expanded below the shallow soil layer to probe the deep subsurface critical zone, defined here as the portion of the subsurface that ranges from weathered bedrock to minimally altered bedrock that can extend metres to hundreds of metres (see Riebe et al. 2017 for definitions of different CZ materials; Karlstrom et al. 2025; Richter and Markewitz 1995). Deep subsurface properties (e.g., permeability, porosity, and mineralogy) are increasingly recognised as important regulators of near-surface processes such as soil development and transport, water storage and routing, and nutrient availability (Heimsath and Whipple 2019; Uhlig and von Blanckenburg 2019; Xiao et al. 2021). Despite its significance, the deep critical zone remains largely unexplored due to the limited ability of traditional field methods such as soil pits, trenching, and hand augering to advance into the deep subsurface. Drilling overcomes these limitations by directly accessing the deep subsurface, which is essential to achieve a holistic understanding and improve process-based models of critical zone evolution and function.

Drilling campaigns are interdisciplinary science and engineering efforts to characterise, sample, instrument, and monitor the subsurface critical zone (e.g., Cosans et al. 2024; Krone et al. 2021; Lazar et al. 2019; Moravec et al. 2020; Figure 1). However, drilling campaigns may require special considerations and potential trade-offs across all stages to ensure scientific goals are met within practical constraints (e.g., time, cost, feasibility). In addition, boreholes are often needed in remote or logistically challenging locations (e.g., steep slopes, headwater catchments, and densely vegetated areas) where data gaps exist or where specific geological features can be studied. While there is extensive documentation on drilling practices for industrial and geotechnical objectives (e.g., Bruce 2003; Schnaid et al. 2025) and for applications to oceanic or lacustrine settings (Cohen 2012; Exon and Arculus 2022), these resources do not address limitations specific to the critical zone, such as the difficulty of recovering core from both highly weathered saprolite and intact bedrock.

This review synthesises the emerging scientific goals that motivate critical zone drilling and outlines strategies and practices for borehole sampling, monitoring, and imaging within the deep subsurface. Additionally, we highlight the powerful approach of integrating indirect measurements from geophysical surveys with drilling campaigns to determine borehole placement and quantify critical zone processes beyond the borehole at landscape scales (Dumont and Singha 2024). Further, this review offers methodological guidance while recognising that successful drilling campaigns require site-specific adaptations based on research objectives, geological conditions, and practical constraints. We focus on three core research themes: (1) subsurface physical and chemical weathering, (2) water storage and partitioning, and (3) solute, microbial, and gas dynamics. For each theme, we outline key methods, challenges, and emerging opportunities, acknowledging that the research themes are interrelated and approaches often serve shared goals. We conclude by offering a vision for improved drilling technological advances, borehole data-model integration and cross-site data syntheses, with the aim of maximising the long-term value of borehole infrastructure for critical zone science.

2 | Subsurface Weathering Within the Critical Zone

Physical and chemical weathering processes transform unweathered bedrock into soil, saprolite, and weathered bedrock (Anderson et al. 2002; Graham et al. 2010; Hayes et al. 2019). In eroding landscapes, the critical zone is often conceptualised as a conveyor belt where fresh rock enters the weathering zone via uplift at depth and is eventually removed through chemical and physical erosion towards the surface (Anderson et al. 2007; Sharp 1982). Weathering rates and subsurface properties (e.g., thickness) can vary substantially due to differences in topography, climate, lithology, and geologic setting (Bazilevskaya et al. 2013; Callahan et al. 2022; Karlstrom et al. 2025; Riebe et al. 2021; West 2012). Near-surface geophysical techniques (e.g., seismic refraction) provide indirect representations of landscape-scale weathering variability through subsurface models (e.g., seismic velocities), but these interpretations must be constrained with direct measurements of subsurface properties (e.g., porosity). Therefore, drilling remains one of the most powerful tools to directly quantify subsurface weathering processes and develop a holistic understanding of critical zone evolution.

2.1 | Drilling Locations and Depths

Weathering profiles and bedrock properties can vary substantially within landscapes both laterally, as a function of geomorphic position, and vertically, as a function of depth (Flinchum et al. 2018; Gu, Mavko, et al. 2020; Pedrazas et al. 2021). Consequently, drilling boreholes at distinct landscape positions (e.g., ridgetop, midslope, valley, and in-stream) is required to capture this heterogeneity and determine the dominant controls on porosity production (e.g., Gu, Heaney, et al. 2020; Gu, Mavko, et al. 2020; Gu, Rempe, et al. 2020; Figure 2). Exact drilling locations and depths are commonly determined from seismic refraction and other geophysical approaches (e.g., ground penetrating radar, electromagnetic methods) that infer landscape-scale variability in the weathering degree of subsurface material (Comas et al. 2019; Flinchum et al. 2018; Moravec et al. 2020; Parsekian et al. 2015). For example, numerous studies have used P-wave velocities to delineate low-porosity zones that are typical of unweathered bedrock across diverse lithologies including granitic bedrock (e.g., 4–6 km/s; Flinchum et al. 2022; Holbrook et al. 2014) and sedimentary rocks (e.g., 2–4 km/s; Callahan et al. 2024; Gu, Mavko, et al. 2020; Gu, Rempe, et al. 2020; Hudson Rasmussen et al. 2023) which can inform drilling campaigns. In addition or in the absence of geophysical surveys, target depths or locations may be determined from nearby drill logs or features such as roadcuts and landslide scars that may expose the weathered bedrock profile.

Ridgetops are frequently targeted for long-term weathering studies because they serve as 1-d hillslope boundary conditions with predominantly vertical water fluxes and minimal lateral sediment inputs, enabling weathering comparisons across sites (Bazilevskaya et al. 2013). At ridgetop positions, the target depth is often defined by the depth to 'fresh' or minimally weathered

FIGURE 1 | Drilling within the critical zone photoseries: (a) Portable hand held drill with water tank, (b) portable drill that can allow for greater access to rugged terrain, (c) track-mounted drill rig navigating steep terrain with dense vegetation, (d) dry auger starting borehole and bringing cuttings to the surface, (e) drill pipe connected to subsurface for standard penetration testing, (f) recovered core from standard penetration test, (g) arranged cuttings samples by depth to show lithologic colour variability, (h) drilling without water can generate large amounts of dust, which requires personal protective equipment, (i) recycled drilling fluid and mesh to capture coarse fraction cuttings, (j) end of core barrel, the 'shoe' (bottom section of each core run), (k) example station for onsite rock core characterisation with PVC core carrier and core boxes, (l) example of core with highly weathered interval, (m) drill fluid additives such as foaming agents help flush drill cuttings to the surface, improve borehole stability, and reduce equipment wear, (n) temporary structure (green) provides a controlled workspace for onsite core characterisation and subsampling, (o) subsampling core interior with hammer and chisel, (p) polyurethane foam used to fill borehole casing annulus, (q) specialised sleeve with sensors and ports for vadose zone monitoring. Photographs by authors.

bedrock to quantify weathered profile thickness and establish geochemical mass-balance baselines (Dixon et al. 2009; Riebe et al. 2003). However, drilling to fresh bedrock may pose scientific, technical, and logistical challenges. For example, transitions to fresh bedrock are often indicated by significantly reduced fracture density and diminished oxidation throughout the rock core that may appear gradual or incomplete (Anderson et al. 2002; Brantley et al. 2011, 2013). Identifying these transitions is complicated by factors such as pervasive fracturing due to contemporary or past tectonic activity (Callahan et al. 2024; Karlstrom et al. 2025), lithologic layering with distinct weathering susceptibilities (Goodfellow et al. 2014), and the presence of isolated corestones throughout the saprolite (Buss et al. 2013). When apparent fresh bedrock is encountered, it is common practice to extend drilling further to confirm the transition and ensure adequate characterisation of unweathered conditions.

Field teams must balance logistical constraints such as equipment, cost, and time limitations when deciding to drill deeper or prioritise additional boreholes to improve spatial coverage. In cases where research questions seek to explore the relationship between topography and weathering, drilling depths and locations may be prioritised along hillslopes or in valley bottoms to capture these features (Cosans et al. 2024; Pedrazas et al. 2021;

