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1 **Medium frequency electromagnetic device to measure electrical conductivity and**
2 **dielectric permittivity of soils**

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16 **Running Title:** Medium frequency EM prototype

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22

23 **Abstract**

24 An electromagnetic tool working in the medium frequency range allows the
25 determination of both electrical conductivity and dielectric permittivity of soils with a single
26 measurement. It brings information about different state parameters of soils, especially their
27 water and clay contents for a significant volume of investigation. To investigate these
28 properties, a medium frequency range EM prototype, the CE120, was built using a PERP
29 (perpendicular coils) Slingram configuration with a working frequency of 1.56MHz and a
30 fixed coil spacing of 1.2m. This configuration was chosen using modeling with the purpose of
31 measuring electrical resistivities up to a few thousands ohm-m and relative dielectric
32 permittivities as low as 2. These thresholds match the expected parameters in the medium
33 frequency range. Moreover, the CE120 characteristics allow for an investigation depth
34 between 2 and 2.5m, depending on the nature of the soil. The prototype was tested on two
35 different soils: sandy alluvia and clay-loam soil. The electrical conductivities of the sandy
36 alluvia can reach $10000\Omega\text{m}$, which is close to the detection threshold of the CE120.
37 Consequently, the measured dielectric permittivity only includes high frequency effects
38 (dielectric polarization) and can be converted to apparent volumetric water content. For the
39 clay-loam soil, both the electrical conductivity and dielectric permittivity are measured and
40 the volumetric water content in this case is obtained using an empirical relationship
41 previously established in the laboratory on known samples. In both cases, the obtained results
42 are coherent with the direct mass water content measurements.

43

44 *Key-Words:* EM prototype, medium frequency range, dielectric permittivity, electrical
45 conductivity, water content, clay content

46

47 **Introduction**

48 The electrical and magnetic properties, such as the electrical conductivity, the
49 dielectric permittivity and the magnetic susceptibility are frequently used to estimate different
50 soil state parameters (Friedman, 2005; Liu *et al.*, 2012). These electrical properties can be
51 measured by electromagnetic prospection devices. Depending on their working frequencies,
52 different kinds of instruments have been developed. For the past fifty years, only EMI
53 (Electro-Magnetic Induction) devices working in the low frequency (LF) range and ground
54 penetrating RADAR (GPR) using high frequencies (HF) have been employed. In the low
55 frequency range, the EMI instruments measure: (i) the soil electrical conductivity σ , which is
56 strongly related to the soil water content, texture and clay content; (ii) the soil magnetic
57 susceptibility κ , which is mainly linked to the different pedogenetic processes. Most of the
58 devices use a Slingram geometry with separated transmitter and receiver coils and respect the
59 low induction number (LIN) approximation. Both their investigation depth and their lateral
60 resolution are determined by their geometrical parameters (mostly coil orientation and inter-
61 coil spacing). In this frequency range, polarization processes occurring in the ground cannot
62 be measured due to the dominant conduction processes, with the exception of measurements
63 taken over very resistive terrains (Huang and Fraser, 2002). In the high frequency range,
64 dipolar polarization processes, due to water presence, dominate. The measured dielectric
65 permittivity ϵ is thus directly linked with the soil volumetric water content. This frequency
66 range offers high resolution, but measurements cannot be performed on conductive soils, such
67 as clay rich soils, where attenuation is significant (Walther *et al.*, 1986; Knight, 2001).

68 The interest in developing devices working in the medium frequency (MF) range is
69 quite new but presents different kinds of advantages, especially regarding the estimation of
70 both soil water and clay content. To the best of our knowledge, no commercial EM device
71 working in the medium frequency range has been produced and only two other prototypes

72 were built (Stewart et al., 1994; Bourgeois et Lenain, 2002). This situation is explained by the
73 difficulties encountered in the measurements interpretation: (i) no simplification of the
74 Maxwell equations can be made; (ii) the electrical parameters both depend on the real and
75 imaginary parts of the measured magnetic fields; (iii) the electrical conductivity and the
76 dielectric permittivity are dispersive. An inversion procedure is thus needed to deduce the
77 electrical conductivity and the dielectric permittivity from the complex magnetic fields.
78 Tabbagh (1994), Stewart et al. (1994) and Bourgeois and Lenain (2002) all developed their
79 own forward modeling and inversion schemes include the dielectric permittivity in the
80 calculations. Yet, none of the proposed modeling takes into account the dispersive characters
81 of the electrical properties: the electrical conductivity and the dielectric permittivity are
82 assumed to be constant at all frequencies.

