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### ► To cite this version:

Simone Di Prima, Thierry Winiarski, Rafaël Angulo-Jaramillo, Ryan Stewart, Mirko Castellini, et al.. Detecting infiltrated water and preferential flow pathways through time-lapse ground-penetrating radar surveys. *Science of the Total Environment*, 2020, 726, pp.138511. 10.1016/j.scitotenv.2020.138511 . hal-02565311

**HAL Id: hal-02565311**

**<https://univ-lyon1.hal.science/hal-02565311>**

Submitted on 7 Jan 2021

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1 **Detecting infiltrated water and preferential flow pathways through time-lapse ground-**  
2 **penetrating radar surveys**

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16 **Highlights:**

- 17 • We combined time-lapse GPR surveys with automatized single-ring infiltration tests.  
18 • Preferential flow (PF) paths were detected from the 360-degree view of the wetted zones.  
19 • Results revealed a link between lithological heterogeneity and the occurrence of PF paths.  
20 • Results revealed a link between shrub root system and the occurrence of PF paths.  
21 • The approach offers a simplified way to detect preferential flow pathways in the field.

22 **Abstract**

23 The objective of this paper was to identify the incidence and extent of preferential flow at two  
24 experimental areas located in Lyon, France. We used time-lapse ground-penetrating radar (GPR)  
25 surveys in conjunction with automatized single-ring infiltration experiments to create three-  
26 dimensional (3D) representations of infiltrated water. In total we established three 100 cm × 100 cm  
27 GPR grids and used differenced radargrams from pre- and post-infiltration surveys to detect wetting  
28 patterns. The analyzed time-lapse GPR surveys revealed the linkage between nonuniform flow and  
29 heterogeneous soil structures and plant roots. At the first experimental area, subsurface coarse  
30 gravels acted as capillary barriers that concentrated flow into narrow pathways via funneled flow.  
31 At the second experimental area, the interpolated 3D patterns closely matched direct observation of  
32 dyed patterns, thereby validating the applied protocol. They also highlighted the important role of  
33 plant roots in facilitating preferential water movement through the subsurface. The protocol  
34 presented in this study represents a valuable tool for improving the hydraulic characterization of

35 highly heterogeneous soils, while also alleviating some of the excessive experimental efforts  
36 currently needed to detect preferential flow pathways in the field.

37 **Keywords:** nonuniform flow, GPR, water infiltration, wetting zone, infiltrometer, non-Newtonian  
38 fluid.

## 39 **1. Introduction**

40 Infiltration basins are increasingly used in urban areas for flood protection, groundwater  
41 recharge, and stormwater disposal (Fletcher et al., 2015). To ensure sufficient infiltration capacity,  
42 these structures are usually established over highly permeable and strongly heterogeneous soils.  
43 Water treatment can also occur when mobile contaminants become filtered and sorbed by the soil.  
44 However, the filtration capacity of infiltration basins can be strongly affected by the occurrence of  
45 preferential flow (PF) pathways (Ben Slimene et al., 2017), making it important to detect the  
46 presence of PF, its effect on infiltration, and related risks for groundwater contamination.  
47 Developing non-invasive and easily replicable procedures to study infiltration processes and the  
48 occurrence of PF pathways is crucial for assessing hydraulic functioning of infiltration basins and  
49 other soil-based green infrastructure.

50 Currently, PF pathways are identified either by using invasive techniques (e.g., Abou Najm et  
51 al., 2010; Stewart et al., 2014) or by direct observation of disturbed soil profiles. Dye- staining,  
52 using compounds such as uranine, brilliant blue FCF, or methylene blue, can reveal PF pathways  
53 (e.g., Alaoui et al., 2011; Kodešová et al., 2012; Kung, 1990; Luo et al., 2019; Weiler and Naef,  
54 2003). The dyes can be sprinkled onto the soil surface (Gerke et al., 2015) or injected during  
55 infiltration experiments (Sander and Gerke, 2007), for instance with the help of infiltrometers (Cey  
56 and Rudolph, 2009). However, an adequate observation of deep dye patterns requires sectioning the  
57 soil along different vertical or horizontal planes, which necessitates extensive effort and destroys  
58 the soil in the process. Moreover, dye- staining often only reveals preferential pathways that are

59 directly connected to the source (Beven and Germann, 2013). Other investigations have used  
60 different tracers, such as  $^{18}\text{O}$ -enriched water or bromide, to get an insight on PF (e.g., Ahuja et al.,  
61 1995; Angulo-Jaramillo et al., 2000; Jardine et al., 1989; Köhne and Gerke, 2005). These  
62 approaches require the collection of multiple samples in time and space to get information on tracer  
63 distribution within the porous medium, thus providing only discrete information about the tracer  
64 concentrations.

65 Ground-penetrating radar (GPR) surveys constitute a valid alternative to these traditional  
66 methods for characterizing PF paths. For the purposes of GPR, the soil may be thought of as an  
67 ensemble of multiple homogeneous regions with contrasting electromagnetic properties (e.g.,  
68 dielectric permittivity, electrical conductivity), that are separated by interfaces. A GPR system  
69 sends into the soil a pulse of high-frequency electromagnetic waves (radiowaves) which oscillate  
70 near a particular frequency. When radiowaves come into contact with an interface, portions of the  
71 incoming radiowaves are reflected, transmitted and refracted. A GPR system thus allows the user to  
72 identify these interfaces and thereby gain information about subsurface structures.

73 Water flow within the unsaturated zone causes a variation of the dielectric contrast between  
74 interfaces that alters the reflection coefficient (Truss et al., 2007). These variations are manifested  
75 as amplitude changes. Based on this principle, time-lapse three-dimensional (3D) ground-  
76 penetrating radar surveys can be used to obtain differenced radargrams from pre- and post-wetting  
77 surveys (Birken and Versteeg, 2000), which has been used to investigate links between non-uniform  
78 flow and heterogeneous soil structures. For instance, Kung and Donohue (1991) first used the GPR  
79 method to detect deep soil layers with textural discontinuities that triggered PF paths on a sandy  
80 soil. This technology allowed Harari (1996) to observe non-uniform downward water movement  
81 along more active pathways in sand dunes. Truss et al. (2007) collected two-dimensional (2D) time-  
82 lapse GPR surveys before, during, and after rainfall events. The 2D time-lapse surveys were  
83 subsequently used to create a 3D GPR dataset from which these authors derived the geometry of PF  
84 paths and wetting fronts. Guo et al. (2014) combined trench infiltration tests with time-lapse GPR

85 surveys along parallel transects to study the subsurface hydrologic dynamic of a complex lateral PF  
86 network in a hillslope. Allroggen et al. (2015) studied the potential of time-lapse GPR surveys in  
87 conjunction with rainfall simulations and brilliant blue dye injection to improve the interpretation of  
88 soil cross-sections and wetted patterns photographed after excavating the site. Guo et al. (2020)  
89 combined time-lapse GPR surveys with another non-invasive geophysical technique, electrical  
90 resistivity tomography (ERT), to trace stemflow infiltration and identify root-derived preferential  
91 flow beneath an American beech tree.

92 Similar approaches were adopted by other investigations for non-invasive monitoring of  
93 temporal and spatial distribution of water flow and PF detection (e.g., Birken and Versteeg, 2000;  
94 Guo et al., 2019; Jackisch et al., 2017; Klenk et al., 2015; Trinks et al., 2001). Most of these  
95 investigations were conducted at the hillslope scale along transect survey lines, given that PF  
96 incidence and connectivity need to be characterized at appropriate scales. However, non-uniform  
97 and preferential flow phenomena may be induced by various types of soil heterogeneity (e.g., sealed  
98 soil, multi-porosity and permeability systems, porous media of contrasting materials), and can  
99 emerge at the point scale (Angulo-Jaramillo et al., 2019). In such cases, infiltration measurements  
100 combined with time-lapse GPR surveys may allow for 3D visualization of active preferential  
101 flowpaths. However, obtaining precise 3D imaging of soil wetting at small spatial scale still remains  
102 challenging, as it requires high accuracy in GPR position during the repeated surveys (Allroggen et  
103 al., 2015).

104 In this investigation, we combined time-lapse GPR surveys with automatized single-ring  
105 infiltration experiments to gain insight on the occurrence of PF at two experimental sites located in  
106 Lyon, France. The sites were chosen to represent two different conditions that lead to the  
107 establishment of preferential flows: lithological heterogeneity and deeply developed root systems.  
108 The present study aimed to provide experimental evidence on PF processes, with the specific  
109 objective of evaluating the ability of time-lapse GPR surveys to identify, at a small-plot scale (i.e.,  
110  $100 \times 100$  cm), the incidence and extent of preferential flow. To achieve this objective, we used a

111 non-invasive and easily replicable procedure to visualize the 3D wetting behaviors under ponding  
112 experiments.