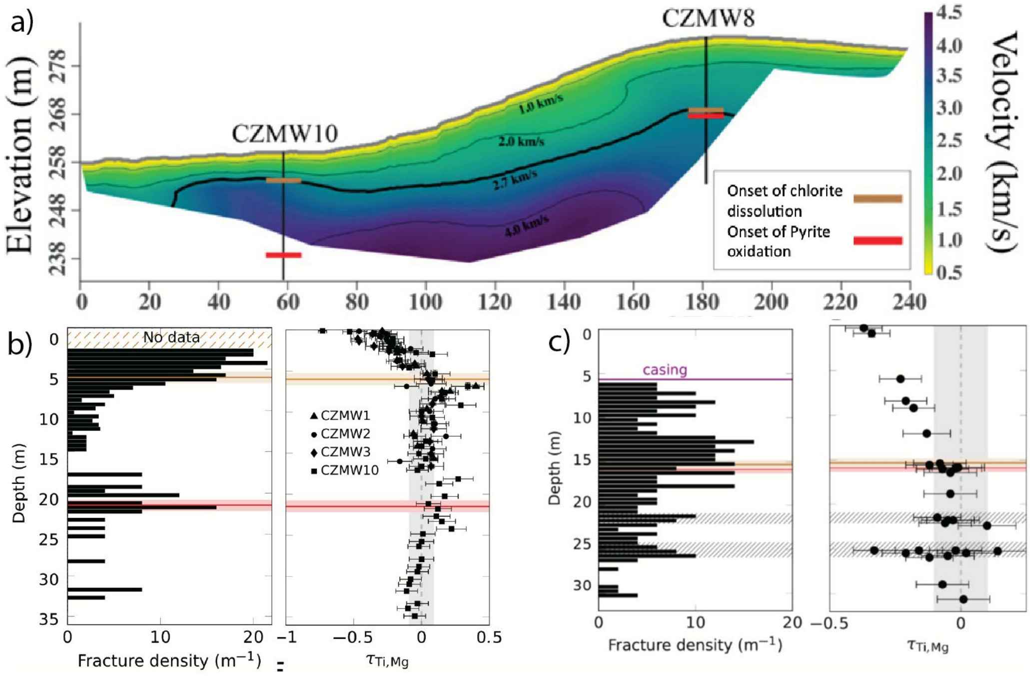

FIGURE 2 | (a) Velocity model from a seismic refraction survey and borehole locations at the Shale Hills Critical Zone Observatory. Red and brown lines indicate the onset of the pervasive bulk reaction of pyrite and chlorite, respectively (modified from Gu, Heaney, et al. 2020; Gu, Mavko, et al. 2020; Gu, Rempe, et al. 2020). (b) Fracture density averaged from optical and acoustic televiewer observations and the normalised concentrations (τ) of magnesium from valley boreholes ($n=4$). (c) Fracture density averaged from optical televiewer observations and the normalised concentrations (τ) of magnesium from CZMW8. The cross-hatched bars mark two fractured and weathered zones below the water table observed in core material. The error bar represents uncertainty of elemental measurements in each depth and variations of parent materials. The grey shaded zone shows one standard deviation of uncertainty in τ due to variable parent composition. Before drilling borehole CZMW10, slower seismic velocities in the shallow subsurface (e.g., <8 m below land surface, mbls) were interpreted to predominantly reflect fracture density (West et al. 2019). However, chemical data from samples retrieved during drilling reveal the onset of chlorite dissolution aligns with the contour of P-wave velocity $=2.7$ km/s under both valley and ridge. Therefore, changes in P-wave velocity are now predominantly attributed to porosity generated from chlorite dissolution with potential effects from fracture density.

Wang et al. 2021). However, access to these locations may require specialised drilling equipment that may increase project budgets or be logistically infeasible. Together these examples emphasise the importance of establishing clear research priorities and maintaining flexibility for adaptive decision-making in the field based on emerging observations.

2.2 | Drilling, Recovering Material and Stabilising the Borehole

2.2.1 | Cutting Through Rock

All drilling campaigns must advance through subsurface material (i.e., cut rock), bring material to the surface, maintain borehole stability, and prevent loss or damage to drilling equipment. Critical zone drilling is commonly achieved through a combination of auger drilling, direct push or percussive coring, sonic coring, air or mud rotary drilling, and diamond coring (see Table 1 and Kallmeyer 2017 for descriptions).

Auger and direct push or percussive coring methods are typically more suitable for shallow investigations, softer materials, and campaigns that have limited access, lower costs, and are less time intensive (Trost et al. 2018). For shallow drilling in softer material like saprolite, direct push or percussive methods such as standard penetration testing (SPT) offer advantages because material structure is retained, sample depth is constrained, minimal disturbance to the borehole wall occurs, and no fluids are introduced. Alternatively, while dry augering does not allow for the rock structure to be retained, it does generate continuous samples that are more quickly routed via auger flighting (helical screw components) to the surface. This is in contrast to augering with fluid, where particles are hydraulically sorted by size and density as they travel up the drill stem, which biases the sample and makes it difficult to constrain depths.

For deeper drilling and advancing through harder materials it is often necessary to use other drilling techniques that involve higher-speed rotation or vibration compared to augering. Sonic coring uses high-frequency vibration and minimal rotation to advance the drill bit, generally without fluid circulation. Sonic coring is effective in soft and varying lithologies but may partially mix or disrupt the sample and therefore special considerations should be taken to determine sampling interval (Cosans et al. 2024). Sonic techniques require fluid circulation to cool the bit in thick intervals with harder lithologies, and the rate of penetration declines significantly. In comparison, air and mud rotary drilling techniques do not generate core samples but quickly open a borehole and return cuttings (rock fragments) to the surface. Compressed air used in air rotary drilling produces larger, more intact cuttings

TABLE 1 | Comparison of common drilling and sampling methods with their relative advantages and limitations.

Method	Description	Penetration depth/rotation speeds	Material suitability	Sample type	Advantages	Limitations	Cost/time
Auger	Drill bit attached to rotating helical screw (auger flights) to loosen and lift soil and soft weathered materials to the surface, generally without drilling fluids. Material returns to the surface between borehole wall and auger flights.	Shallow (< 10 m)/40–120 rotations per minute (RPM)	Soil, saprolite	Disturbed material (rock fragments) only	Low cost; minimal site disturbance; no fluids needed; continuous samples	Shallow depth and soft lithologies only; sample bias and mixing; structure not retained	Low cost; fast
Direct push and/or percussive coring	Machine or manual force to push (direct push) or hammer (percussive) a tube directly into the ground without rotation, allowing rapid sampling or in situ mechanical strength testing via standard penetration test (SPT)	Shallow (< 10 m)/ no rotation	Soil, saprolite	Continuous core	Retains formation structure; best depth control; minimal borehole disturbance; no fluids introduced; SPT provides strength and relative density data	Shallow depth and soft lithologies only; sample bias and deformation increase with use of percussion	Low to moderate cost; slow
Sonic	High-frequency vibrations of drill rods combined with varying amounts of rotation to penetrate soil and soft to hard bedrock. Fluid circulation is not required in soft lithologies but necessary in hard rock. Material returns to the surface within hollow drill rods.	Deep (> 20 m)/50–120 RPM+ High-frequency vibration: 50–200 Hz	Soil, saprolite, fractured bedrock, limited fresh bedrock	Continuous core	Effective in a wide range of formations; highest recovery rates in soft and varying lithologies; fast penetration in soft lithologies	Sample vibration/mixing and deformation possible in soft lithologies; in hard lithologies slow progress and require fluid circulation	High cost; fast
Air/mud rotary	Rotating solid drill bit with compressed air or drilling fluid to cut through soil and soft to hard bedrock. Air/drilling fluid lifts cuttings to the surface and cools the drill bit.	Deep (> 20 m)/40–250 RPM	Soil, saprolite, fractured and fresh bedrock	Cuttings only	Large depth range; fast drilling; effective in all lithologies	Depth uncertainty and limited sample sizes, especially with mud rotary; size- and density-biased sampling; may require fluid	Moderate to high; variable speed
Diamond coring (conventional or wireline)	Rotating drill bit (diamond-impregnated) to cut through rock; drilling fluids required; cores retrieved through pipe trips (conventional) or tool trips (wireline).	Deep (> 20 m)/300 to 1600+ RPM, varies depending on bit size and rock type	Soil, saprolite, fractured and fresh bedrock	Continuous core	Best sample quality in hard rock; good depth control; structure preserved; near-continuous sampling	Requires fluids; expensive; slow progress; sample bias and poor recovery in varying lithologies	Highest cost, time intensive

with greater depth accuracy. However, cuttings can be biased by size and density, and the technique offers limited management of borehole conditions and consequently a reduced depth range. In contrast, fluid circulation used in mud rotary drilling allows greater control of borehole conditions and better depth range but this method produces only fine-grained cuttings with significant depth uncertainty, and fluid use requires contamination considerations (see Section 4.2).

Diamond coring involves high-speed rotation of diamond-impregnated coring bits with continuous fluid circulation to cut through harder materials. It is generally favoured for core collection and physical and geochemical subsurface characterisations because it allows for near-continuous sampling and precise depth delineation. When paired with wireline core retrieval, a cable system that retrieves samples without pulling the entire drill string, the process is highly efficient. However, diamond coring is often more expensive than other techniques and works best in consolidated, unfractured, and homogeneous material and can yield low recovery with uncertain depths in soft or variable lithologies (Orlando et al. 2016). The term 'recovery' refers to the fraction of the core barrel (the tube that receives and holds the core during drilling) that has the sample. For example, if a core barrel penetrated 5 ft. (1.5 m) but only 3 ft. (0.9 m) of core in the barrel, then 2 ft. (0.6 m) of sample was unable to stay in the core barrel and recovery was 60%.

2.2.2 | Bringing Material to the Surface

Poor recovery can occur when unconsolidated material is flushed away by the progressing drill bit and fluid, when samples fall out of the core barrel on the way back up towards the surface, or when sample lithologies with high porosity are compressed during drilling. Coring does not preserve macropores or open fractures, but quantifying recovery during the coring process is one method to shed light on the presence of these features at the depth resolution of the coring interval (e.g., Buss et al. 2013). Poor recovery limits the depth control of samples and thus should be avoided when possible. To improve sample recovery and reduce disturbance in highly weathered materials, triple tube core barrels can be used to provide an additional protective liner that maintains core integrity during retrieval. Additionally, to improve recovery, low fluid pumping rates and rotation speeds, and larger diameter tooling can help avoid flushing the core away. Strategies for enhancing depth control during poor recovery include taking detailed field notes about lithologic discontinuities that may be caused by unrecovered material and comparison of downhole geophysical logs. Regardless, collecting samples from the 'shoe' of the core barrel (Figure 1) and sampling rock chips from the recirculating drill fluid are best practices to ensure that future analyses are representative of the formation. Clear communication with drilling contractors about research objectives, expected lithologic variability, and specific sampling requirements is essential for successful core recovery and proper depth control.