83 Both Stewart et al. (1994) and Bourgeois and Lenain (2002) choose to adapt the well-
84 known Slingram geometry in EMI for their prototypes. They could work at variable
85 frequencies and spacings, allowing their use for 1D soundings and/or profiles. Stewart et al.
86 (1994) developed a prototype measuring both vertical and horizontal magnetic fields with
87 frequencies ranging from 800kHz to more than 20MHz. In the two field surveys they
88 mention, they use inter-coil spacings of 1, 2, and 4m in order to determine the electrical
89 properties of the first 5m of soil. The use of these various spacings raises some important
90 issues about assuring an accurate loop orientation in the field, leading to the increase of
91 uncertainty in measurements. This issue, added to the temperature and electrical cable drifts,
92 decrease the accuracy of the primary magnetic field. Normalized fields can't be calculated;
93 instead the tilt angle and ellipticity of the magnetic field polarization ellipse are used to
94 determine the electrical parameters. Moreover, if their results are promising, Stewart et al.
95 (1994) encountered some technological limitations for: (i) spacing larger than 3m, leading to
96 low signal strength, (ii) frequencies higher than 20MHz, and (iii) the inversion process that

97 required 20 hours of computation for 18 measurement stations. Bourgeois and Lenain (2002)
98 propose a similar approach with spacings ranging from 2 to 32m and frequencies that can be
99 chosen between 391 kHz and 12.5 MHz. If the signal strength in the higher frequency range
100 and the speed of the inversion program has been improved, the issues regarding the loop
101 orientation in the field and the measurement speed are still real.

102 We propose a novel approach using a fixed Slingram geometry allowing a better
103 control of the mechanical strength and the loop relative orientations. Instead of focusing on
104 1D sounding, we want to develop a method of mapping the electrical conductivity and the
105 dielectric permittivity of the first meters of the soil in a time efficient way. After a description
106 of the prototype's characteristics, we present two different case studies with different water
107 contents: sandy alluvia and clay loam.

108 For the frequency ranges, we adopt the International Telecommunication Union radio
109 regulation rules: Low Frequencies (LF) for $30\text{kHz} < f < 300\text{kHz}$, Medium Frequencies (MF)
110 for $300\text{kHz} < f < 3\text{MHz}$ and High Frequencies (HF) for $3\text{MHz} < f < 30\text{MHz}$.

111

112 **Definition of the prototype's characteristics**

113 We choose to adapt the Slingram configuration technology, using a transmitter and a
114 receiver coil, originally developed in the LF range, for the MF range. In fact, another
115 development path would be to design an electrical field sensor, but this type of sensor is too
116 sensitive to changes in its elevation. To reduce this disagreement the use of electrodes stuck in
117 the ground is necessary. This practice will greatly decrease the measurement speed and the
118 production of maps at a field scale would be thus limited. Moreover, our laboratory acquired
119 lots of feedback in the low frequency range, developing prototypes using Slingram geometry.
120 Since the secondary fields measured in the LF domain are smaller than those expected in the
121 MF range, the mechanical design conditions are much more drastic in the LF frequency range.

122 Our knowledge in the development of EMI devices should ensure the construction of a
 123 mechanically robust and well-adapted instrument.

124

125 Different characteristics of the Slingram configuration can be chosen not only to adjust
 126 the investigation depth of the prototype, but also to ensure its ability to measure both
 127 electrical parameters. Modeling of a homogeneous ground and a layered ground with varying
 128 electrical parameters were performed using the forward modeling schemes developed by
 129 Tabbagh (1994).

130 The goal of modeling is to evaluate the value of the secondary magnetic field \vec{H}_S
 131 created by the ground, normalized by the primary field \vec{H}_P emitted by the transmitter coil T_x .
 132 Tabbagh (1994) showed that the influence of the magnetic permeability μ is weak in the
 133 medium frequency range; its value is thus taken to be equal to the magnetic permeability of
 134 free space ($\mu = \mu_0 = 4\pi \cdot 10^{-7} H/m$). The primary magnetic field in the air is determined
 135 using the quasi-static approximation. Indeed, at 10MH and for a 1m inter-coil spacing, the
 136 difference between the total primary field and the quasi-static primary field is equal to 2% or
 137 less. For a moment of the transmitter coil equal to 1, the primary field is thus equal to

$$138 \quad H_p = 1/(4\pi r^3) \quad (1)$$

139 For the determination of the secondary field, in this frequency range, the displacement
 140 currents occurring not only in the ground, but also in the air must be taken into account
 141 (Bourgeois and Lenain, 2002). The air is considered a dielectric infinite half space with a
 142 dielectric permittivity equal to the free space dielectric permittivity ($\varepsilon = \varepsilon_0 = 8.85 \cdot 10^{-12} F/m$)
 143 and an electrical conductivity equal to 0 ($\sigma = 0 S/m$). Moreover, as the transmitter coil is
 144 taken for a magnetic dipole, the Schelkunoff electrical potential vector \vec{F} is introduced so that
 145 the electrical field \vec{E} is expressed by $\vec{E} = -\overrightarrow{rot}(\vec{F})$:

146 (i) in the air, the secondary electrical potential \vec{F}_S satisfies the equation:

147
$$\Delta \vec{F}_s + \varepsilon_0 \mu_0 \omega \cdot \vec{F}_s = 0 \quad (2)$$

148 (ii) in the ground, the total electrical potential \vec{F} satisfies the equation:

149
$$\Delta \vec{F} - i\sigma\mu\omega \cdot \vec{F} + \varepsilon\mu\omega^2 \cdot \vec{F} = 0 \quad (3)$$

150 The magnetic field can thus be expressed as a function of the electrical potential \vec{F} :

151
$$\vec{H} = (1/i\omega\mu) \cdot \overrightarrow{rot}(\overrightarrow{rot}(\vec{F})) \quad (4)$$