## 113 **2. Material and methods**

### 114 **2.1. Experimental areas and sampling scheme**

115 The first field site was a stormwater infiltration basin, named Django Reinhardt basin, located in  
116 Chassieu in the eastern suburbs of Lyon, France. A detailed description of the experimental area can  
117 be found in Goutaland et al. (2008) and Winiarski et al. (2006). The infiltration basin was  
118 constructed above a heterogeneous glaciofluvial deposit by mixing together the upper 50–80 cm of  
119 the soil profile. The glaciofluvial deposit was composed of four main lithofacies: i) the uppermost  
120 mixture of the soil matrix and gravel, ii) a mixture of the soil matrix and gravel with a bimodal  
121 particle size distribution that formed most of the deposit below 50–80 cm, iii) large lenses of sand,  
122 and iv) smaller lenses of matrix-free gravel (Ben Slimene et al., 2017; Goutaland et al., 2013).  
123 Previous investigations identified how PF pathways affect groundwater quality at the studied basin,  
124 especially with regards to the transfer of pollutants (e.g., heavy metals, organics) carried by  
125 infiltrating water (Coutinho et al., 2015; Lassabatere et al., 2010, 2007, 2004). Previous modeling  
126 investigations have reported that lithological heterogeneities in the basin may induce PF, thus  
127 increasing water flux rates by more than a factor of ten compared to surface infiltration rates (Ben  
128 Slimene et al., 2017).

129 For the second site, the trials were carried out in an open-air flume located in an experimental  
130 garden within the La DOUA scientific campus in the municipality of Villeurbanne (France). The  
131 sampled area was colonized by ray grass and a few shrub plants with more developed root systems.  
132 The upper horizon was a mixture of matrix and gravel, 20 cm thick, under which lay a dense  
133 horizon acting as restrictive layer. The two horizons appear quite homogeneous without any  
134 lithological heterogeneity apart from layering. At the DOUA site, we determined the soil bulk  
135 density from 24 undisturbed soil cores ( $\sim 100 \text{ cm}^3$ ) collected at different depths from 0 to 50 cm

136 (Table 1). In contrast to the first site, which was dedicated to the study of the effect of lithological  
137 heterogeneity on flow pattern, this second site was used to detect preferential flow due to plant roots  
138 in a layered profile.

139 Two locations (referred to as A and B) were sampled at the Django Reinhardt infiltration basin  
140 and one (referred to as DOUA) at the experimental site of “Parc de La DOUA”. At each site, a GPR  
141 grid (100 cm × 100 cm), consisting of six horizontal (1-6) and six vertical (A-F) parallel survey  
142 lines with 20 cm intervals between them, was established using white/red signaling tape (**Figure**  
143 **1a-b**). The vertical lines were oriented along the north-south axis. Within each grid, an infiltration  
144 test was conducted. Two GPR surveys were carried out just before and then 20 min after the  
145 infiltration test. A total of 72 (3 sites × 2 GPR surveys × 12 survey lines) time-depth cross-sections  
146 (radargrams) were collected by moving the antenna along the survey lines following the sampling  
147 scheme reported in **Figure 1d**. Radar depth penetration and spatial resolution both vary with  
148 antenna frequency (Guo et al., 2019), so we elected to use a GSSI (Geophysical Survey System  
149 Inc., Salem, NH) SIR 3000 system with a 900-MHz antenna as the best compromise between high  
150 resolution and adequate penetration for the spatial scale of our wetting experiments.

## 151 **2.2. Automated ponding experiments**

152 In this investigation, the use of dyes at the Django Reinhardt basin was restricted for operational  
153 reasons. We therefore infiltrated only water at this location. In contrast, we carried out our  
154 infiltration experiment at the DOUA site using a solution that was prepared by adding 1 g L<sup>-1</sup> of dry  
155 Xanthan gum powder and 1 g L<sup>-1</sup> of brilliant blue dye (E133) to beakers of deionized water and  
156 allowing them to mix with magnetic stirrers. The xanthan gum created a shear-thinning viscous  
157 solution that was expected to fill preferential pathways with limited infiltration into the soil matrix,  
158 and thus reveal complex geometries or macropore networks in highly heterogeneous soils (Abou  
159 Najm and Atallah, 2016; Atallah and Najm, 2019; Stewart et al., 2014). The Xanthan solution was  
160 used to boost preferential flow in the root system of the shrub plants.

161 At each site we used the automated single-ring infiltrometer proposed by Concialdi et al (2020)  
162 to infiltrate a volume of water corresponding to a total cumulative infiltration of 28 cm, based on an  
163 infiltration surface of 94 cm<sup>2</sup> (**Figure 1a-b**). We used a stainless steel ring with a 15-cm inner  
164 diameter inserted shallowly into the soil according to the Beerkan procedure for single-ring  
165 infiltration experiments (Lassabatere et al., 2006). To setup the experiment, we followed the  
166 procedure described in Di Prima (2015) and Di Prima et al. (2016). We firstly positioned a plastic  
167 film on the soil surface inside the ring and applied a small water head of 0.2-0.3 cm, depending on  
168 the surface roughness. The infiltrometer was positioned inside the ring and regulated in height so  
169 that the base was in contact with the ponded water. The Mariotte bottle was filled with the fluid, and  
170 then activated through lifting the piston, at which time data acquisition began. Finally, the  
171 infiltration experiment started when the plastic film was removed. At the DOUA site, the infiltration  
172 surface was established around the root system of hawthorn shrub after removing its shoot system  
173 (**Figure 1c**). At the end of the infiltration experiment, we excavated the soil to expose the dyed  
174 patterns.

175 The automated procedure proposed by Concialdi et al. (2020) to treat the transducer output was  
176 subsequently applied to determine the cumulative infiltration curve. A video tutorial showing the  
177 field procedure and the data processing can be viewed online (Di Prima, 2019). The use of the  
178 automatic infiltrometers in this protocol simplified the field setup, while also reducing the amount  
179 of effort needed to characterize water infiltration. During the infiltration tests the GPR antenna was  
180 maintained in a static position close to the ring with the SIR 3000 sets for point data collection  
181 (**Figure 1a-b**). We recorded a single scan (i.e., one complete reflected wave from transmission to  
182 reception) every one minute in order to monitor the time evolution of infiltrated water. The first ten  
183 scans, representative of the pre-wetting condition, were recorded before starting the infiltration  
184 process. The acquisition was stopped twenty minutes after the end of the test, and a picture of the  
185 infiltration bulb at the infiltration surface was taken. Then we carried out the GPR survey on the



186 established grid. These radargrams were combined with the infiltrometer data. This coupling of  
187 information allowed us to monitor movement of water from the infiltration surface in real-time.

### 188 **2.3. GPR data processing and solid modeling**

189 A GPR display typically consists of a radargram, namely a collection of time-series returns,  
190 giving a time-depth cross-sections (Al-Nuaimy et al., 2002). We processed each collected  
191 radargram using the GSSI Radan 7 software. The process consisted of distance normalization, a  
192 static time shift to align direct ground wave arrival to 0 ns, and exponential scaling to compensate  
193 GPR energy attenuation with propagation depth. In accordance with Truss et al (2007), the same  
194 gain curve (established using the pre-wetting data) was applied to all data acquired within a time-  
195 lapse series. The distance normalization allowed us to obtain an equal distance between the 20 cm  
196 marks taken along the survey line intersections.

197 To determine the appropriate velocity to convert two-way travel times into actual depths we  
198 relied on previous GPR-based sedimentological studies performed on the site (Goutaland et al.,  
199 2013, 2008). Those authors performed a Common-Mid-Point (CMP) acquisition to determine  
200 velocity profiles at two nearby profiles. The velocity profiles were generally uniform, with values  
201 on the order of  $0.1 \text{ m ns}^{-1}$  (**Figure 2a**). In addition, the authors confirmed their estimated velocities  
202 by excavating two trenches and measuring the real distances between soil surface and several  
203 interfaces detected by the GPR, which resulted in mean values of  $0.100$  and  $0.103 \text{ m ns}^{-1}$  for the two  
204 trenches (Goutaland, 2008). Based on these results, we assumed a uniform wave velocity in our  
205 analysis.

206 For each grid area, the amplitude values, G, from the 12 radargrams were combined to build a  
207 unique XYZG dataset, with the X, Y, and Z values representing location coordinates (easting,  
208 northing, and elevation). The elevation, Z, was determined from the wave time, given by GPR  
209 acquisition and considering the value of wave velocity mentioned above. We therefore obtained  
210 three pre-wetting and three post-wetting XYZG datasets, one for each site (**Figure 3**).

211 Next, we created three other datasets based on absolute differences between pre- and post-  
212 wetting G values. Indeed, water flowing within the unsaturated zone caused a variation of the  
213 dielectric contrast between layers that altered the reflection coefficient (Truss et al., 2007). These  
214 variations were manifested as amplitude changes. Therefore, the differenced datasets were  
215 constructed to highlight the amplitude fluctuations between repeated GPR radargrams collected  
216 over the same survey lines before and after the infiltration tests (e.g., Guo et al., 2019; Holden,  
217 2004). We assumed that the absolute difference between the pre- and post-wetting amplitude values  
218 were negatively correlated with the soil water pressure head (Birken and Versteeg, 2000). We  
219 therefore expected strongest reflection differences in correspondence to the saturated soil bulb that  
220 extended outwards from the infiltration surface, and decreasing reflection differences in the  
221 partially saturated (transmission) zone that surrounded the wetting bulb. In this zone, the water  
222 pressure head decreases as the wetting front moves away due to soil capillarity from the saturated  
223 bulb (Angulo-Jaramillo et al., 2016). For each site, we considered all differential amplitude values  
224 greater than 1.5 standard deviations of the mean absolute amplitude for each differenced XYZG  
225 dataset to represent substantial changes in reflection due to infiltrated water. A similar criterion  
226 considering amplitudes greater than two standard deviations from the mean was used by Guo et al.  
227 (2019) to identify preferential flow through saprock. Note that we used a less strict criterion because  
228 we were interested in identifying the entire wetted soil volume.