2.2.3 | Maintaining Borehole Stability

Well designs, including diameters and depths, casing material (e.g., steel, aluminium, polyvinyl chloride [PVC]), casing diameters, depths, and installation type (temporary or permanent), has significant implications for the long-term utility of the borehole (Fisher et al. 2017). The depth to which casing is installed can generally be finalised during drilling based on conditions encountered. This depth often marks the transition from unstable to more consolidated materials, where borehole stability increases. For example, Flinchum et al. (2018) compared driller-defined borehole casing depths to seismic velocities at these depths within granitic terrain in Laramie, Wyoming (Figure 3). While casing depth varied by a factor of three (6–18 m), the seismic velocities at the casing base were remarkably consistent, varying less than 30% (1.06–1.35 km/s), and the drilling observations confirmed that this velocity boundary represented the transition to weathered bedrock rather than variations in water saturation. In some landscapes with significant weathering and fracturing, weaker sections of rock may lie between harder, more consolidated portions of bedrock (Buss et al. 2013; Krone et al. 2021). These conditions can complicate decisions about casing depth and may require the use of drilling fluids to stabilise the borehole and avoid cavitation or collapse. Borehole casing reinforces the unconsolidated part of the borehole and allows for the deployment of downhole geophysical tools but also constrains which depths can be logged (see Section 2.4; Holbrook et al. 2019; Moravec et al. 2020).

2.3 | Common In Situ Drilling and Core Characterisations

Multiple methods are used to characterise rock properties, including data collected during the drilling process, downhole geophysical logging, and post-drilling laboratory analyses on collected samples. For example, shallow drilling methods such as SPT can be used to gauge the in situ strength of the subsurface material (Fletcher 1965; Rogers 2006). SPT uses a hammer of a known weight (typically 140 lbs. [63.5 kg]) dropped from a known height (typically 30 in. [760 mm]) to drive a split spoon sampler tube into the ground, and the number of blows

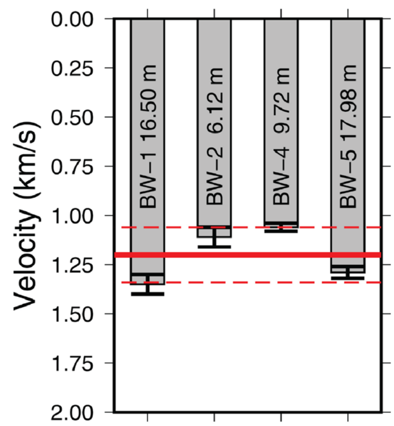

FIGURE 3 | P-wave velocity (km/s) from seismic refraction of material at the bottom of casing at four borehole locations on a ridge top within granitic terrain in Laramie, Wyoming. Numbers within each bar indicate the casing depth (m) at that location. Despite casing depths varying by a factor of three, seismic velocities at the bottom of casing remained consistent at 1.2 ± 0.14 km/s across all sites. This seismic velocity was interpreted as the saprolite to weathered bedrock interface. Figure from Flinchum et al. (2018).

per depth is recorded as a measure of material competence (Fletcher 1965). Lower SPT blow counts (< 10 counts/ft. [< 33 counts/m]) are typically characterised by unconsolidated materials such as soil or saprolite, while increasing blow counts (> 50 counts/ft. [> 164 counts/m]) or SPT refusal signal a transition into more competent weathered bedrock (Pedrazas et al. 2021). SPT refusal depths often are used as a proxy for the depth to the saprolite to weathered bedrock transition (Callahan et al. 2024; Pedrazas et al. 2021) and may signal the depth to which surface casing should be used to stabilise borehole walls.

Core characterisation can occur both in the field and in the lab to inform sampling for subsequent geochemical and physical analyses. Common core lithologic descriptions include recovery, colour, texture, friability, fracture density and the presence of oxidation, weathering rinds, quartz veins or HCI reactivity (see Supporting Information S1 for example logging sheet). Indices such as rock quality designations can provide summative metrics reflecting these observations (Deere et al. 1967). Horizontal or jagged discrete fracture features observed in core samples or borehole imaging may be drilling-induced artefacts rather than natural fractures. Cores are typically cleaned and then photographed to qualitatively document material changes with depth (Figure 4), and to provide a reference for other core scanning datasets and for sample orientation and order. Multisensor core loggers can generate datasets of parameters such as magnetic susceptibility, natural gamma, gamma density, resistivity, and sonic velocity that allow direct comparison with downhole geophysical logs and improved depth alignments, particularly in intervals of incomplete core recovery (Smith et al. 2020).

2.4 | Common Downhole Logging Techniques

Downhole logging tools provide useful measurements of the physical, chemical, and structural changes associated with rock weathering (Holbrook et al. 2019; Moravec et al. 2020). Multiple logging methods can identify and characterise fractures with distinct advantages and limitations. For example, calliper logs detect fractures by measuring borehole diameter enlargements, but may be insensitive to microfractures that do not significantly enlarge the borehole but may be hydrologically significant (Gellasch et al. 2013). Acoustic televiewers

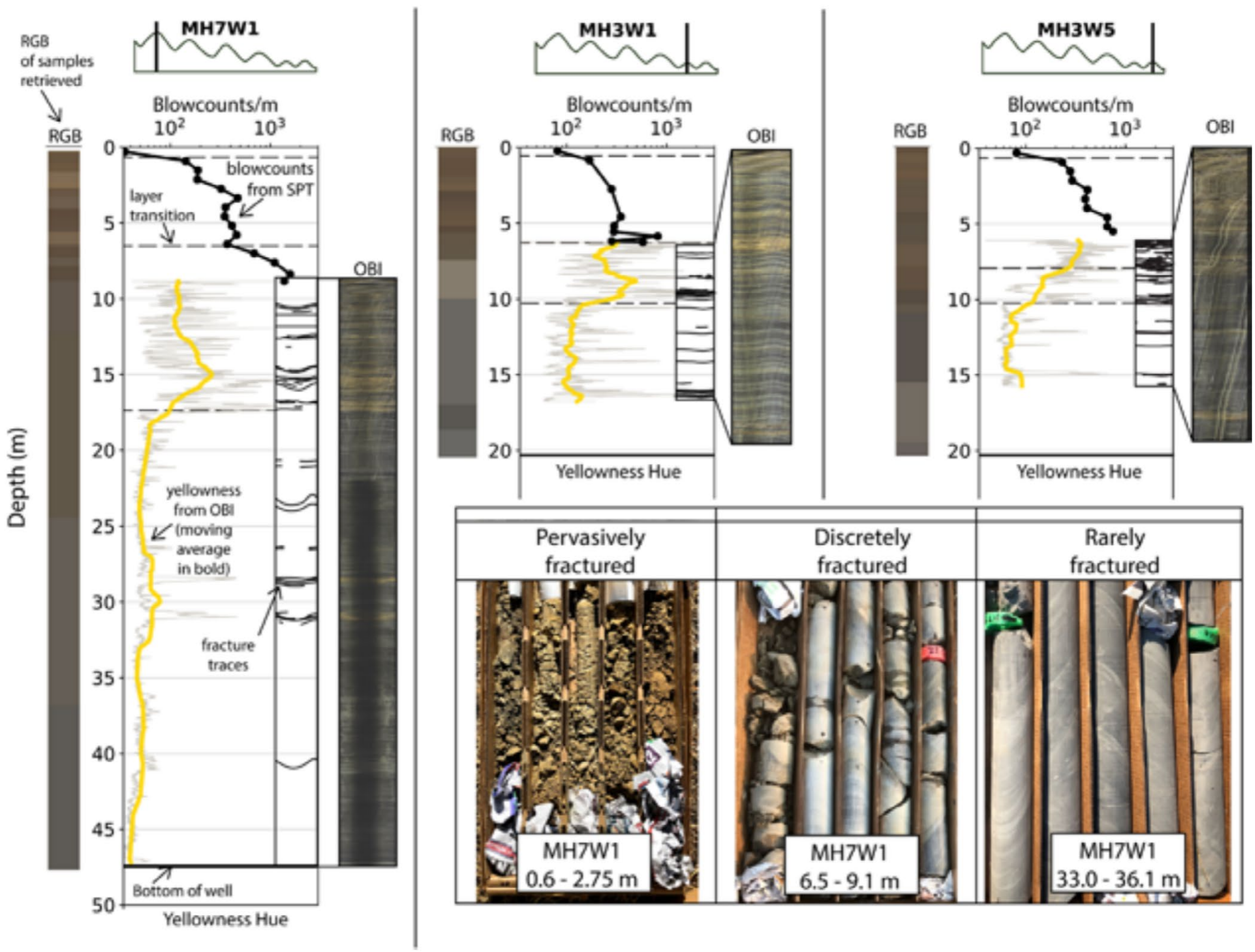

FIGURE 4 | From Pedrazas et al. (2021) vertical profiles at ridgetop boreholes of colour (RGB), blow counts (standard penetration testing), yellowness and fracture traces from the optical borehole imager (core image on right of depth-profiles). Example photos of pervasively fractured bedrock, discretely fractured bedrock, and rarely fractured bedrock are shown in the bottom right inset. Pedrazas et al. (2021) demonstrated that at ridgetops, the fraction of the hillslope relief that is weathered scales with hillslope length.

use ultrasonic imaging to create 360° borehole wall images in water-filled, mud-filled, or in some instances cased boreholes (Williams and Johnson 2004). Acoustic logs can detect lithologic changes, foliation, bedding and fractures even when no changes in borehole size occur if there is sufficient acoustic contrast. Alternatively, optical televiewers provide high-resolution visual images of borehole walls in air or clear water, allowing detailed characterisation of fractures, filling materials and other lithologic structures. The choice of logging method depends on borehole conditions (e.g., rough or coated with mud), target fracture types, and the specific hydrologic or structural information needed (Williams and Johnson 2004).