152 In the PERP configuration, using the Hankel transform, the ratio between the secondary and
153 the primary magnetic field is equal to:

154
$$\frac{H_s}{H_p} = -r^3 \cdot \int_0^{+\infty} e^{-2u_0 h} \frac{\lambda^3}{u_0} R(\lambda) \cdot J_0(\lambda r) d\lambda \quad (5)$$

155 where J_0 is the Bessel function of the first kind of order 0; h is the height between the ground
156 surface and the coil center; r is the inter-coil spacing; λ is the integration spatial frequency; u
157 and u_0 are two variables depending on λ and on the complex wave number k ($u = \sqrt{\lambda^2 - k^2}$

158 and $u_0 = \sqrt{\lambda^2 - k_0^2}$ with $k^2 = -i\sigma\mu\omega + \varepsilon\mu\omega^2$ and $k_0^2 = \varepsilon_0\mu_0\omega^2$) and $R(\lambda) = \frac{u_0 - u}{u_0 + u}$.

159

160 A complete study presenting the different Slingram configurations is available in
161 Kessouri (2012).

162

163 ***Choice of the Slingram configuration***

164 We chose to adopt a PERP configuration with a transmitter T_x and a receiver R_x taken
165 respectively as an horizontal magnetic dipole and a vertical magnetic dipole (Figure 1). This
166 configuration is, for 1D terrain, theoretically strictly equivalent to the one having a transmitter
167 with a vertical axis and a receiver with a horizontal axis but, with this choice, the influence of
168 the electromagnetic fields created by the surrounding LF or MF transmitters are reduced and
169 the signal to noise ratio is thus improved. The prototype is named CE120: C for conductivity;
170 E for epsilon (the Greek character symbolizing the dielectric permittivity); 120 for 1.20m (the

171 inter-coil spacing T_x-R_x). The first in situ measurements were performed using a 1.56MHz
172 working frequency, but it is possible to reach lower and higher frequencies with the same
173 coils. The height of the device above the ground is equal to 0.1m.

174 The response of this chosen configuration to electrical resistivity and dielectric
175 permittivity variations is presented in Figure 2 for a homogeneous ground. For a fixed 40
176 relative dielectric permittivity value, the response of the CE120 is determined with electrical
177 resistivities ranging from 1 to $10^4\Omega\text{m}$. For a fixed $50\Omega\text{m}$ electrical resistivity value, the
178 response of the CE120 is determined for dielectric permittivities comprised between 1 and
179 1000. These electrical resistivity and dielectric permittivity values are based on values
180 measured from different soil types in laboratory tests (Smith-Rose, 1933; Scott et al., 1967;
181 Kutrubes, 1986; Olhoeft, 1987; Knoll and Knight, 1994).

182 Noise sources must be evaluated in order to determine a detection threshold for the
183 measurements (Kessouri, 2012). Besides the ambient electromagnetic noise, the device itself
184 is a source of noise. Indeed the electronic components and the coaxial cables create a first
185 electromagnetic noise. The geometric strains create a second one. Taking into account these
186 noise sources and after a series of tests, a detection threshold of the ratio H_s/H_p equal to
187 100ppm can be adopted.

188
189 In Figure 2, we can see that the chosen configuration allows the simultaneous
190 measurements of the electrical conductivity σ (or the electrical resistivity $\rho=1/\sigma$) and the
191 relative dielectric permittivity ϵ_r , for $\rho \leq 2185\Omega\text{m}$ (with a homogeneous relative dielectric
192 permittivity fixed to 40) and for $\epsilon_r \geq 2.6$ (with a fixed homogeneous electrical resistivity equal
193 to $50\Omega\text{m}$). These threshold values are still valid for higher fixed soil resistivities such as 500,
194 1000 or 5000 Ωm . These determined ranges of measurable properties fit the expected ranges
195 of soil electrical conductivities and dielectric permittivities in the medium frequency range.

196 The adopted configuration is thus well suited for the simultaneous measurements of the
197 electrical conductivity and the dielectric permittivity at 1.56MHz.

198

199 *Influence of the investigation depth*

200 We want to design a device that measures the apparent electrical conductivity and
201 dielectric permittivity of the shallow subsurface, for a volume of soil being at least 1m thick.
202 To check the investigation depth that can be reached with the chosen characteristics of the
203 CE120, we test its ability to detect a thin moving layer. The investigation depth represents the
204 depth until which this thin layer can be detected. The former modeling equations are now
205 applied to a 3 layered ground where the electrical conductivity and the dielectric permittivity
206 of the upper and bottom layers are identical: $\rho_1 = \rho_3 = 50\Omega\text{m}$; $\varepsilon_1 = \varepsilon_3 = 40$. The electrical
207 resistivity of the second thin layer is fixed to $5\Omega\text{m}$ for figures 3a and 3b, and to $500\Omega\text{m}$ for
208 figure 3c and 3d. The relative dielectric permittivity can be equal either to 5, 50, or 100. The
209 thickness of the second layer is fixed to 0.1m for both modeling. Taking into account a
210 detection threshold equal to 100ppm, the thin conductive layer (Figures 3a and 3b) can be
211 detected until a 2.6m depth. The investigation depth is significantly lower for the thin resistive
212 layer (Figures 3c and 3d): with the same detection threshold, the investigation depth is now
213 equal to 2m. Even though it is lower than for a conductive target, this investigation depth is
214 important compared to those reached by LF slingram devices. Indeed, it is well known that
215 the electromagnetic devices are not very sensitive to resistive features. This lack of sensitivity
216 is even emphasized when the measurement's frequency is becoming lower. With our
217 prototype, we are able to detect a thin resistive layer until 2m. This result is promising in
218 terms of detection of resistive targets using medium frequencies.