229 The interpretation of differenced radargrams may be complicated by the occurrence of spurious  
230 amplitude differences due to geometrical mismatches between measurements. In addition,  
231 infiltrated water causes an increase in bulk dielectric constant, which in turn increases the travel  
232 time and lowers the reflection position, resulting in net time shifts (Truss et al., 2007). To alleviate  
233 these problems, we smoothed the radargrams by applying a moving-average filter with a window of  
234 7 vertical time samples and 5 horizontal traces. This procedure allowed us to reduce the geometric  
235 mismatch between time-lapse survey lines, yielding lower differences between corresponding pre-  
236 and post-wetting amplitude values. A similar approach was also adopted by Guo et al. (2014), who

237 corrected the mismatch in the Z direction by stacking successive samples on each trace using their  
238 mean value.

239 In this investigation, we checked the efficiency of the moving-average filter by comparing the  
240 absolute differences between the pre- and post-wetting amplitudes of the processed and unprocessed  
241 data. **Figure 2b** depicts an example involving two survey lines at Site A. In this example, only  
242 Survey line 2 crosses the infiltration bulb. Consequently, for this survey line the amplitude values  
243 substantially increased after the infiltration of water. That is the reason why the magnitudes scored  
244 approximately 0.0318 for Survey Line 2 (impacted by the infiltration bulb) versus 0.0185 for  
245 Survey Line 1 (less impacted by the infiltration bulb). However, in both cases, the moving-average  
246 filter reduced the difference in amplitude, with a shift from 0.0328 to 0.0318 for Survey Line 2, and  
247 0.0188 to 0.0185 for Survey Line 1 (Figure 2b). In both cases, the mismatch correction was  
248 effective, yielding smaller differences between pre- and post-wetting. Based on this finding, we  
249 were confident that this process reduced the difference in amplitude that resulted from the time shift  
250 induced by the change of velocity with wetting, while keeping the difference in amplitude that  
251 resulted from the change in water content.

252 We used the RockWorks 17 software (RockWare, Inc., 2015) and the inverse-distance  
253 anisotropic modeling method to perform a 3D interpolation of the differenced datasets. This type of  
254 directional search can improve the interpolation of voxel (volumetric picture element) values that  
255 lie between data point clusters, and it has been applied in different geophysical investigations (e.g.,  
256 Attwa and El-Shinawi, 2017; Lange-Athinodorou et al., 2019; Longo et al., 2014). Here, the method  
257 assigned a voxel node value on the basis of the weighted average of neighboring data points looking  
258 in each 90-degree sector around the node. The amplitude value of each data point was weighted  
259 according the inverse of its distance from the voxel node, taken to a power of 2 (inverse-distance  
260 squared).

## 261 3. Results

### 262 3.1. Determination of the 3D representation of wetted zones

263 The GPR determination of the wetted zone is illustrated for the Django Reinhardt site. The  
264 absolute differences between the pre- and post-wetting amplitude values ranged from 0 to 0.394 for  
265 Site A and from 0 to 0.293 for Site B. According to our stated criterion (i.e., amplitude values  
266 greater than 1.5 standard deviations), the estimated thresholds used to filter the differenced XYZG  
267 datasets were equal to 0.04 (Site A) and 0.025 (Site B), which corresponded to cumulative  
268 frequencies of 0.92 and 0.88 (**Figure 4**). Thus, only 8 to 12% of the amplitude values measured by  
269 the radargrams showed substantial changes between pre- and post-wetting.

270 After filtering, 3D interpolation was used to visualize and quantify the wetted soil volumes  
271 associated with each infiltration experiment. The 3D diagrams clearly demarcated the dimensions  
272 and shapes of the wetted zones created during both experiments (**Figures 5a** and **5f**). Then, we  
273 compared these demarcated wetted zones with the observations of the infiltration bulbs at the soil  
274 surface at the end of the experiment. **Figure 6** illustrates the comparison between the observed  
275 infiltration bulb at the surface (**Figure 6a**, delineated on the picture) and the expansion of the  
276 wetted zone in the 3D diagram at the soil surface (**Figure 6b**), based on results from Site A. Similar  
277 results were obtained for Site B. The correspondence between the two shapes constituted a first  
278 encouraging signal of the validity of the 3D interpolation procedure to determine the wetted pattern  
279 at the soil surface. However, dye-staining results obtained at the DOUA site better supported the  
280 use of GPR to identify 3D wetting patterns, as discussed in the next section.

281 Both experiments had hemispherical-shaped wetted zones in the upper soil horizon that extended  
282 to depths of approximately 20 cm (**Figure 5**: Site A in subpanels **c-d** and Site B in subpanels **h-j**).  
283 In this hemispherical zone, infiltration was mainly controlled by the matrix, resulting in a uniform  
284 distribution of water. Below this upper layer, the wetting patterns became vertically elongated and  
285 irregularly shaped. As discussed in the next section, these patterns were assumed to be associated  
286 with PF paths (Regalado et al., 2005). The estimated volumes of the wetted zones were 48.1 L (Site

287 A) and 72.8 L (Site B), with the second volume characterized by lower reflection changes (**Figure**  
288 **7**). Given that identical volumes of water infiltrated during the tests at both locations, we argue that  
289 the expansion of the wetting front due to capillary forces was more relevant at Site B, yielding a  
290 larger volume of wetted soil with a smaller degree of wetting (Moncef et al., 2002).

### 291 **3.2. Detection of preferential flow pathways**

292 At the DOUA site, dyed zones were observed after excavating the soil (**Figure 8**). The use of  
293 time-lapse GPR surveys in conjunction with staining-dye tracer allowed us to verify the 3D  
294 interpolation procedure. The GPR data resolved water perching above a shallow restrictive layer  
295 (demarcated zone **Z1** in **Figure 8a-c**), which was confirmed by the concentration of dye at that  
296 interface (**Figure 8c**). Below this layer, the 3D diagram showed elongated and irregularly shaped  
297 wetting patterns (demarcated zones **Z2** and **Z3** in **Figure 8a-b**), which corresponded with roots  
298 present at 30 and 40 cm depths (demarcated zones **Z2** and **Z3** in **Figure 8c**). The GPR data and dye  
299 staining patterns therefore both indicated that water infiltrated through this restrictive layer mainly  
300 following the plant root system, revealing that roots act as important flow pathways at the studied  
301 site.

302 At the Django Reinhardt basin, the use of dyes was restricted for operational reasons; thus, the  
303 main PF paths were firstly identified from the 360-degree view of the wetted zones. Then,  
304 horizontal and vertical slices were extracted from the 3D diagrams to identify zones with strong  
305 reflection differences corresponding to patches of wetted soil located below the main wetting front  
306 (**Figure 5**: Site A in subpanels **c-e** and Site B in subpanels **h-j**; also shown in a video included as  
307 supplementary material). The slices were then overlapped with the pre-wetting radargrams to  
308 identify the source of spatial heterogeneity that triggered PF. In both sites, subsurface coarse gravels  
309 with low capillarity, and thus low unsaturated hydraulic conductivity (Goutaland et al., 2013), acted  
310 as capillary barriers that concentrated flow into relatively narrow pathways (**Figure 9**), in a process  
311 commonly referred to as funneled flow (Kung, 1990). In Site A, the 3D diagram showed that flow

312 channeling occurred at a depth of 22 cm. In the underlying horizons the soil had finer soil textures  
313 and likely greater capillary forces, which encouraged lateral spreading of the wetting front. In Site  
314 B, the 3D diagram showed that flow channeling occurred at a depth of 43 cm. The wetting front  
315 exceeded the maximum soil depth sampled by GPR surveys in Site B (70 cm). As a result, the  
316 wetted soil volume was likely underestimated at this location.

### 317 **3.3. Real time monitoring of infiltration at surface (GPR punctual acquisition)**

318 We also analyzed the ability of GPR punctual acquisition to provide real-time monitoring of  
319 infiltration processes from the soil surface. Our first finding here was that no clear information is  
320 provided when the wetting bulb is too small to be detected by the antenna. That was the case of the  
321 location B of the Django Reinhardt site. The wetted zone here expanded mainly in the southeast  
322 direction, far from the position of the antenna (which was located northwest side of the ring).  
323 Consequently, the point GPR measurements collected during the infiltration test at that site did not  
324 provide clear evidence of water flow.

325 However, we measured substantial reflection changes below the antenna position during the  
326 infiltration test at Site A, where initial infiltration rates were relatively low before starting to  
327 increase ~2 minutes after the start of the experiment (**Figure 10**). The resultant cumulative  
328 infiltration curve exhibited a convex shape typically associated with soil water repellency (Alagna  
329 et al., 2018; Di Prima et al., 2019; Lassabatere et al., 2019a). This infiltration impedance caused a  
330 delayed response of reflection changes, which were initially detected 3 minutes after infiltration  
331 started (**Figure 10a**). In addition, the antenna was positioned at the northwest edge of the  
332 infiltrometer, so detection was possible only after sufficient lateral expansion of the wetted zone. At  
333 the end of the infiltration test (i.e., at time = 18 min), a strong increase in signal amplitude appeared  
334 at approximate depths of 50 and 70 cm, indicating the wetting zone reached the lower boundary of  
335 70 cm (**Figure 10a**). After that, drainage and water redistribution rates diminished and the water  
336 profile approached hydrostatic conditions, as signaled by constant amplitudes for the final 15

337 minutes of the measurement. Because the wetted zone did not change in shape and dimension at the  
338 end of the infiltration run, we assume that water drainage and redistribution was slow enough to  
339 allow proper acquisition of GPR over the complete grid survey. In other words, the last GPR  
340 acquisition (last Survey line) described the same soil moisture condition than the first survey line.  
341 Consequently, all survey lines described the same wetted zone and can be concatenated to form a  
342 3D representation of the entire wetted zone.