Beyond fracture characterisation, logging methods can also assess other rock properties and weathering processes. For example, optical borehole imagers or digital core scanning can also be used to quantify changes in core or borehole wall colour, such as the progression of colour change ('yellowness') associated with oxidation and iron mobilisation, providing a visual proxy for weathering intensity (Holbrook et al. 2019; Pedrazas et al. 2021). Sonic velocity logs provide estimates of elastic properties and can be used to infer fracture density, lithologic changes, and degree of weathering (Flinchum et al. 2022; Gu, Rempe, et al. 2020; Holbrook et al. 2019). Natural and spectral gamma logs further support mineralogical interpretations by recording the concentration of radioactive elements which can be mobilised (e.g., K) or concentrated (e.g., Th) during chemical weathering (Holbrook et al. 2019). Lastly, nuclear magnetic resonance (NMR) logging (see Section 3.3.2 for more details) directly measures water-filled porosity and pore-size distribution in weathered bedrock (Cosans et al. 2024; Figure 5). NMR measurements taken in the saturated zone can be used to estimate total porosity in situ, capturing pore space in both large-scale fractures and fine-grained weathering products which are often excluded from lab-based measurements of porosity (Pedrazas et al. 2021).

2.5 | Common Post-Drilling Characterisations

Weathering studies rely on geochemical and mineralogical analyses including bulk elemental concentrations (e.g., XRF or ICP-MS), mineral identification (e.g., XRD), and isotopic tracers (e.g., $\delta^{13}C$, $\delta^{34}S$; Moravec et al. 2021; Sullivan et al. 2016). Some of the most common geochemical analyses include the elemental mass transfer coefficient (tau; τ) which quantifies the gain or loss of an element during weathering relative to an immobile element (i.e., Ti, Zr) and the bulk mass

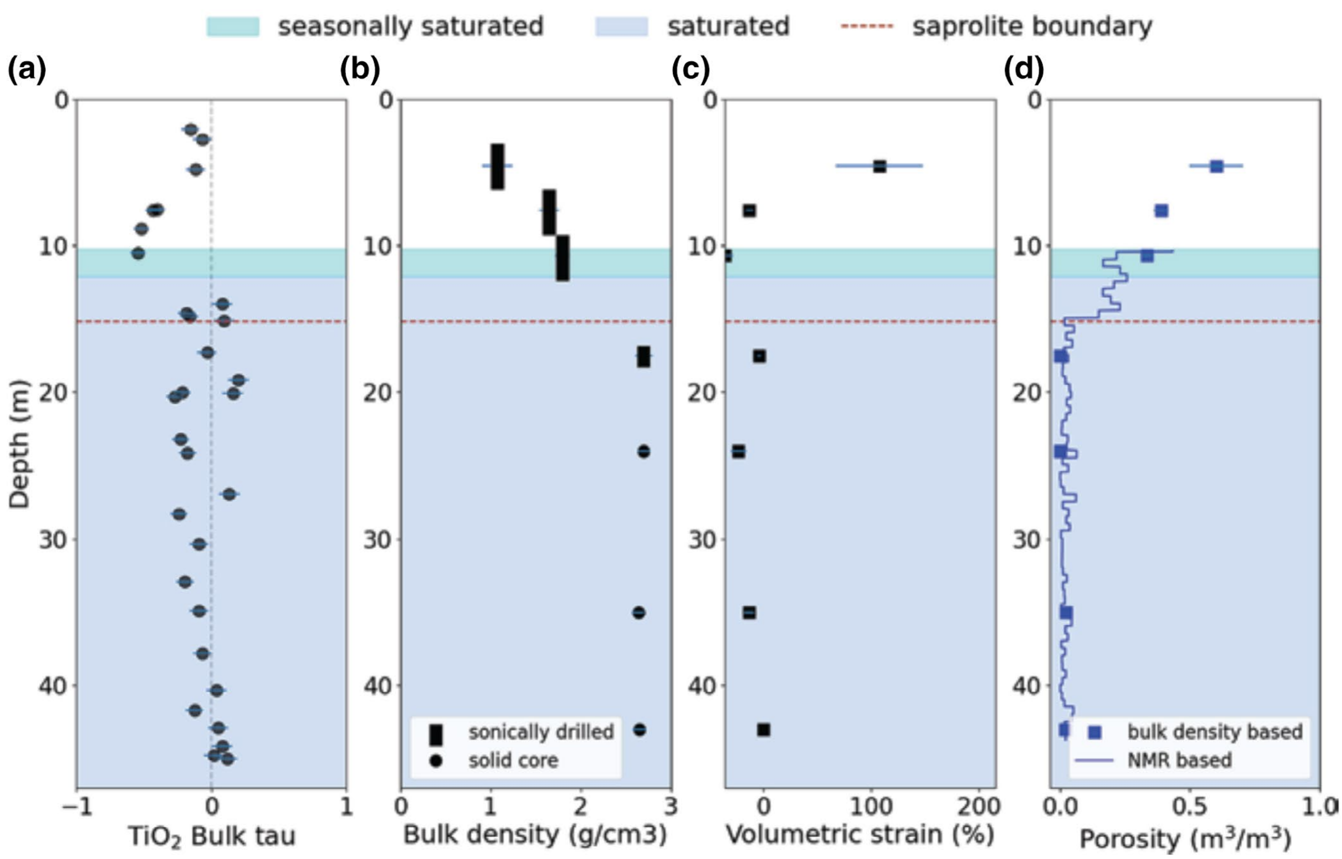

FIGURE 5 | (a) Bulk tau values calculated using titanium as the immobile element. (b) Bulk density from both the sonic drilled and solid core sections with no values above 3 m due to sample volume loss. (c) Volumetric strain calculated from the bulk density and bulk tau values. (d) Below the water table, water-filled porosity determined from borehole NMR, and a separate total porosity estimate calculated using the bulk density values. Modified from Cosans et al. (2024) who suggest that saprolite weathering fronts may be controlled by the depth of oxidation reactions and the position of the water table within a Piedmont region site. They highlight that their data-driven model is consistent with the hypothesised 'valve' model (Lebedeva and Brantley 2020) where reaction-generated porosity controls the transport of reactants and solutes, which in turn controls where and how weathering reactions proceed.

transfer coefficient (bulk tau) which estimates the amount of total mass loss during chemical weathering (Merrill 1897; Ague 1991; Brimhall and Dietrich 1987). Several studies show that elements traditionally considered immobile, such as Ti and Zr, can exhibit variable chemical and physical mobility depending on site-specific conditions, highlighting the need to carefully evaluate immobile element assumptions for accurate mass balance calculations (Bern and Yesavage 2018; Bern et al. 2011; Kim et al. 2018). Assessing elemental gain or loss can also be complicated when working with compositionally heterogeneous lithologies where defining a representative parent material composition is challenging (Price and Velbel 2003).

Additionally, it is important to consider site-specific geochemical measurements that may reflect dominant weathering or erosion processes. For example, in quartz-rich lithologies, samples can be collected during drilling for cosmogenic nuclide beryllium-10 analysis to infer long-term erosion and chemical weathering rates (e.g., Riebe et al. 2003). However, precise depth information and large sample masses are needed to adequately constrain nuclide concentrations and soil production rates. Furthermore, studies at shale-dominated sites have shown that measurements of bulk sulphur depletion due to pyrite oxidation provide key insights into water infiltration, microbial activity, and porosity development (Brantley et al. 2013; Gu, Heaney, et al. 2020).

Characterising physical properties such as bulk density, porosity, and volumetric strain provides essential complementary information to geochemical alteration for quantifying the degree of subsurface weathering (Callahan et al. 2020; Krone et al. 2021). For example, Hayes et al. (2019) demonstrated in the southern Sierra Nevada that, towards the surface, saprolite doubled in volume relative to the initial volume of the parent bedrock with minimal chemical mass loss. This work revealed that physical weathering processes such as root wedging, biotite alteration, frost cracking, or topographic stresses may drive subsurface weathering more than previously hypothesised. Accurate measurements of physical properties require careful core preservation (e.g., vacuum sealing or sleeved liners), precise logging of core diameter, length, and recovery, and measurement of both wet and dry mass (Cosans et al. 2024). Volumetric strain is typically calculated by comparing the bulk density of weathered samples to that of unweathered bedrock, with full recovery and minimal disturbance being critical to reduce uncertainty (Brimhall and Dietrich 1987; Hayes et al. 2019). When measurements of volumetric strain are paired with estimates of total chemical mass loss (tau), the fraction of porosity generated from chemical and physical weathering processes can be calculated to better understand the dominant drivers of porosity production across different landscapes (Riebe et al. 2021).

3 | Water Storage and Partitioning Within the Critical Zone

Quantifying how incoming precipitation is partitioned between vegetation water use, streamflow generation, and shallow and deep groundwater recharge is essential for predicting and preparing for climate-driven changes in forest health and regional water supplies (Fan et al. 2019). The present-day structure of the critical zone including vegetation cover, hillslope steepness, regolith thickness, and bedrock stratigraphy exerts strong controls on how water is stored and routed through terrestrial landscapes (Wlostowski et al. 2021). The variably thick unsaturated zone within soils and weathered bedrock governs both the capacity for plant-available water storage and the timing and magnitude of streamflow and groundwater recharge (Buttle et al. 2004; Dralle et al. 2023; Hahm et al. 2019). While field studies have demonstrated the importance of water storage and cycling within unsaturated weathered bedrock (termed *rock moisture*), rock moisture has received less direct study than soil moisture and groundwater (McCormick et al. 2021). Drilling provides access to both the unsaturated and saturated zones for documentation of moisture dynamics that are essential to resolve critical zone water storage and partitioning.