219 The chosen properties for our prototype looks optimal not only in terms of range of
220 values detected, both for the electrical conductivity and the dielectric permittivity, but also in

221 terms of reached investigation depth, which is close to 2m, even in the worst cases. The
222 CE120 prototype (Figure 4) was built using this specific configuration. The rigid box that
223 contains the transmitter and the receiver coils is fixed on a three-wheel trolley that is
224 electrically non-conductive and made with polyethylene. This configuration permits a fast
225 measurement rate. After a calibration stage, the CE120 was tested at a field scale.

226

227 *Determination of the electrical parameters*

228 In order to map the electrical parameters of the soil, a calibration step of the prototype
229 is necessary. Indeed, two steps are needed to transform the raw measurements into electrical
230 conductivity and dielectric permittivity data: (i) a calibration step allowing to transform the
231 raw data, expressed in an arbitrary electronic unit (digit), into real and imaginary parts of the
232 magnetic field (in ppm), using a calibration coefficient (in ppm/digit); and (ii) an inversion
233 scheme transforming these magnetic fields (expressed in ppm) into electrical parameters.

234 For the calibration process, explained in detail in Thiesson et al. (2014), we measure
235 the response of the CE120 to a small conductive sphere and compare it to the expected
236 theoretical variations. A calibration coefficient is obtained from this comparison. Moreover,
237 to double check this result and to determine the zeros of the prototype (the offset variations
238 that are mainly caused by the internal electrical noises of the device), a second
239 experimentation is led, where the response of the CE120 for different elevations is measured.
240 The theoretical response of the prototype is calculated using an electrical sounding at the
241 same location. The comparison of the theoretical and measured responses of the CE120 for
242 different elevations then allows for a check of the calibration coefficient and for a calculation
243 the offset occurring both in the in phase and quadrature components.

244 At these frequencies, the electrical parameters are both influencing the real and
245 imaginary parts of the magnetic fields. If, in the low frequency range, simple linear

246 relationships exist between the magnetic fields and the electrical parameters, in the medium
247 frequency range, an inversion procedure is needed to transform the real and imaginary parts of
248 the magnetic fields into electrical parameters. The relationships can be found numerically by
249 solving an inverse problem using the classical Newton-Raphson procedure or abacus
250 (Thiesson et al., 2014).

251

252 **Field case studies**

253 *Objectives*

254 The prototype has been tested on two different soil types: sandy alluvia and clay loam.
255 The objective was to determine the ability of the CE120 to detect water content variations first
256 in a clay-free context, then in a clay-rich environment. Indeed, the water and clay content of
257 soils are two of the main state properties governing the electrical parameters in the medium
258 frequency range: they are mostly responsible for polarization mechanisms observed in the MF
259 range. The volumetric water content of soil can be directly linked with the dielectric
260 permittivity in the high frequency range and its role persists in the medium frequency range.
261 The physical explanation of this major effect is the following: water molecules are dipolar
262 molecules, possessing permanent electrical momentums; the application of an electrical field
263 makes them rotate, creating a dipolar polarization.

264 In addition to this high frequency polarization effect, polarization processes are
265 occurring at the interface between the different components of the porous medium between a
266 few kHz and a few MHz. These mechanisms can be macroscopically brought together as
267 Maxwell-Wagner effects or interfacial polarizations (Chen and Or, 2006; Leroy et al. 2008;
268 Tabbagh et al., 2009). Two main mechanisms corresponding to Maxwell-Wagner effects can
269 be observed in the medium frequency range. In presence of an electrical field, cations and
270 ions are moving in opposite directions in the electrolyte until reaching interfaces between the

271 solid grains and the electrolyte. An accumulation of positive charges on one side of the
272 interfaces and negative charges on the other side can then be observed. Moreover, in presence
273 of charged particles at the grain surfaces, the ions repartition in the electrical double layer
274 changes and an electrochemical interfacial polarization can be observed. The measured
275 dielectric permittivity is thus influenced by the nature of the charged particles, particularly
276 their specific surface area and their cation-exchange capacity (CEC). The presence of clays,
277 possessing a high specific surface area and a large CEC, play an important role and can
278 significantly increase the value of the dielectric permittivity in the medium frequency range.

279

280 *Measurements on sandy alluvia*

281 A 20×8m plot of Quaternary sandy alluvia at the INRA d'Orléans (France) was chosen
282 to explore the measured answer on a clay-free soil. A water content contrast was created
283 artificially: the center of the plot was covered up using a 6×8m canvas sheet during 6 months
284 before any measurement was made. The measurements were made during the dry period (in
285 May) and half of the plot was sprinkled during 6 hours prior to the recordings. Three different
286 zones, corresponding to three different water contents, were created that way. The
287 measurements were taken every 1m, leading to 160 measurement points on the plot.