343 GPR punctual acquisition and time-lapse GPR (3D block) were crossed-checked. At the end of  
344 the measurement, we identified the depth of the stronger signal amplitudes in the final scans of the  
345 radargram (**Figure 10a**). We subsequently extracted horizontal slices from 3D diagram at the  
346 corresponding depths (**Figure 10b**). There was a perfect agreement between stronger signal  
347 amplitudes and the occurrence of deep wetter patches positioned vertically below the antenna.  
348 These observations increased our confidence in the 3D interpolation procedure that was previously  
349 performed to determine the wetted zone volume.

#### 350 **4. Discussion**

351 The use of time-lapse GPR surveys in conjunction with staining-dye tracer at the DOUA site  
352 allowed us to verify the 3D interpolation procedure. Here the comparison confirmed that the GPR  
353 was able to accurately resolve perched water above a shallow restrictive layer along with deeper  
354 preferential flow associated with a shrub plant root system (**Figure 8**). That pattern is in line with  
355 the expected water infiltration in layered systems and with the potential role of leaks by the plant  
356 root systems in layered soils (Gerke et al., 2015). However, the wetted zones detected by the GPR  
357 in the vicinity of the root system were larger than the zones visibly stained with dye. Further  
358 investigations are thus needed to better understand the dimensions of flow pathways detectable with  
359 GPR, including whether the technology is able to resolve very small fingers or pores.

360 For the Django Reinhardt site, we observed a uniform distribution of water with hemispherical-  
361 shaped wetted zones in the upper layer where the soil matrix controlled water flow, and vertically

362 elongated and irregularly shaped wetting patterns corresponding to the coarse gravels below.  
363 Therefore, the 3D observation of the wetted zones using GPR allowed the detection of preferential  
364 funneled flow due to lithological heterogeneities. This result can be viewed as an experimental  
365 confirmation of previous modeling investigations carried out at the same infiltration basin by  
366 Coutinho et al. (2015) and Ben Slimene et al. (2017). The latter study speculated that lithological  
367 heterogeneities in the basin (e.g., the subsurface gravel lenses) may induce funneled flow, so the  
368 present study provides experimental evidence showing that this process does commonly occur (as  
369 we observed PF at both tested locations). Moreover, the 3D diagrams provided additional insight  
370 into spatial differences in PF processes. Here, the depth of funneled flow varied between locations  
371 in the same site, as did the subsequent shape, volume, and depth of wetting in the finer-textured  
372 underlying soil. The two infiltration tests introduced nearly identical volumes of water into the soil,  
373 so the GPR scans were crucial to identify actual differences in infiltration and wetting that occurred.

374 Our findings clearly show that GPR can be used for the detection for preferential flow and to get  
375 a picture of water pathways for both cases: lithological heterogeneity and root systems. These data  
376 have notable practical applications. For example, infiltration patterns measured at the surface of a  
377 stratified medium are often influenced by hydraulic behaviors of any restrictive layers, yet  
378 infiltration data alone typically do not contain sufficient information to characterize different layers.  
379 This limitation was identified by Lassabatere et al. (2010) for the case of the sediment settlement in  
380 the Django Reinhardt basin, as well as by many authors in other locations (e.g., Alagna et al., 2019;  
381 Di Prima et al., 2018; Yilmaz et al., 2013, 2010). Similarly, when water flows simultaneously  
382 through the soil matrix and a macropore network, both flow domains contribute to the hydraulic  
383 properties of the soil (Lassabatere et al., 2019b, 2014; Stewart, 2019). Our analysis showed that  
384 non-uniform wetting patterns are detectable using GPR, so this information could be used to  
385 improve the parameterization of hydraulic properties for both homogeneous and heterogeneous  
386 soils.



387 One potential limitation of the applied protocol is the uncertainty associated with spurious  
388 amplitude differences. This problem depends in part on small differences of the antenna position  
389 between successive surveys. Also, the lowering of the reflection position after the increase of the  
390 water content may induce a time shift and consequently a mismatch in the vertical direction. In this  
391 investigation, we alleviated these problems, at least in part, by smoothing the radargrams both in the  
392 horizontal and vertical directions. The smoothing process proved satisfactory for removing these  
393 potential artifacts while retaining sufficient resolution to demarcate the extent and degree of wetting  
394 during localized infiltration processes. Therefore, we encourage other practitioners to employ  
395 similar techniques when using GPR-based measurements to analyze preferential wetting behaviors.

## 396 **5. Summary and conclusions**

397 In this study, we combined time-lapse GPR surveys with automated single-ring infiltration  
398 experiments. The proposed procedure used non-invasive monitoring of the spatial distribution of  
399 infiltrated water to create 3D representations of infiltrated water. A dye-staining experiment  
400 conducted at one of the experimental sites provided verification that the applied procedure was able  
401 to identify preferential flow caused by shrub roots. In all experimental sites, the 3D diagrams  
402 created using the proposed procedure clearly demarcated the wetting zone dimensions and shapes,  
403 and facilitated detection of preferential flow pathways and funneled flow in the subsurface. In the  
404 future such information may serve to verify hydraulic characterization procedures using water  
405 infiltration experiments, and may be particularly useful in highly heterogeneous soils, including  
406 sealed soils, multi-porosity/multi-permeability systems, and stratified profiles. Indeed, this study  
407 can be viewed as a step towards time-lapse GPR surveys becoming more widely applied in the field  
408 as a reliable and non-invasive way for investigating linkages between non-uniform flow and  
409 heterogeneous soil structures.

410

411 **Funding:** This work was supported through i) the INFILTRON Project (ANR-17-CE04-0010,  
412 Package for assessing infiltration & filtration functions of urban soils in stormwater management;  
413 <https://infiltron.org/>), ii) the European Regional Development Fund (ERDF) and the Italian Ministry  
414 of Education, University and Research (MIUR) through the “Programma Operativo Nazionale  
415 (PON) Ricerca e Innovazione 2014-2020 (Linea 1 - Mobilità dei ricercatori, AIM1853149, CUP:  
416 J54I18000120001), and iii) the Short Term Mobility (STM) Program 2019 of CNR (Research  
417 Programme: “Innovative techniques for hydraulic characterization of soil”).

418 **Acknowledgements:** The authors thank Sara Puijalon and the Lyon city Field Observatory for  
419 Urban Water Management (OTHU), for technical and scientific support, and Jean-Philippe Bedell  
420 for advices on plant root systems.

421 **Author Contributions:** S. Di Prima and L. Lassabatere outlined the investigation and carried out  
422 the field experiments at the Django Reinhardt infiltration basin. S. Di Prima and G. Capello carried  
423 out the field experiment at the DOUA site. S. Di Prima analyzed the data and created the video. All  
424 authors contributed to discussing the results and writing the manuscript.

425 **Conflicts of Interest:** The authors declare no conflict of interest.

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606

607 **List of Figures**

608 **Figure 1.** Experimental setup at the (a) Django Reinhardt infiltration basin and (b) Parc de La  
609 DOUA. (c) Infiltration surface at the Parc de La DOUA established in correspondence of a  
610 hawthorn shrub after cutting its shoot system. (d) Scheme of the GPR survey lines.

611 **Figure 2.** (a) Common-Mid-Point (CMP) determination of the velocity profile over depth (acquired  
612 in previous studies and adapted from Goutaland, 2008), and (b) comparison of the absolute  
613 differences between the pre- and post-wetting amplitudes of Survey lines 1 and 2 at the A site,  
614 with and without the filter.

615 **Figure 3.** Flowchart illustrating the procedure to obtain the 3D diagram of the wetting zone from  
616 pre- and post-wetting ground-penetrating radar surveys.

617 **Figure 4.** Cumulative frequency distributions of the absolute difference between pre- and post-  
618 wetting amplitude values for the A and B sites. The identified thresholds in amplitude  
619 differences (0.04 and 0.025) correspond to frequencies that were 1.5 times the standard  
620 deviations of each dataset.

621 **Figure 5.** (a), (f): Three-dimensional representation of the wetting zones at Sites A and B. (b), (e),  
622 (g), (j): Horizontal slices extracted from the 3D diagrams at different depths from the soil  
623 surface. (c), (h): North-south oriented (east view) and (d), (i): West-east oriented (south view)  
624 vertical slices. Red arrows highlight the detected preferential flow pathways. Colors scales  
625 indicate the absolute difference between pre- and post-wetting amplitude values. A video  
626 included as supplementary material shows a 360-degree view of wetting zone at Site A.

627 **Figure 6.** Comparison between (a) the infiltration bulb observed at the end of the experiment  
628 (delineated on the picture) and (b) the wetted zone identified by GPR survey at the soil surface  
629 for Site A.