3.1 | Drilling Depths and Locations

In hydrologic investigations, the success of a drilling campaign is defined by the ability to deploy downhole monitoring tools (i.e., electric water level metres, pressure transducer, neutron probe) within boreholes to quantify subsurface water cycling and storage. In contrast to weathering studies that require high-quality sample recovery, hydrologic drilling prioritises establishing functional boreholes for well installation and long-term monitoring. For instance, installation of open or fully screened boreholes are valuable for tracking water levels in unconfined aquifers, but care must be taken when the goal is to monitor confined groundwater that is disconnected from the overlying vadose zone or perched aquifers. This is critical because isolated water stores may have distinct chemistry and screening specific intervals or nesting wells at discrete depths allows researchers to hydrologically and chemically characterise these unique stores (White et al. 2019). Fluids introduced during drilling may cause temporary artificial water level responses within the monitored boreholes (Figure 6), and sample contamination from the drill fluids must be minimised (see Section 4.2).

Designing borehole placement for ecohydrologic investigations requires careful consideration of subsurface material properties, topographic position, and overlying vegetation and may be limited by access constraints imposed by drilling method selection. Geophysical surveys (e.g., electrical resistivity tomography, seismic refraction) may allow for the identification of the water table and changes in physical properties (e.g., porosity, permeability) that inform borehole placement. To capture different flowpaths associated with topographic position, boreholes should span multiple landscape positions including ridgetop, midslope, the riparian zone, and channels (Gnann et al. 2025). Ridgetops are dominated by vertical recharge with little to no lateral water input from upslope areas, whereas lower landscape positions receive upslope contributions with complex lateral and vertical flow paths. In-stream boreholes, particularly piezometer nests, facilitate direct measurement of groundwater–surface water interactions and hydraulic gradients at the stream (Kalbus et al. 2006; Montgomery and Dietrich 1995). Furthermore, vegetation distribution is critical in site selection to capture how rooting depth, plant water uptake, and canopy interception

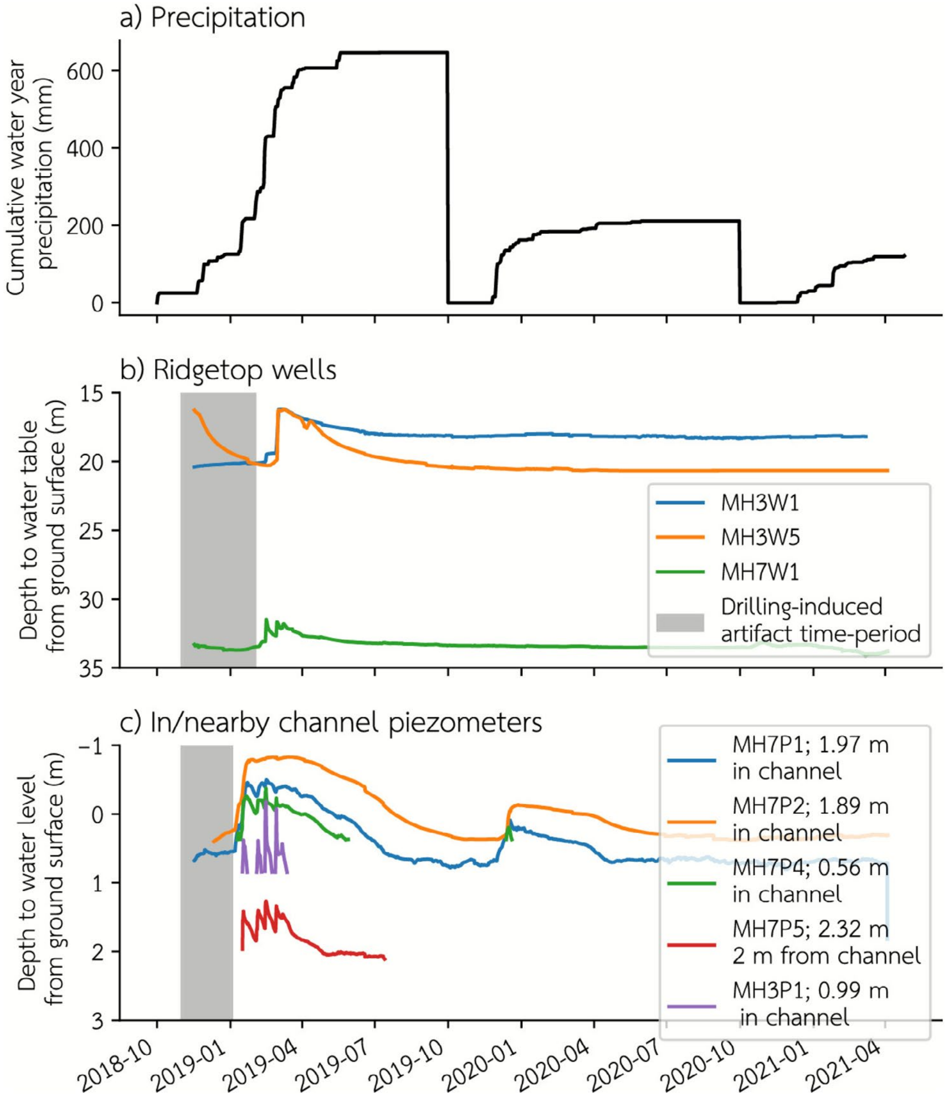

FIGURE 6 | From (Hahm et al. 2022) (a) precipitation, (b) water level responses in screened wells at ridgetops and (c) piezometers in/nearby stream channels. Initial shaded region denotes artificial water level dynamics induced by drilling. Missing data denotes times when water level receded below the transducer. Numbers in legend refer to the depth of the bottom of the piezometer opening from the ground surface.

impact subsurface moisture dynamics (Metzger et al. 2017). Therefore, leveraging site locations with distinct vegetation distributions enables the investigations of plant-water interactions (Zwieniecki and Newton 1996) and the role of vegetation in other processes such as subsurface microbial diversity (Küsel et al. 2016).

3.2 | Groundwater Monitoring

Critical zone studies tend to focus on the dynamics of unconfined hillslope aquifers, though permeability contrasts and shallow stratigraphic layers have been recognised to drive complex, disconnected, and sometimes confined stores of saturated water (Benton et al. 2022; Ohad et al. 2025). The position of the water table is typically documented by establishing boreholes that are completed as wells, with continuously screened or slotted casing. This allows groundwater to freely migrate laterally from the surrounding formation into the well, and the top of the water column is interpreted to be the surface at which water is at atmospheric pressure, the common definition for the water table (Baird and Low 2022; Freeze and Cherry 1979). When vertical gradients in hydraulic heads are of interest or drilling within confined aquifers, boreholes are typically completed as piezometers. In a piezometer, the hydraulic head is measured at only a single point: the opening of the piezometer. When completing a borehole as a well or piezometer, the annulus surrounding the screened interval is commonly backfilled with well-sorted silica sand with a specific grain size that allows for water to move laterally into and out of the screened opening without clogging with finer sediments. Above this layer, bentonite is added to prevent vertical flow of water in the borehole annulus around the casing.

Monitoring groundwater levels in boreholes is typically achieved via deployable electric water level metres (for a single point in time) or in situ pressure transducers (for continuous monitoring). For both approaches, an important step in completing the borehole is to establish an (ideally) permanent stick-up level near the ground surface, which will serve as a reference level for all future measurements and is essential for returning a probe to the same location after removal for maintenance or replacement. To account and correct for atmospheric pressure fluctuations, pressure transducers must be either vented to the surface, or a separate measurement of barometric pressure must be made. These standardised approaches for groundwater monitoring provide a foundation for understanding saturated zone dynamics (See Masood et al. 2022 for more detailed review) but vadose zone characterisation requires different methodological considerations (Arora et al. 2019).

3.3 | Vadose Zone Monitoring

3.3.1 | Time-Domain Methods

Studies of the critical zone extend beyond the traditionally monitored soil layer and into underlying saprolite and weathered bedrock. Within unconsolidated materials like soils or highly weathered saprolite or rock, sensors such as time-domain reflectometry (TDR) and time-domain transmissometry (TDT) are common techniques used to quantify near-continuous water content because they are able to measure the large contrast in the dielectric properties of liquid water and dry soils (Brisco et al. 1992). TDR can be installed in backfilled boreholes; however, moisture contents reflect the hydraulic properties of the backfill material, making it challenging to quantify the magnitude moisture storage change in the vadose zone (Sakaki and Rajaram 2006; Salve et al. 2012; Salve and Rempe 2013). Nonetheless, the timing of wetting is well captured (Salve et al. 2012). TDR probe installations directly into saprolite can capture moisture dynamics; however, gap effects must be minimised and calibrations specific to the saprolite may be needed (Sakaki and Rajaram 2006; Salve et al. 2012; Salve and Rempe 2013). Recently, flexible TDR or TDT sensors have been established to document moisture content in weathered bedrock and saprolite (Dahan et al. 2003; Rimon et al. 2007). These sensors have been deployed on flexible sleeves as part of 'Vadose Zone Monitoring Systems' (VMS). VMS provides a novel and promising approach to quantify water fluxes where the vadose zone is composed of weathered bedrock that is not amenable to conventional water measurements (see Section 4.1 for more details; Dahan et al. 2003, Rimon et al. 2007).