288 Besides measurements with the prototype, the electrical conductivity was also
289 evaluated using a resistivity-meter (RMCA-4 from CNRS) and a pole-pole array (Figure 5)
290 with a 1 x 1m² mesh. The apparent electrical resistivity values are very high, ranging from
291 650Ωm to more than 10000Ωm. Three areas can be clearly identified: (i) the covered-up area
292 where the resistivities are lower (from 650Ωm in the middle to 2410Ωm at the boundaries);
293 (ii) the resistivities of the watered area are ranging between 2100 and 4650Ωm; (iii) the most
294 electrically resistant area is found on the south-eastern part of the plot where the electrical
295 resistivities reach values above 10000Ωm for the bare soil. We used the same scale frame to

296 represent electrical resistivities measured by the CE120 prototype (Figure 6). The values
297 obtained are slightly lower than those measured using the resistivity-meter. The three different
298 areas cannot be differentiated, but the boundaries of the covered up area are marked by lower
299 resistivity zones. Looking at the resistivity values, it is clear that we reached the boundary of
300 the noise level of the EM prototype. These observations are in good agreement with the
301 previous modeling (Figures 2 and 3) where the sensitivity limit of the prototype to the
302 electrical resistivity was determined equal to $2185\Omega\text{m}$ (for a homogeneous ground with $\epsilon_r =$
303 40). Even if we reached the sensitivity limits, the lateral boundaries between the three
304 different moisture areas are detected, which indicate a significant sensitivity of the CE120 to
305 the boundaries between areas with changing electrical resistivities.

306

307 The apparent dielectric permittivity was also determined using the CE120
308 measurements (Figure 7). Three different areas, corresponding to the three different moisture
309 contents can be identified: (i) the lower dielectric permittivities correspond to the bare soil
310 area; (ii) in the middle of the plot, the higher dielectric permittivities are measured in the
311 covered up area; and (iii) in the watered area, the dielectric permittivities are varying from 8 to
312 18.

313 An interesting artifact is observed in the covered up area, which can be divided into
314 two distinct zones. In the north-west area, the values of the dielectric permittivity are higher
315 than in the south-east area. This variation can be explained by the fact that the north-west area
316 has been not only covered-up for 6 months, restricting the water evaporation, but also watered
317 for 6 hours prior to measurements. This distinction is only visible on the dielectric
318 permittivity map and is not detected by the DC resistivity measurements. The dielectric
319 permittivity is thus an interesting parameter bringing along new information.

320 The values, ranging from 1.5 to 19.5, are close to those expected for sands in the high
 321 frequency range. The interfacial polarization processes (Maxwell-Wagner effects) expected in
 322 the MF range don't seem to occur in this clay-free context. Consequently we can apply the
 323 Topp et al. equation (Topp et al., 1980) to the relative dielectric permittivities ϵ_r in order to
 324 deduce the volumetric water content θ_v :

$$325 \quad \theta_v = -5.3 \cdot 10^{-2} + 2.92 \cdot 10^{-2} \cdot \epsilon_r - 5.5 \cdot 10^{-4} \cdot \epsilon_r^2 + 4.3 \cdot 10^{-6} \cdot \epsilon_r^3 \quad (6)$$

326 The obtained volumetric water content map can be compared to mass water content
 327 measurements of soil samples (Figure 8). The samples were taken from the surface to a depth
 328 of 60cm, every 10cm. Because of the hardness of the soil, we were not able to dig deeper with
 329 the auger. The values of mass water content are consistent with the expectations: they are
 330 lower (between 3 and 4%) in the bare soil area, constant and close to 7.5% in the covered up
 331 area, and decrease from 10-15% to 6-7% as we go deeper for the watered area. If we compare
 332 the calculated volumetric water content and the measured mass water content at the sounding
 333 point, we obtain a mean apparent dry density equal to 1.3g/cm^3 . Indeed, the relation between
 334 the two water contents is equal to:

$$335 \quad w = \theta_v \cdot \frac{\rho_w}{\rho_{as}} \quad (7)$$

336 Where w is the mass water content over the dry specific mass; θ_v is the volumetric water
 337 content; ρ_w is the water density and ρ_{as} is the apparent dry density.

338 The calculated mean apparent dry density is in good agreement with apparent dry
 339 densities found for sandy soils (Donahue et al., 1977). In a clay-free soil, the volumetric water
 340 content can be calculated applying classical high frequency relations like Topp *et al.* equation
 341 to the dielectric permittivities measured with the CE120 at 1.56MHz.

342

343 ***Measurements on a clay-loam soil***

344 In order to test the influence of clay on the CE120 measurements, we performed a
345 survey on a clay-loam soil at the ORE ACBB from INRA Estrée-Mons (France). Water
346 content variations on the plot were generated by the crop growth. Indeed, the 8×3m plot was
347 set at the border between the bare soil and the soil covered by wheat. Measurements were
348 taken in March and in May 2011. In March, the wheat had just been planted and no water
349 contrast was expected between the two areas, but in May, the wheat root network had
350 developed and reached 1m depth, creating important water contrasts between the wheat cover
351 and the bare soil.