630 **Figure 7.** Volumes of the wetted zones for Sites A and B (left Y-axes) and associated cumulative  
631 frequency distributions (right Y-axis) of the interpolated values that define the color ranges of  
632 the solid diagrams.

633 **Figure 8. (a):** Three-dimensional representation of the wetting zones at the DOUA site. **(b):**  
634 Horizontal and vertical slices extracted from the 3D diagrams. **(c):** Picture of the soil profile  
635 excavated after the post-wetting GPR survey. The green and red demarcated zones **Z2** and **Z3**  
636 highlight bypass flow within the plant root system. The yellow demarcated zone **Z1** highlights  
637 the accumulation of water within the interface of the two layers.

638 **Figure 9.** Overlapping of selected vertical slices extracted from 3D diagrams with the pre-wetting  
639 radargrams. Red arrows highlight the detected preferential funneled flow.

640 **Figure 10. (a)** Overlapping of the cumulative infiltration curve with the radargram measured at the  
641 A site during the infiltration test. **(b)** Horizontal slices extracted from the 3D diagram at depths  
642 corresponding to the strongest changes in signal amplitudes.

643

644 **Table 1.** Bulk density values ( $\text{g cm}^{-3}$ ) measured at the DOUA site.

Depth (cm)	Sample size	Min	Mean	Max
0-10	9	0.928	1.074	1.173
10-20	3	1.046	1.090	1.168
20-30	6	1.349	1.479	1.648
30-40	3	1.587	1.658	1.738
40-50	3	1.677	1.716	1.763

645



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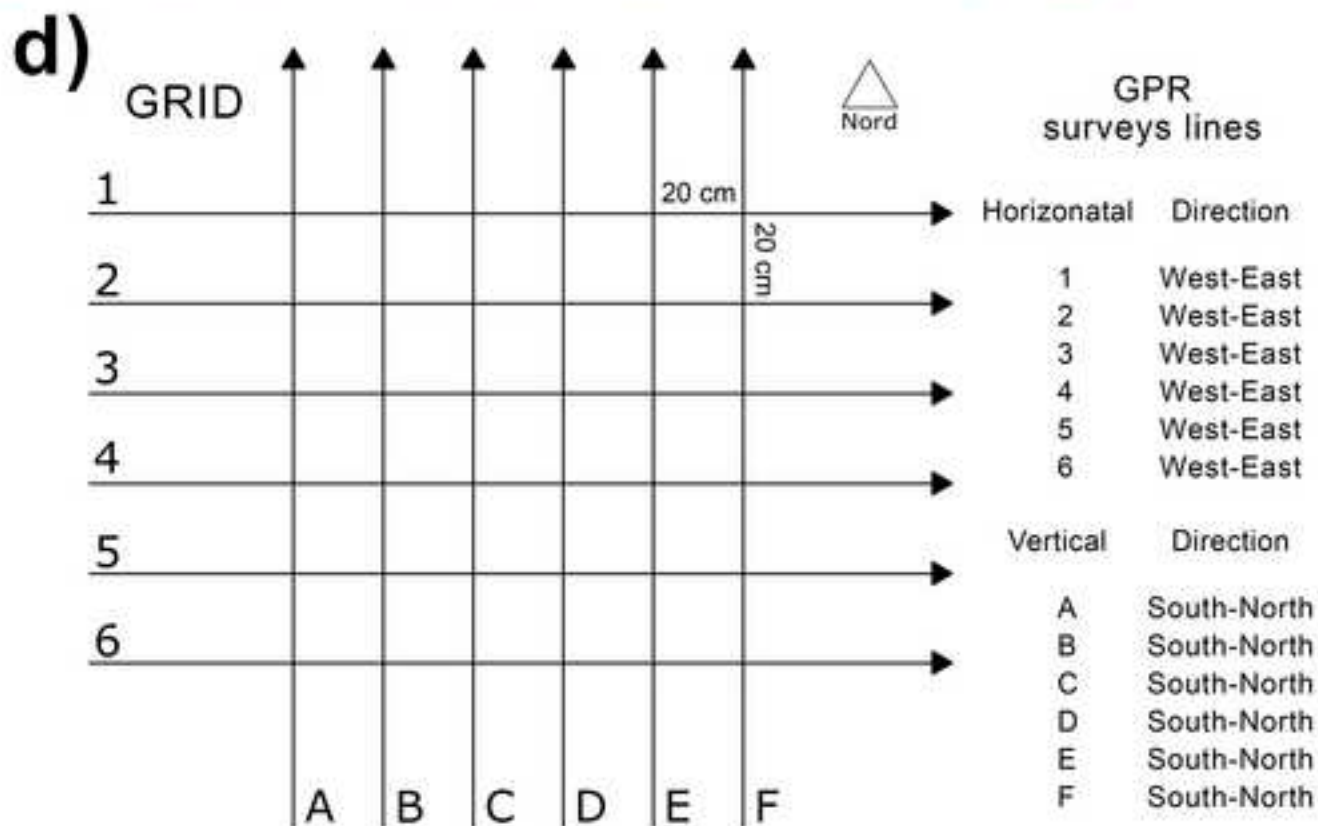
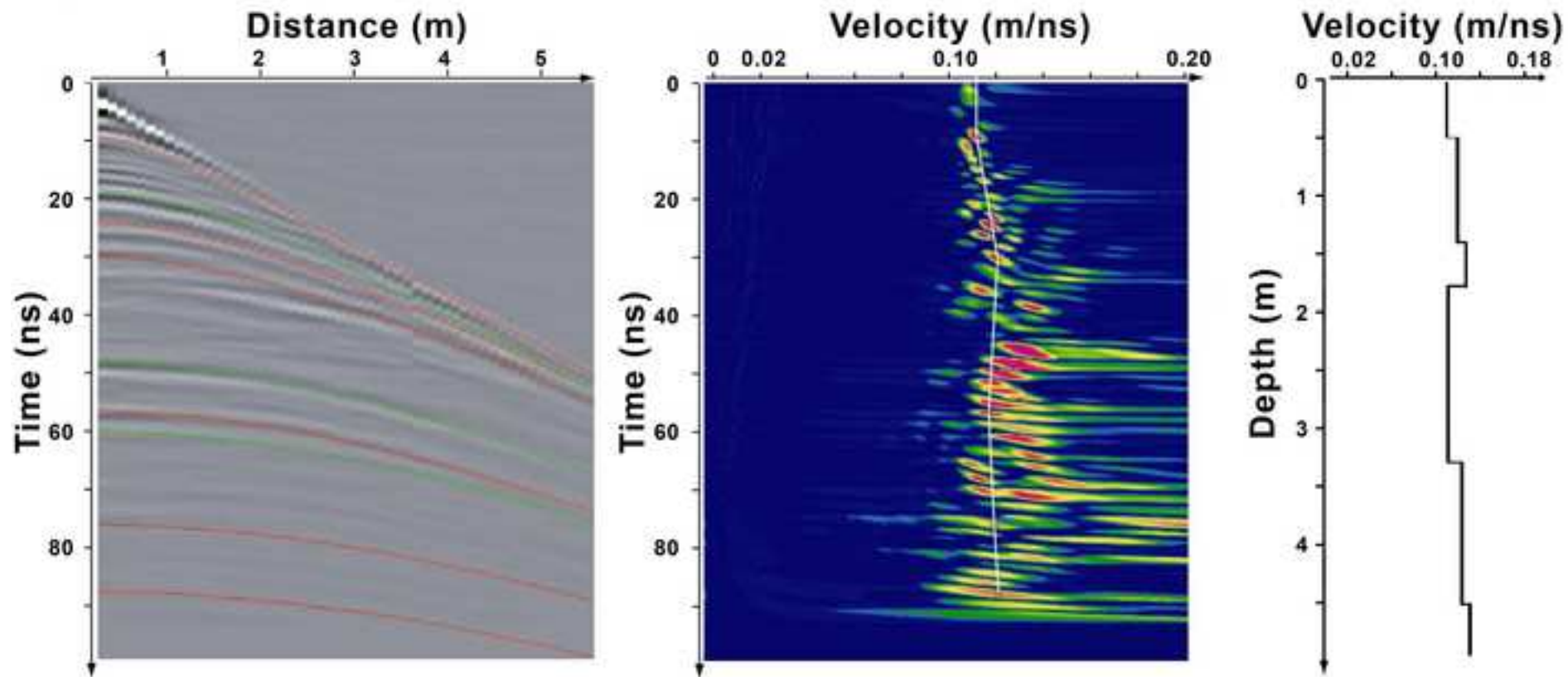


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### a) CMP and velocity profile