3.3.2 | Downhole Geophysical Methods

Borehole neutron probe surveys and recently, nuclear magnetic resonance (NMR) are reliable tools for point measurements of moisture content within weathered and fractured bedrock (see Flinchum et al. 2019; Lesparre et al. 2020; Schmidt and Rempe 2020 for details; Figure 7). For example, within two seasonally dry sites in California, Schmidt and Rempe (2020) demonstrated that woody-vegetation transpiration drives bedrock water storage depletion, primarily within fractures rather than the fine-grained matrix, and 10%–15% of water storage remained at the end of the dry growing season. These findings reveal that, in some places, vegetation is reliant on water stored within fracture bedrock during the prolonged dry season and suggest that dynamic storage depth may represent effective rooting depth which is otherwise difficult to constrain (Schwinning 2010). Moreover, these methods enable the quantification of interannual water storage carryover that may influence streamflow and groundwater recharge dynamics within the subsequent rainy season (Barling et al. 2025).

Briefly, within a borehole, neutron probes estimate water content with depth by emitting fast neutrons from a radioactive source (Am-241/Be) which are slowed upon interaction

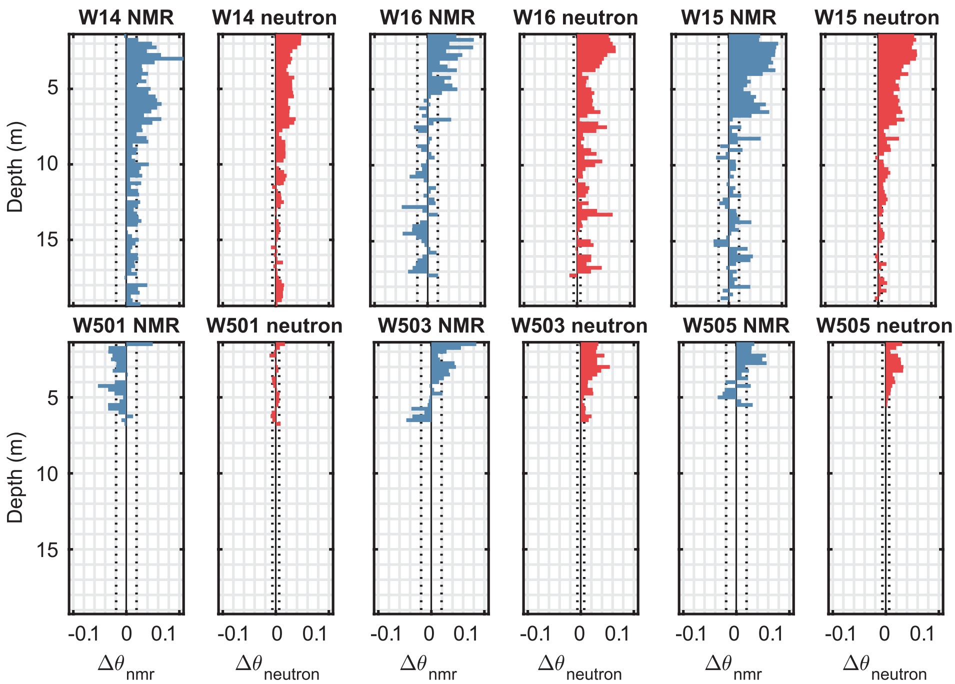

FIGURE 7 | Water content change depth profiles measured with NMR ($\Delta\theta_{nmr}$) and neutron ($\Delta\theta_{neutron}$) well logs in the unsaturated zone between May and October 2017 from two sites in the Northern California Coast Ranges. Figure adapted from Schmidt and Rempe (2020).

with hydrogen atoms primarily in water and backscattered and then counted by the detector (Long and French 1967). In comparison, NMR probes measure the response of hydrogen nuclei in liquid water to magnetic pulses and not only estimate volumetric water content, but also provide information on pore-size distributions through T2 relaxation times, offering insights into the hydrologic function of different pore domains (Behroozmand et al. 2015). The effective measurement radius varies with moisture conditions from 12 to 15 cm (NMR) and 15 to greater than 30 cm (neutron probe) under wet to dry conditions (Gardner 1986; Schmidt and Rempe 2020). Absolute volumetric water content measurements with a neutron probe are challenging and require probe, borehole-diameter, and site-specific calibration equations (Rempe and Dietrich 2018). However, by contrasting a single pair of wet and dry season observations, relative changes in recorded neutron counts can provide an often easier and potentially more precise characterisation of moisture changes (Hahm et al. 2020; Seyfried et al. 2001; Williams and Sinclair 1981).

3.3.3 | Borehole Design Considerations

Proper drilling approaches and borehole construction are essential for obtaining reliable neutron probe and borehole NMR measurements because both methods are highly sensitive to casing material, borehole diameter, and the annular materials surrounding the casing. Ideally, drilling is conducted without water or drilling fluid and with drilling techniques that produce a narrow borehole diameter such as augering, direct push, or air rotary. Neutron probes require a borehole that is relatively narrow ($\leq$10 cm in diameter) to reduce the air space between the probe and the formation (Visvalingam and Tandy 1972). In comparison, downhole NMR may require borehole diameters ranging from 7.5 to 15 cm depending on the NMR probe model and to ensure the probe is centered within the borehole to avoid signal distortion.

For both geophysical methods, the borehole-casing annulus should not be backfilled with materials such as sand, grout, or bentonite which can absorb and release water leading to inaccurate measurements. The ideal casing material for neutron access tubes is aluminium; however, PVC is commonly used because aluminium is incompatible with NMR and other downhole electromagnetic methods. Ideally, the casing is in direct contact with the borehole wall but where an air gap is unavoidable, polyurethane foam may be used, which has previously been shown to not interfere with the neutron probe signal (Tokumoto et al. 2011). Careful discussion with local permitting authorities may be needed to obtain approval for the use of the nonstandard completion protocols described above. While multiple boreholes designed with specific purposes are ideal, in some cases researchers use a single borehole for groundwater and downhole logging but this approach requires careful consideration of water table fluctuations and instrument limitations.

4 | Solutes, Gases, and Microbes Within the Subsurface Critical Zone

Solutes such as major and trace elements reflect water-rock interactions and redox conditions that influence water quality (Fox et al. 2022; Yesavage et al. 2012). Gases such as oxygen, carbon dioxide, and methane are produced and transported within weathered bedrock, where they connect deep subsurface processes including microbial activity, root respiration, and mineral reactions to global carbon and nitrogen cycles (Akob and Küsel 2011; Osorio-Leon et al. 2025). Therefore, critical zone studies increasingly emphasise in situ characterisation of dissolved solutes, isotope systems (i.e., oxygen, hydrogen, lithium), gases, and microorganisms in the vadose zone to better understand ecosystem functions (Golla et al. 2021; von Blanckenburg and Schuessler 2014). Emerging borehole designs, such as VMSs, often integrate hydrologic sensors with water and gas samplers to track subsurface dynamics in situ over time (Rimon et al. 2007). These innovations, coupled with expanding microorganism sampling and core incubation efforts, represent an exciting frontier for quantifying complex biogeochemical interactions (Napieralski et al. 2022).

4.1 | Drilling and Sampling for Solutes, Gases, and Microbes

Water sampling in drilled boreholes is a standard practice for hydrogeologists and has been used to characterise downhole geochemistry and groundwater flow (USGS 2018). Vadose zone sampling has also been widely used in the shallow subsurface using lysimeters and soil gas probes (Hasenmueller et al. 2015; Hodges et al. 2019; Singh et al. 2018). VMSs represent a specialised approach for installing depth-distributed sensors and samplers within boreholes for hydrologic and biogeochemical monitoring below the soil and above groundwater (Linneman et al. 2022). Although designs may vary, VMSs typically include water content, temperature, and matric potential sensors alongside pore water and gas samplers (Figure 8). Example detailed operational descriptions can be found in Dahan et al. (2003) and Rimon et al. (2007). While vertical boreholes have traditionally been used, angled boreholes (35°–55°) are increasingly employed to minimise sediment and water flowpath disturbance (Figure 8). Drilling for angled VMS installations has been done using flight augers, rotary systems, and push probes (Dahan et al. 2003; Rimon et al. 2007). Specifically, boreholes are drilled to a specific diameter (typically 15–20 cm) to accommodate a flexible PVC liner fitted with flexible TDR probes that measure temperature and water content, along with ports designed to collect water held under tension (Tune et al. 2020). A second, co-located borehole can be installed with a sleeve containing sampling ports for freely draining water and perforated tubing for gas sampling. Sensors and ports are positioned on the upward side of the sleeve, which is filled with a two-component urethane resin that expands under hydrostatic pressure to fill the void and seal the installation.