352 These contrasts can be observed in the DC electrical conductivity measurements
353 (Figure 9). Two different devices were used, depending on their availability: the RM15-D
354 from Geoscan Research and the RMCA-4 (CNRS). Pole-pole measurements were performed
355 with the RM15-D in March on a 0.5m grid mesh, allowing three different electrode spacing
356 (0.5m, 1m and 1.5m). The RMCA-4 resistivity-meter was used in May with a Wenner α
357 configuration and a 1m electrode spacing. Looking at the 1m electrode spacing in May
358 (Figure 9 d), a clear difference is observed between the western part of the plot, covered with
359 wheat and the eastern part: the electrical conductivity is lower on the wheat cover. Moreover,
360 the values of the bare soil in May are close to those of the entire plot in March. These
361 observations confirm the influence of the wheat grow on the soil water content, and thus on
362 the DC electrical conductivity measurements.

363 The same variations can be observed on the electrical conductivity map calculated
364 with the CE120. However, the electrical resistivity values are higher than those measured for
365 the DC electrical resistivity and the contrast between the bare soil and the wheat cover in May
366 is weaker.

367 The dielectric permittivity map shows the same patterns. The values are generally
368 higher in March than in May. The bare soil of May has lower values, but in the same order of

369 magnitude than in March (around 80-90). The influence of the wheat growing is clearly
 370 visible in May: the western part of the plot has lower values of permittivities (between 40 and
 371 69). Compared to the high frequency relative dielectric permittivities, ranging from 1 (for
 372 vacuum) to 81 (for pure water) in soils, the measured values seem high. Yet, in a clay-rich
 373 context, where the amount of clay is reaching 20%, these values can be expected at 1.56MHz.
 374 To confirm these results, laboratory measurements, using a capacitive cell coupled with a
 375 frequency response analyzer (Kessouri, 2012), were made on samples collected on site
 376 (Figure 11). The relative dielectric permittivity of the samples was evaluated at 1.024MHz
 377 and 2.048MHz for different volumetric water contents. Depending on the water content, the
 378 dielectric permittivity ranges from 3.6 to 367.3, respectively for a dry and saturated sample.
 379 The values obtained in situ are coherent with these measurements. An empirical relationship
 380 between the volumetric water content and the relative dielectric permittivity can be deduced
 381 from the laboratory measurements with a coefficient of determination R^2 equal to 0.778 for 47
 382 data points:

$$\theta = 0.40(1 - e^{-\epsilon_r/62.6}) \quad (8)$$

384 This expression is used to determine the apparent volumetric water content of the soil
 385 in situ (Figure 12). In March 2011, the apparent volumetric water content is fairly
 386 homogeneous and equal to 31% in average.

387 Measurements of the mass water content were also performed on two different
 388 locations (P1 on the wheat cover and P2 on the bare soil) of the plot (Figure 12a and 12b).
 389 The mass water content versus depth appears to be constant and equal to 21%. Using these
 390 values of volumetric and mass water content in equation (7), we found an apparent dry
 391 density equal to 1.5. We used this calculated apparent dry density to evaluate the mass water
 392 content of the soil in May 2011, using the dielectric permittivity measurements. In May, the
 393 volumetric water contents are equal, in mean, to 31% for the bare soil and to 22% for the

394 wheat cover. Using the dry apparent density found for the measurements in March, we obtain
395 mass water contents equal to 20.7% for the bare soil and 14.7% for the wheat cover. These
396 values are coherent with the mean values of the mass water content measurement over depth.

397

398 Using the measured dielectric permittivities in the field and in the lab, we were able to
399 evaluate the volumetric water content variations of a clay rich soil with an investigation depth
400 overpassing 2 m. Since there is a lack of models regarding the relationship between the MF
401 dielectric permittivity and the water content of soils, the laboratory measurements are a
402 necessary step to find a “calibration” equation between these two properties for a given soil
403 and it has to be done for each new soil type.

404

405 **Conclusion**

406 In order to estimate simultaneously the electrical conductivity and the dielectric
407 permittivity of soils, we developed a new EM prototype working in the medium frequency
408 range. Its investigation depth is higher than 2 meters, especially in clay rich context where the
409 GPR imaging is considerably attenuated. The CE120 is using a PERP Slingram geometry
410 with a fixed inter-coil spacing of 1.2m and a working frequency of 1.56MHz. If the inter-coil
411 spacing is fixed to reduce the geometric noise source, the same coil configuration allows for
412 measurements at various frequencies in the medium frequency range.

413 Analytical modeling enables us to check the properties of the prototype: (1) the
414 simultaneous measurement of σ and ϵ_r is possible for electrical resistivities lower than
415 $2185\Omega\text{m}$, and for dielectric permittivities higher than 2.6, which covers the whole range of
416 encountered values in the medium frequency range for soils; and (2) the investigation depth of
417 the CE120 is reaching 3m for conductive targets and becomes close to 2m for resistive

418 targets. It thus represents a good compromise between investigation depth and lateral
419 resolution.

420 To reach the electrical conductivity and the dielectric permittivity using the CE120
421 measurements, two steps are necessary: (1) a calibration step where the calibration coefficient
422 is calculated by comparing modeling to measurements for a known object and/or for a height
423 variation; and (2) an inversion step where the electrical parameters are deduced from the
424 magnetic field ratio with the Newton-Raphson procedure.