### b) Moving average filter and magnitude difference

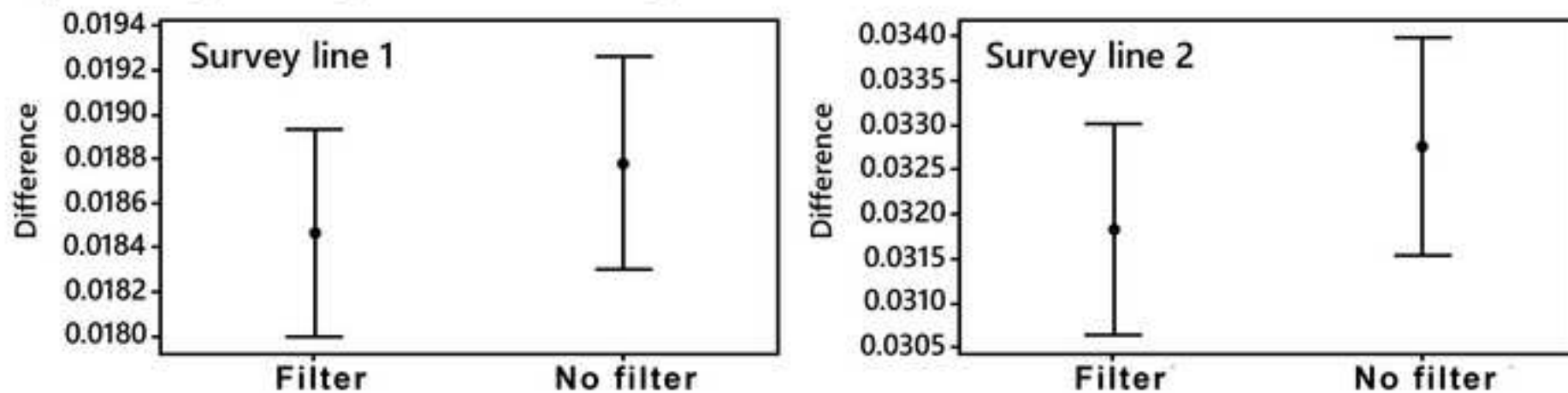




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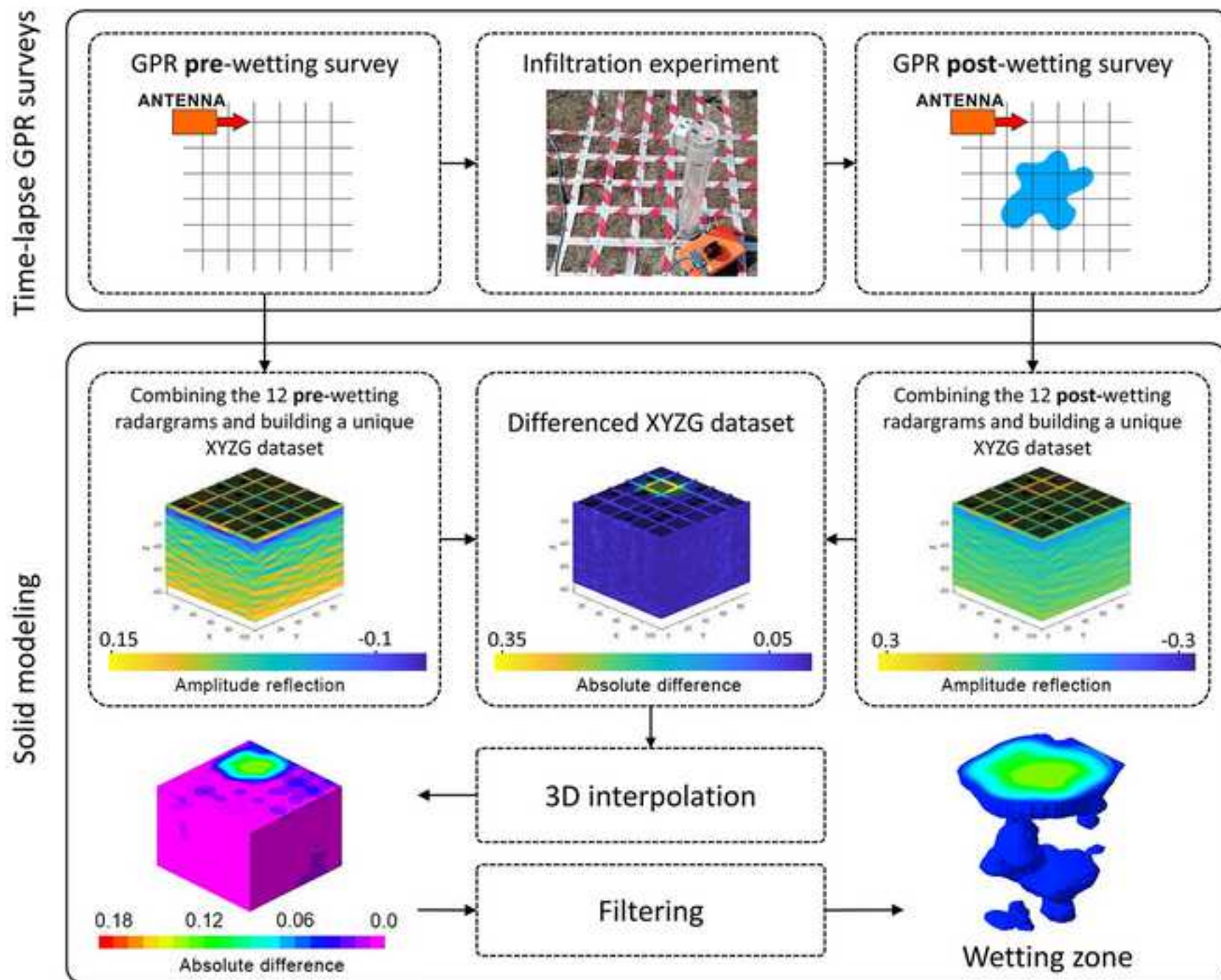


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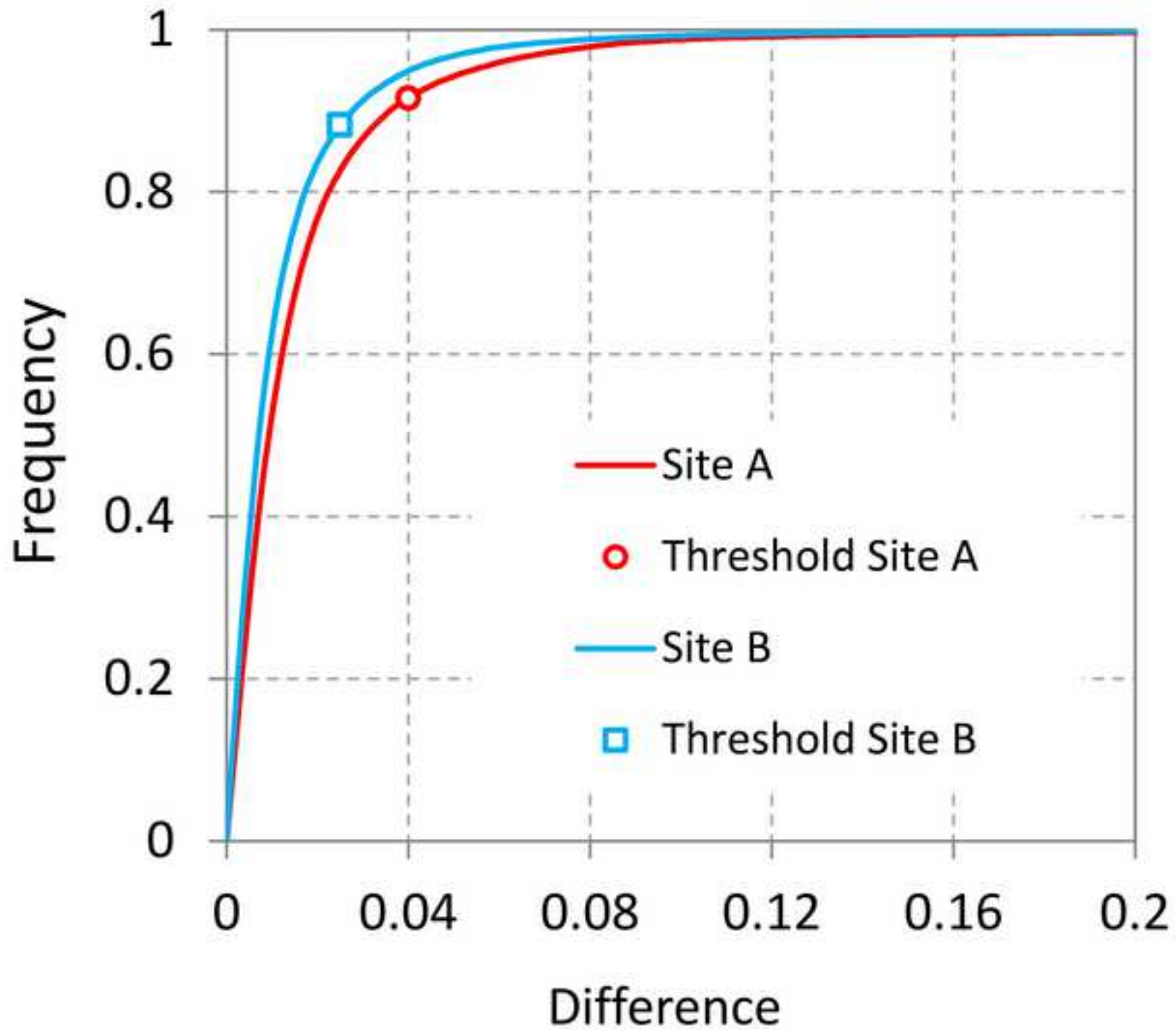