VMSs facilitate depth-resolved gas (i.e., CO_2 and O_2) measurements and sampling alongside water chemistry. Recent studies using VMSs have revealed the importance of co-located gas and water sampling to better understand subsurface carbon cycling in shale-dominated systems. For example, studies have documented substantial subsurface CO_2 production in weathered bedrock that can account for significant portions of surface efflux and export, with seasonal hydrologic dynamics controlling whether carbon is emitted as CO_2 or exported as

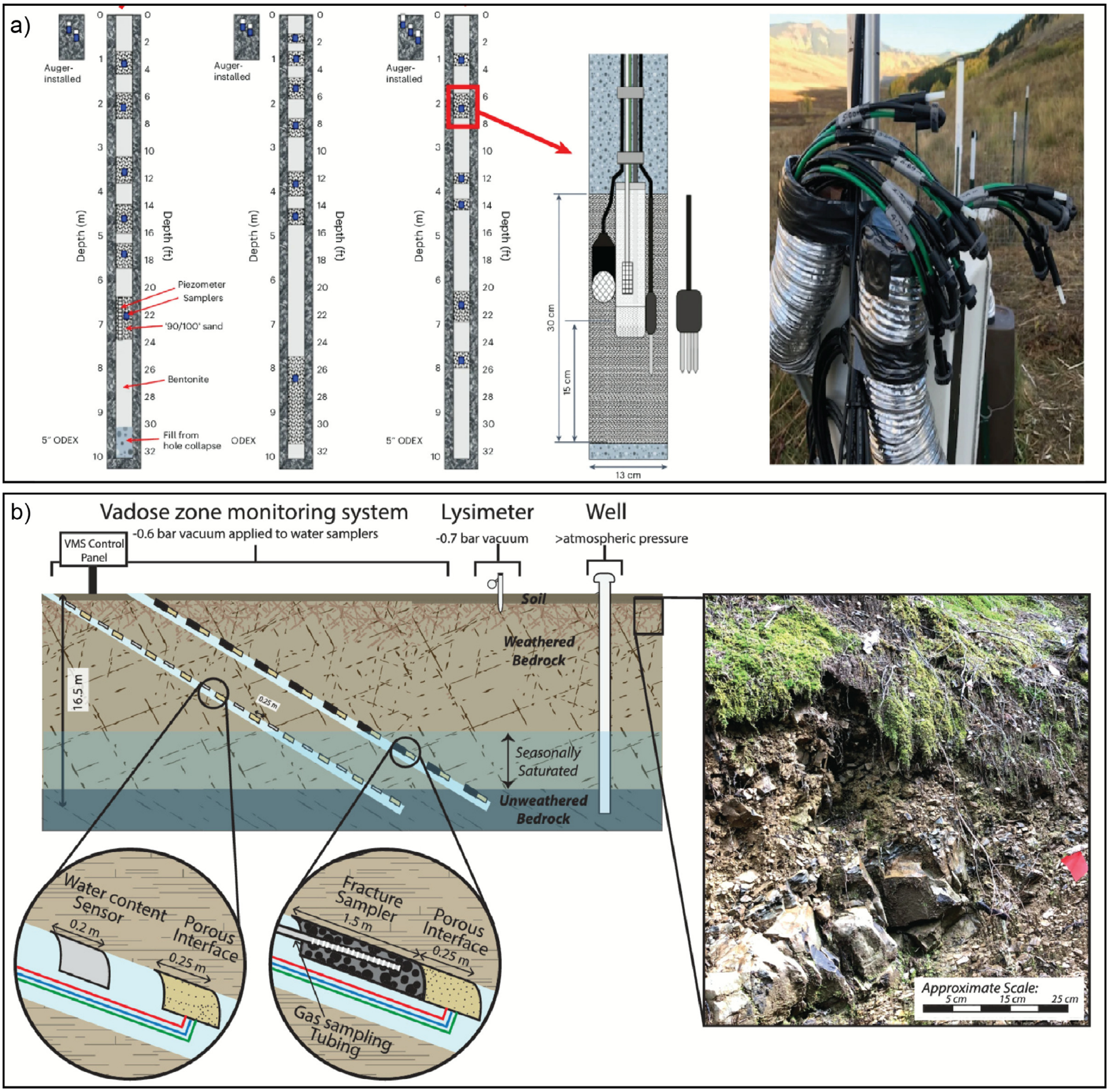

FIGURE 8 | Example (a) vertical and (b) angled instrumentation configurations to monitor and sample vadose zone water and gas dynamics. Figures modified from Wan et al. 2024 and Tune et al. 2020, respectively.

dissolved inorganic carbon (Tune et al. 2020; Wan et al. 2024). Similarly, novel down-borehole designs consisting of a string of CO_2 sensor systems have enabled deep CO_2 measurements that challenge the previously held assumption that petrogenic carbon oxidation is a relatively minor component of the global carbon cycle. For example, Lien et al. (2025) used a passive system to measure CO_2 concentration gradients within fractured black schists in Taiwan to reveal substantial CO_2 fluxes (18.9–132 $\mathrm{mgC\,m^{-2}\,day^{-1}}$) at depths down to 80 m. Together, these borehole-enabled findings demonstrate that organic carbon production and transport within weathered bedrock represents a larger and more complex component of the global carbon budget than previously recognised.

However, in formations with low permeability, such as tight or clay-rich sediments where gases do not readily diffuse and in situ gas sampling via boreholes is challenging, core degassing provides a valuable complementary method. For example, within the Lower Cretaceous Tégulines Clay formation in France, Lerouge et al. (2020) sealed cores in helium-flushed containers and applied core degassing techniques to investigate in situ gas compositions. They observed elevated CO_2 production linked to organic matter degradation, pyrite oxidation, and calcite dissolution down to 10–12 m depth, which aligned with the maximum depth of fossil roots (Lerouge et al. 2020). Through drilling-enabled vadose zone monitoring and sampling, these studies demonstrate that deep seasonal hydrologic dynamics as

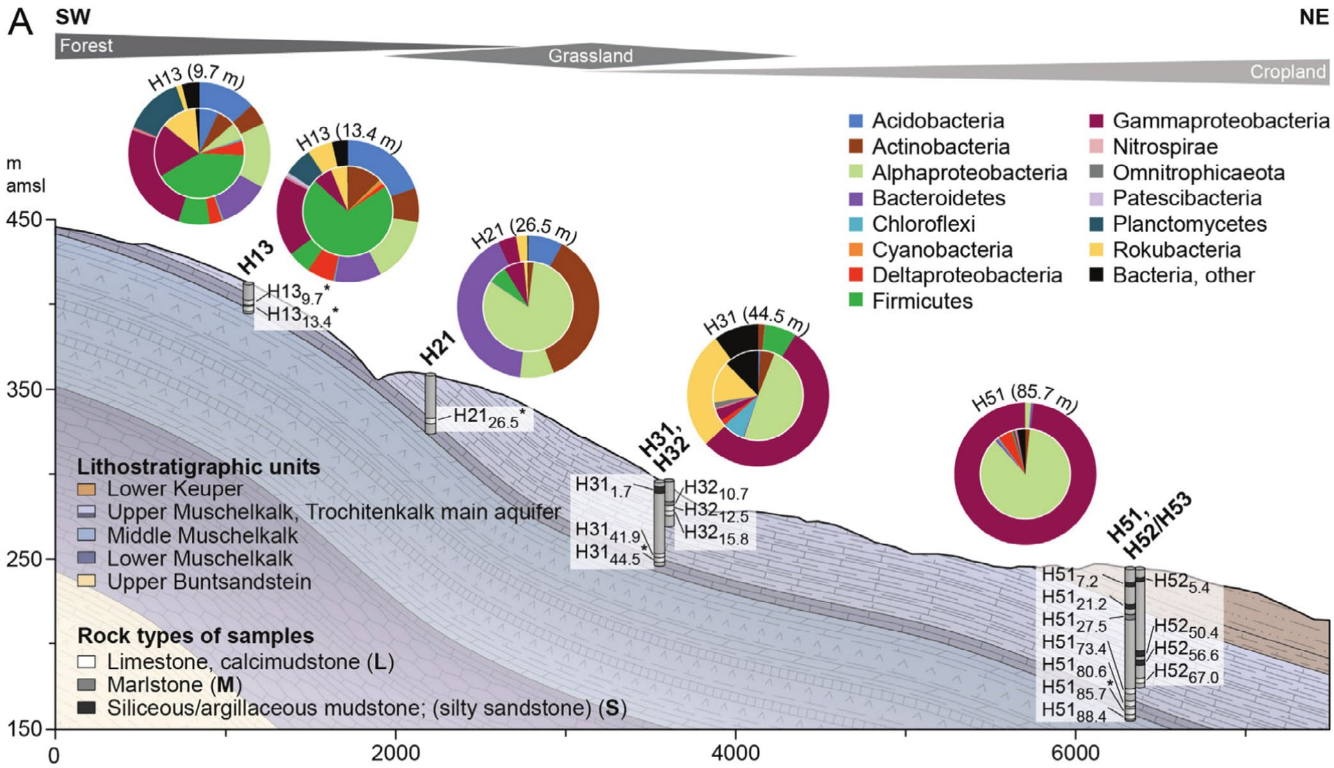

FIGURE 9 | Phylum level bacterial affiliations spanning different strata, depths and topographic positions at the Hainich Critical Zone Exploratory in central Germany. The outer rim corresponds to samples from the fracture surface and the inner circle corresponds to the samples from the rock matrices. Figure adapted from Lazar et al. (2019) which revealed the distinct bacterial communities within the rock matrices, fracture surfaces, and groundwater.

well as past and present biological processes are major drivers of carbon cycling and mineral weathering.