425 Two different field test sites were chosen according to their clay and water content
426 variations in order to study the prototype's response to water variations for a clay-free and a
427 clay-rich soil.

428 For the sandy alluvia, located in the INRA of Orleans, the clay content is close to 0
429 and the water content variations were artificially created. The resistivities measured by the
430 DC resistivity-meter are mostly higher than the resistivities detected by the CE120. The
431 prototype is thus unable to measure properly the soil electrical conductivity. Still, the
432 boundaries between the wet and dry part of the plot are clearly visible. As the LF-EM
433 methods are usually not adapted to very resistive context, this result is encouraging regarding
434 the use of medium frequency EM devices in electrically resistive environments. Moreover,
435 the measured dielectric permittivity has been successfully used to estimate the volumetric
436 water content of the soil using the HF equation of Topp et al. (1980). Indeed, on this resistive
437 kind of soil, the Maxwell-Wagner effects are low and only the polarization of the water
438 molecules is observable. These measurements are all the more consistent that the comparison
439 between the calculated volumetric water content and the measured mass water content is
440 convincing.

441 On the clay loam, the soil state parameters variations are detected not only by ϵ_r , but
442 also by σ , even though the variations are higher for the relative dielectric permittivity. The

443 measured values of ϵ_r are high (close from 100), showing the presence of the Maxwell-
444 Wagner polarization effects at 1.56MHz. With an amount of clay close to 20%, these values
445 can be expected in the medium frequency range. Thus, the Topp et al. equation can no longer
446 be used to calculate the soil volumetric water content. As no general relationships between θ_v
447 and ϵ_r are known in the medium frequency range, a different expression needs to be found for
448 each case study. We determined an empirical relationship from a series of laboratory
449 measurements on the same soil type. The volumetric water contents obtained are coherent
450 with the mass water content measured on site.

451 The CE120 is thus adapted for shallow investigations of water content variations, as
452 well as absolute value estimations, both in electrically conductive and none conductive
453 contexts. One of the restraints of this estimation is the necessity of finding a “calibration”
454 equation linking the dielectric permittivity and the water content for each type of soil. Indeed,
455 laboratory measurements for each survey can be time consuming. Some work needs to be
456 done to explore the relationships between the electrical parameters and the water content of
457 soils in the medium frequency range, both theoretically and experimentally. Moreover, as the
458 dielectric permittivity and electrical conductivity are both frequency dependent, information
459 can be added to the measurements by adding several frequencies to the prototype’s available
460 working frequencies. The same coils and geometry can be used for the whole medium
461 frequency range. Measuring the electrical parameters at different frequencies also includes
462 taking into account the dispersive character of the parameters in the model schemes. This is
463 not easy as there is no model describing the Maxwell-Wagner polarization processes as a
464 function of the state properties of the ground. The medium frequency range thus offers an
465 interesting path to study the frequency dependence of the electrical parameters and their
466 relations with the soil state properties.

467

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470 Séger, not only for letting us prospect one of their plot, but also for their availability and their
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472 Nicolas Brunet and Hubert Boisard for their authorization, their support and their advice
473 while we were prospecting their plots.

474

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530

FIGURE CAPTIONS

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532

533 **Figure 1:** Representation of the measurement device using a PERP Slingram configuration
 534 with the transmitter coil T_x (of moment \vec{M}) in horizontal magnetic dipole configuration,
 535 creating a primary magnetic field \vec{H}_p and the receiver coil R_x measuring the vertical
 536 component \vec{H}_{zs} of the secondary magnetic field \vec{H}_s created by a target in the ground. \vec{H}_t , the
 537 total magnetic field, is the sum of the primary and the secondary magnetic field and \vec{H}_{zt} is its
 538 vertical component.

539 **Figure 2:** Modeling of the real (for a) and c)) and imaginary (for b) and d)) parts of the ratio
 540 between the secondary magnetic field H_s and the primary magnetic field H_p ($H_p = 1/4\pi r^3$,
 541 with $r = 1.20\text{m}$ the inter-coil spacing) for a homogeneous ground. The coils, set in PERP
 542 configuration, are placed at a height of 0.1m . The measurement frequency is fixed at
 543 1.56MHz . The results are represented as a function of the electrical resistivity of the ground
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 545 characteristics of the homogeneous ground are $50\Omega\text{m}$ for the electrical resistivity, 40 for the
 546 relative dielectric permittivity and $30 \cdot 10^{-5}\text{uSI}$ for the magnetic susceptibility. The striped area
 547 corresponds to the area where the variations of the ratios are no longer detected if the
 548 detection threshold is fixed to 100ppm .