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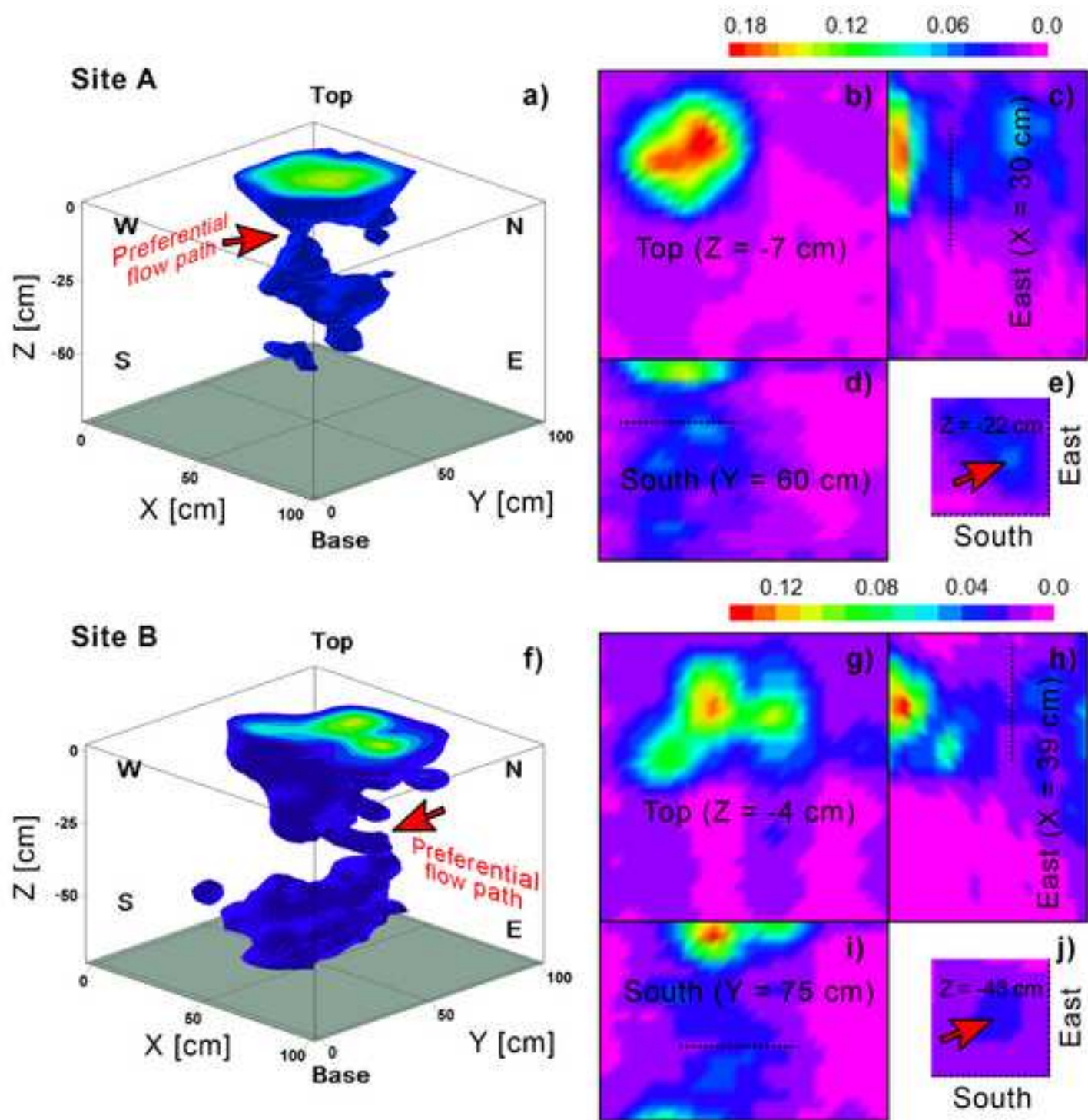




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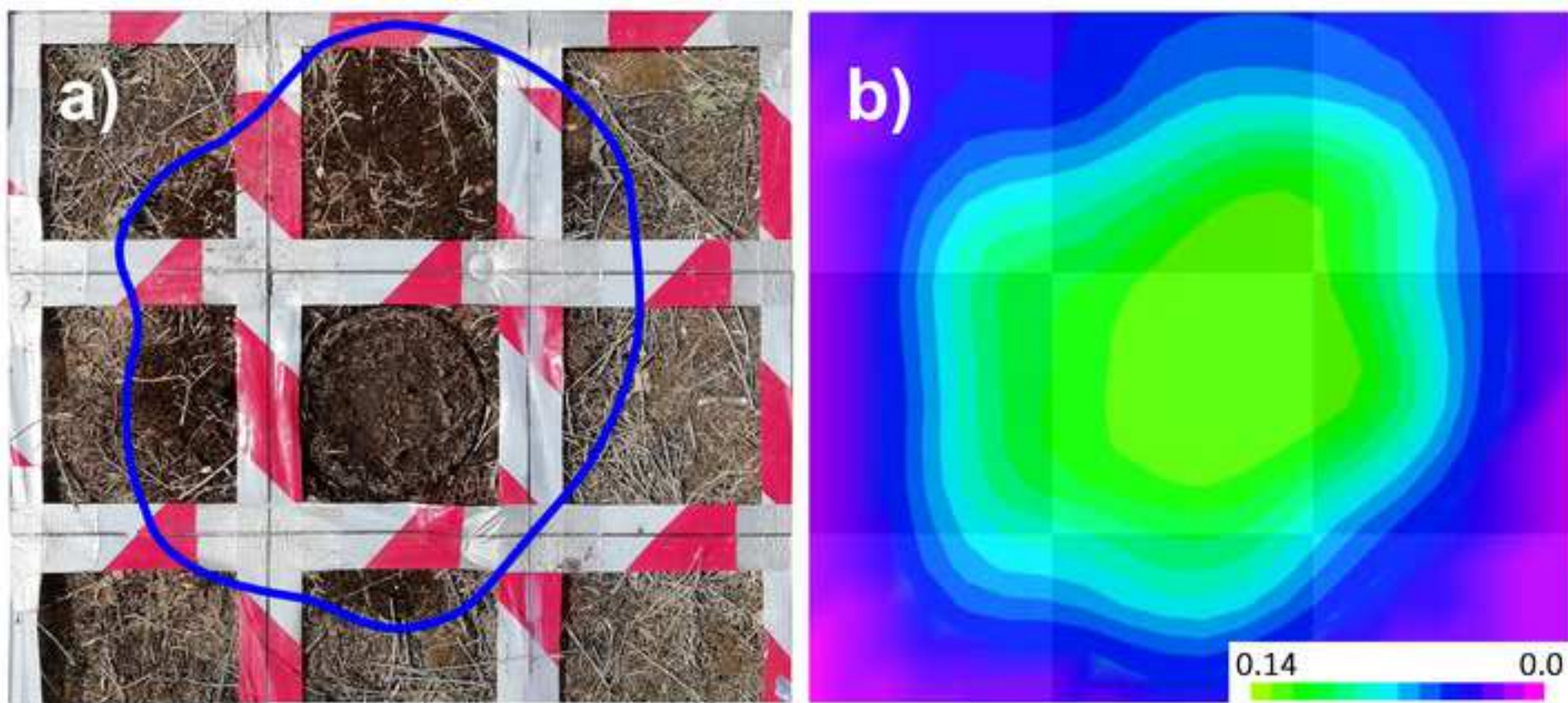


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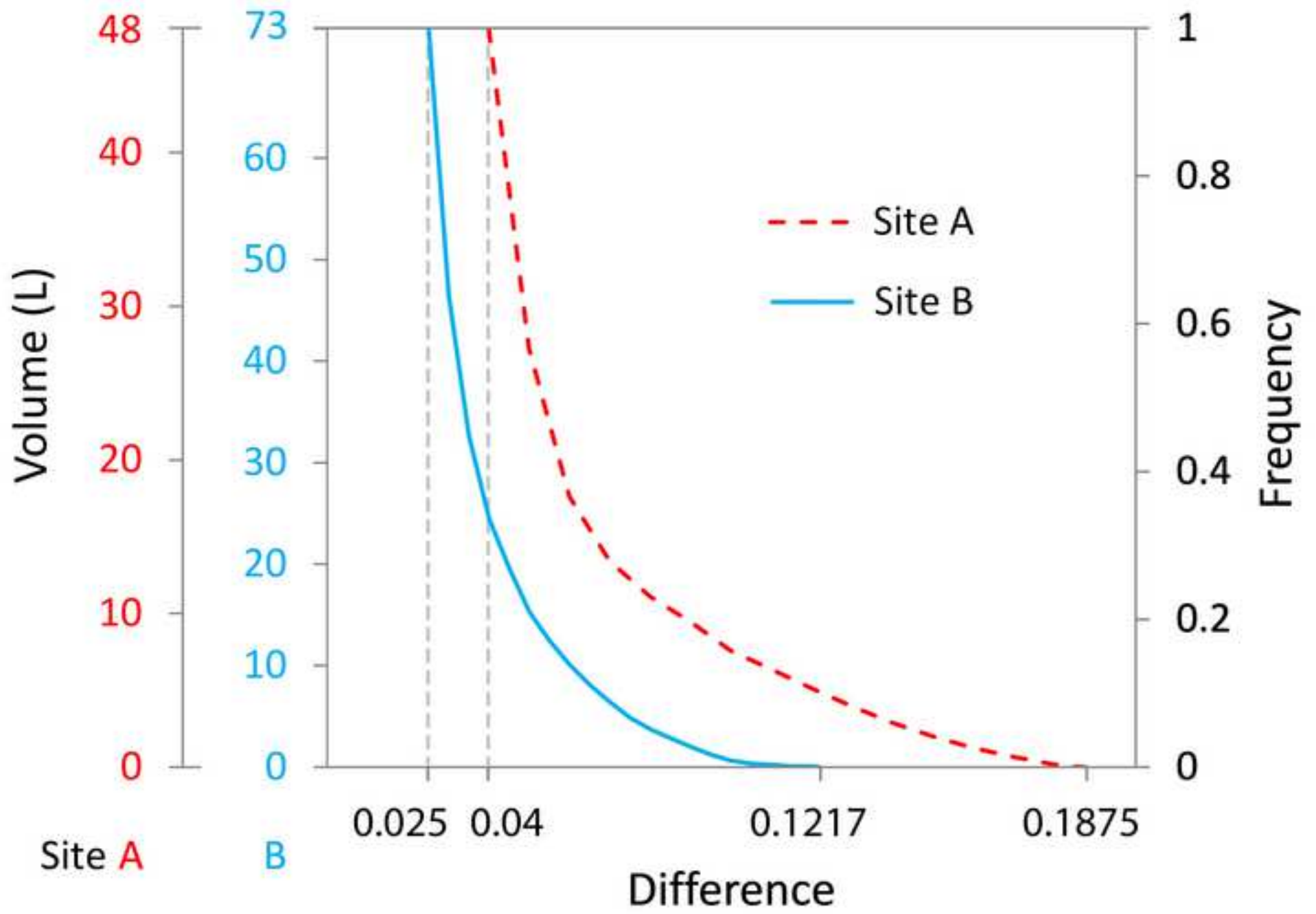