4.2 | Minimising Contamination During Drilling, Sampling and Monitoring

Sampling for water, gases, and microbes within the vadose zone requires careful drilling and sensor installation to minimise contamination (Kallmeyer 2017; Kieft 2010). For example, sampling subsurface water for chemistry and microbial analysis is optimised if drilling fluids are avoided. When fluid circulation is necessary, clean water sources from nearby municipal water supplies or wells must be used in compliance with permitting policies. The use of surface water from streams or lakes is generally not permitted, and commonly poses a greater analytical contamination risk. Fluid additives such as bentonite powder and other viscosifiers and weighting agents may significantly improve core recovery and quality in unconsolidated materials while enhancing borehole stability and drilling performance (Krone et al. 2021). However, the effectiveness of specific fluid compositions may be limited by changes in lithology that typically occur more rapidly than drilling fluids can be adjusted and optimised. Drilling with any fluid circulation is best supported with the addition of a tracer and periodic sampling of the drilling fluid (and any individual additives used) for analysis to determine composition and overlap with analytes of interest. Detailed protocols to track potential contamination effects from drilling have been described by Krone et al. (2021) and Templeton et al. (2021), using a fluorescent pigment tracer based on Friese et al. (2017) and by White et al. (2019) using a LiBr tracer to monitor flushing of drilling fluids from wells prior to sampling.

Beyond standard protocols for water sampling (USGS 2018), drilling to sample microorganisms can require precise drilling and sample handling strategies (Griffin et al. 1997; Kieft 2010). For example, within alternating limestone-mudstone at the Hainich Critical Zone Exploratory, Lazar et al. (2019) used wireline core drilling to reveal that a complex combination of depth below surface, matrix permeability, and mineralogy influenced the bacterial diversity (Figure 9). During the drilling process, they incorporated contamination control measures including de-rusting and steam-cleaning the drilling equipment as well as immediately storing samples in pre-autoclaved bags on dry ice until freezing for long term storage. Similarly, Schwerdhelm et al. (2025) used sterilised tools to extract inner core samples, anoxically stored them at 4°C, and tested drilling fluid against the inner parts of the core for subsequent DNA extractions to conduct microbial cultivation experiments. From these efforts, Schwerdhelm et al. (2025) demonstrated that the deep critical zone (extending to 87 m depth in granitoid quartz monzodiorite rock) contained Fe-metabolising microorganisms that drive weathering despite low precipitation inputs (< 100 mm/year) in the semi-arid Chilean Coastal Cordillera. These anaerobic core handling methods are essential to minimise oxidation during handling, which can significantly alter microbial communities and bias interpretations from oxygen-limited environments. Increased documentation of these drilling protocols enables researchers to accurately quantify subsurface microbial diversity which represents an emerging subdiscipline in critical zone science.

5 | The Future of Critical Zone Drilling

Deep drilling, sampling, and borehole monitoring have revealed that key processes such as mineral weathering, water and nutrient cycling, as well as plant-water uptake and respiration occur well below the soil, extending tens of metres into the weathered bedrock (Hahm et al. 2019; e.g., Krone et al. 2021; Uhlig and von Blanckenburg 2019). This research has only begun to open the 'black box' of the subsurface (Brantley and Lebedeva 2021) and test hypotheses that require direct observations from boreholes combined with near-surface geophysics and process-based models (Fan and Miguez-Macho 2024; Trichandi et al. 2022). Looking ahead, critical zone drilling campaigns should: implement strategic drilling for diverse lithology and multi-objective projects, advance coupling with geophysical methods, and prioritise borehole data-model integration and cross-site comparisons to quantify the dominant controls on critical zone processes across diverse landscapes.

5.1 | Strategic Planning for Diverse Lithology and Steep Slopes

Successful critical zone drilling campaigns require careful consideration of lithologic controls on weathering depth, rock competence, and drilling feasibility to optimise drilling techniques and accomplish project goals. Drilling campaigns across diverse lithologic settings (e.g., carbonate, volcanic, metamorphic bedrock) are essential and each present unique challenges (e.g., fluid loss in carbonate fractures) that require trade-offs between time, cost, depth, and borehole stability. For example, sedimentary rocks commonly have thick weathering profiles requiring deeper boreholes, but they can be more rapidly drilled with cheaper techniques than in fresh crystalline rock, where weathering fronts are shallower. In contrast, collecting core samples from sedimentary lithologies is often more challenging than in fresh crystalline rock, particularly to meet core quality objectives (e.g., Sections 2.2.1, 2.5, 3.1 and 4.2).

Beyond lithologic considerations, site access presents significant challenges in the remote, steep terrain typical of headwater catchments where critical zone processes remain poorly constrained. Portable drilling systems including handheld drills (Pedrazas et al. 2021) and modular systems with components that can be moved by hand or helicopter (Boeckmann et al. 2021; Pierce et al. 2018) enable drilling in otherwise inaccessible locations. Lightweight, high-mobility platforms (e.g., spider excavators) with improved traction and anchoring systems are needed to further enhance drilling operations on steep slopes.

5.2 | Multi-Objective Campaign Design

As project goals become more diverse, compromises and risks become more significant if single boreholes must serve all needs. For example, downhole logging results are best in relatively narrow boreholes designed for the diameters of the logging probes, and drilled with techniques that avoid compromising the borehole wall. Smaller diameter coring systems have been commonly used in critical zone projects due to their broad availability and low cost. Large-diameter coring represents a key opportunity to improve outcomes because it offers greater separation between disturbances caused by the drill bit (e.g., friction, circulating fluids, vibration, heat) and the interior of the core, resulting in improved core recovery, quality, and depth control, and reduced contamination (Annels and Dominy 2003). However, coring operations mechanically disturb borehole walls and require diameters often suboptimal for logging tools. Therefore, while compromises may be justified given limited time, resources, or accessibility, optimal multi-objective campaigns use distinct boreholes, each designed and executed using techniques specific to their intended purpose. Consulting experts in scientific drilling can help to efficiently identify risks, solutions aligned with project goals, and budgetary implications.

5.3 | Downhole, Surface and Airborne Geophysics

Geophysical measurements can image parameters related to weathering, hydrology, and biogeochemistry, providing a means to extend borehole observations to the landscape scale (Parsekian et al. 2015; Oakley et al. 2021). A major limitation of these methods is the uncertainty in linking geophysical signals (e.g., seismic velocity, resistivity, dielectric permittivity) to rock properties (e.g., porosity, permeability, mineralogy, saturation; Parsekian et al. 2015). Many rock-physics models applied in critical zone studies were originally developed for sedimentary reservoir rocks in the oil and gas industry, and therefore may not be applicable for the wide range of weathered materials found in the critical zone. Additionally, scale differences between surface geophysical methods and borehole observations make calibration of rock-physics models challenging (e.g., Callahan et al. 2020). Therefore, future studies should continue to integrate borehole measurements and geophysical methods to improve petrophysical relationships and landscape-scale geophysical interpretations (Knight et al. 2022; Uhlemann et al. 2022).

Recent advances in nodal sensor technology, full waveform inversion, and downhole logging offer new opportunities to produce high-resolution data to help calibrate rock-physics models (Dean et al. 2018; Eppinger et al. 2024). For example, compared to traditional seismic arrays, nodal systems are cheaper, easier to deploy, and capable of dense spatial coverage for fine-scale imaging. Furthermore, full waveform inversions enhance spatial resolution by using the complete seismic wavefield rather than only travel times and provide small-scale images needed for detailed geophysical characterisations. In addition, future studies should integrate in situ geochemical measurements such as downhole X-ray fluorescence (XRF), although improvements in logging speed and sensitivity to borehole-wall conditions are still needed (Queißer et al. 2024). Alternative techniques such as downhole neutron-induced gamma spectroscopy offer a faster logging option for a smaller range of elements (e.g., Ca, Mn, Si, Mg, K and S) and would improve joint geochemical rock-physics models (Queißer et al. 2024).

5.4 | Borehole Data-Model Integration

Integrating borehole-enabled observations of bedrock properties, rooting depths, water cycling, and gas dynamics into process-based models is essential to address pressing ecosystem and water management concerns (Chen et al. 2021; Wang et al. 2025). However, researchers have only recently started to integrate these measurements into ecohydrologic and Earth system models. For example, recent studies demonstrate that incorporating borehole-derived estimates of rock moisture into vegetation models, hydrologic rainfall-runoff models, and reactive transport models dramatically improves their ability to simulate observed transpiration, streamflow, and biogeochemical fluxes (La Follette et al. 2022; Lapides et al. 2024; Osorio-Leon et al. 2025). Borehole-data model integration is required to advance the next generation of hydrologic and Earth system models to improve model interpretation accuracy, predictive power, and guide watershed management decisions (Chen et al. 2021; Wang et al. 2025).

5.5 | Cross-Site Comparisons

The number of drilling locations has greatly expanded over the past 30 years and drilling is now recognised as a vital part of critical zone science (Brantley et al. 2016). Coordinated multi-borehole comparisons across distinct climates, rock types, and vegetation communities are essential to identify both generalisable mechanisms and site-specific controls on critical zone function and evolution (Gu, Rempe, et al. 2020; Richardson et al. 2018). This can be achieved by leveraging archival borehole data to test emerging critical zone hypotheses, and in some cases, by establishing new boreholes to address specific hypotheses or to expand observations into understudied landscapes (e.g., steep tectonically active mountains, tropical, and arctic environments). The critical zone community would greatly benefit from more explicit and transparent reporting of drilling procedures (see Flinchum et al. 2018, Cosans et al. 2024 and Krone et al. 2021 for examples). While full standardisation may be impractical given diverse site conditions and objectives, clear documentation and open sharing of metadata, acquisition parameters for geophysical logs, and derived datasets (e.g., porosity, geochemistry, geophysical logs) are critical for ensuring reproducibility, enabling cross-site comparison, and maximising the long-term value of borehole infrastructure.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** hyp70463-sup-0001-Supinfo.docx.