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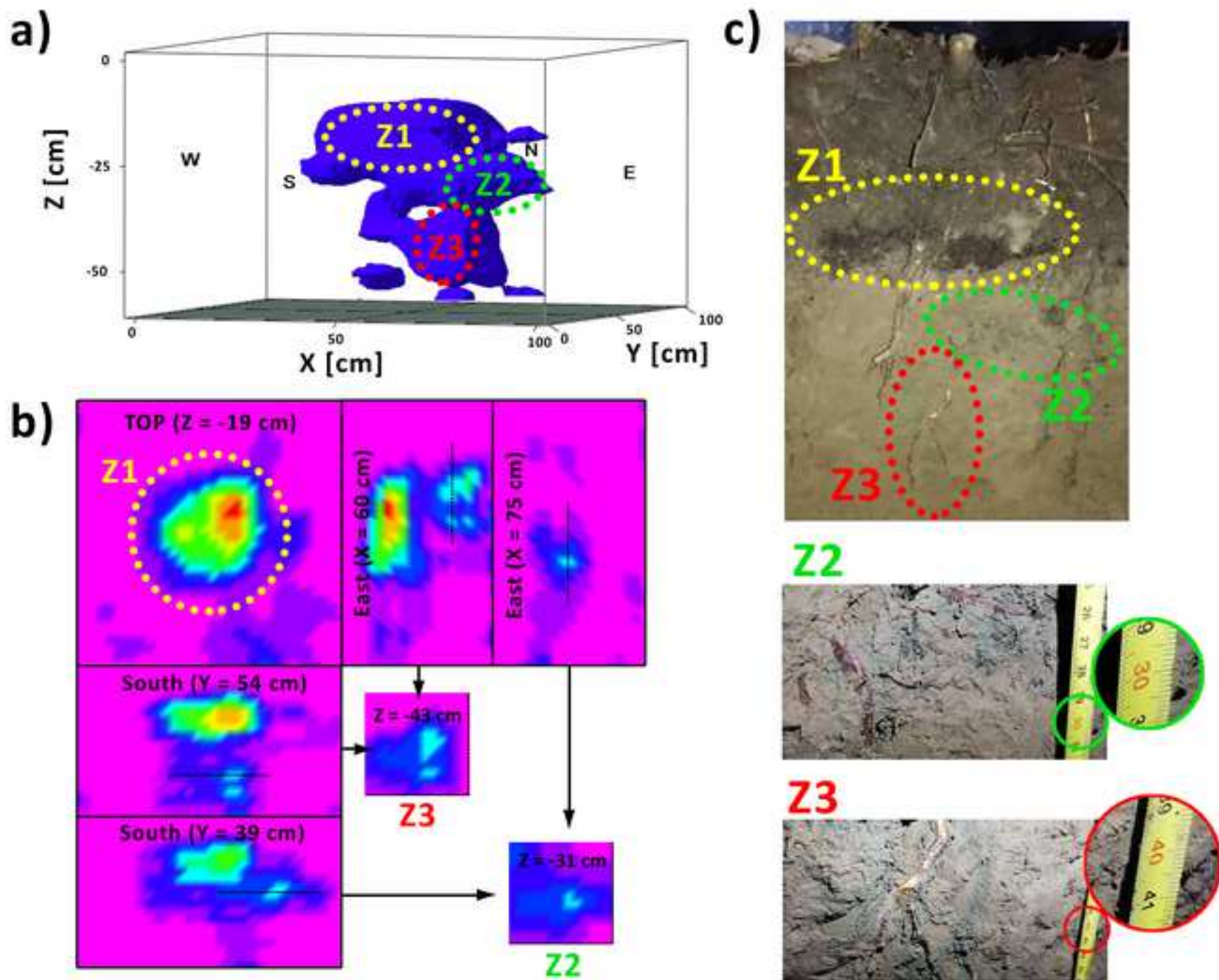




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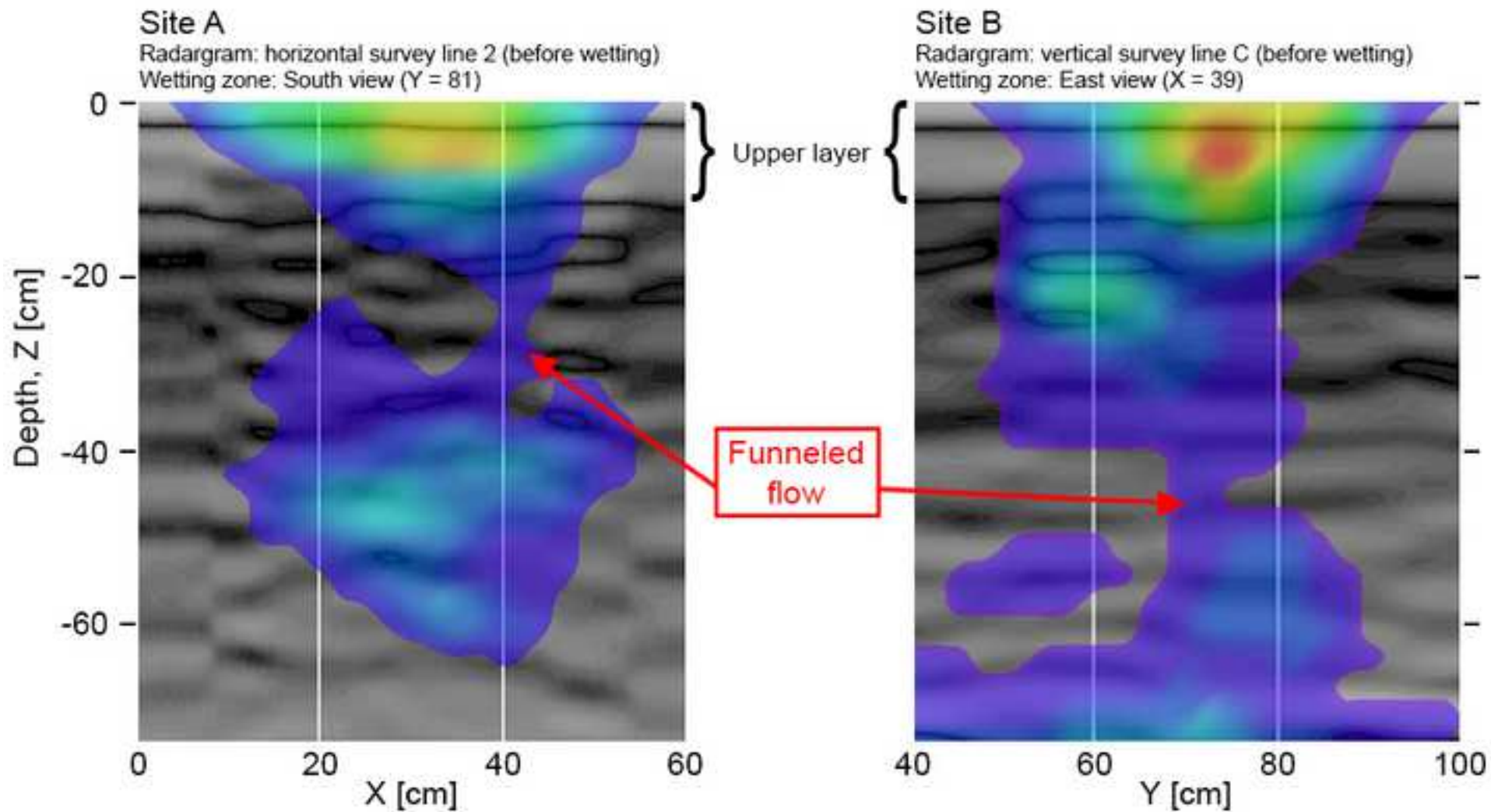


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