549 **Figure 3:** Modeling of the real (for a) and c)) and imaginary (for b) and d)) parts of the ratio
 550 between the secondary magnetic field H_s and the primary magnetic field H_p ($H_p = 1/4\pi r^3$,
 551 with $r = 1.20\text{ m}$ the inter-coil spacing) for a 3-layered ground. The coils, set in PERP
 552 configuration, are placed at a height of 0.1m . The measurement frequency is fixed at
 553 1.56MHz . The results are represented as a function of the 1st-layer thickness e_l for various
 554 electrical parameters of the 2nd layer, considered as the thin mobile layer. The electrical

555 parameters of the 1st and 3rd layers are equal to the reference characteristics of the
556 homogeneous ground ($\rho = 50\Omega m$, $\epsilon_r = 40$, $\kappa = 30 \cdot 10^{-5} uSI$). The thin mobile layer has a
557 thickness e_2 equal to 0.1m, a magnetic susceptibility of $30 \cdot 10^{-5} uSI$, a relative dielectric
558 permittivity equal to either 5, 50 or 100, and an electrical resistivity equal to $5\Omega m$ for the
559 conductive case (for a) and b)) or to $500\Omega m$ for the resistive case (for c) and d)). The striped
560 area corresponds to the area where the variations of the ratios are no longer detected if the
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563 **Figure 4:** Measurement device made up of the CE120 prototype and its trolley, under use on
564 the clay-loam soil, at the threshold between the bare soil and the wheat cover (see Fig.8 to
565 10).

566 **Figure 5:** Map of the electrical resistivity of sandy alluvia, measured with an RMCA-4
567 (CNRS) resistivimeter, using a Pole-Pole electrode configuration ($AM = 1m$) on a 1m grid
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569 months (covered up area) and a sprinkler during 6 hours (watered area). The plot is entirely
570 laid to grass.

571 **Figure 6:** Map of the electrical conductivity of sandy alluvia, measured with the CE120 on a
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575 **Figure 7:** Map of the dielectric permittivity of sandy alluvia, measured with the CE120 on a
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579 **Figure 8:** a) Map of the volumetric water content of sandy alluvia, determined using the
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583 grass. b) Mass water content measured at the PiLj location points on the map a) as a function
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585 **Figure 9:** Maps of the electrical resistivity of a clay-loam soil, measured with an RM15-D
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587 electrode configuration (a) $AM = 0.5m$; b) $AM = 1m$; c) $AM = 1.5m$) on a 0.5m grid
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591 **Figure 10:** Maps of the electrical conductivity (for a) and b)) and the dielectric permittivity
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601 **Figure 12:** c) and d): Maps of the volumetric water content of the clay-loam soil, determined
602 using the CE120 measurements and laboratory experimentations (Kessouri, 2012) on a 0.5m
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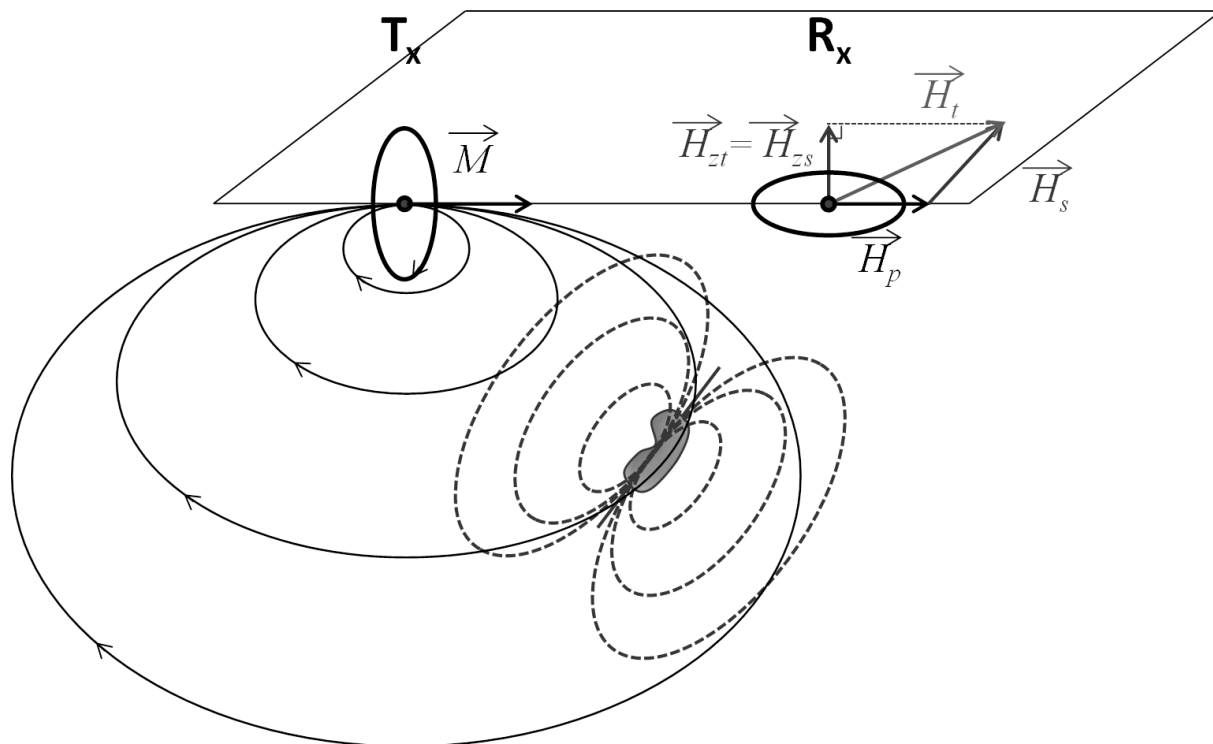
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FIGURES

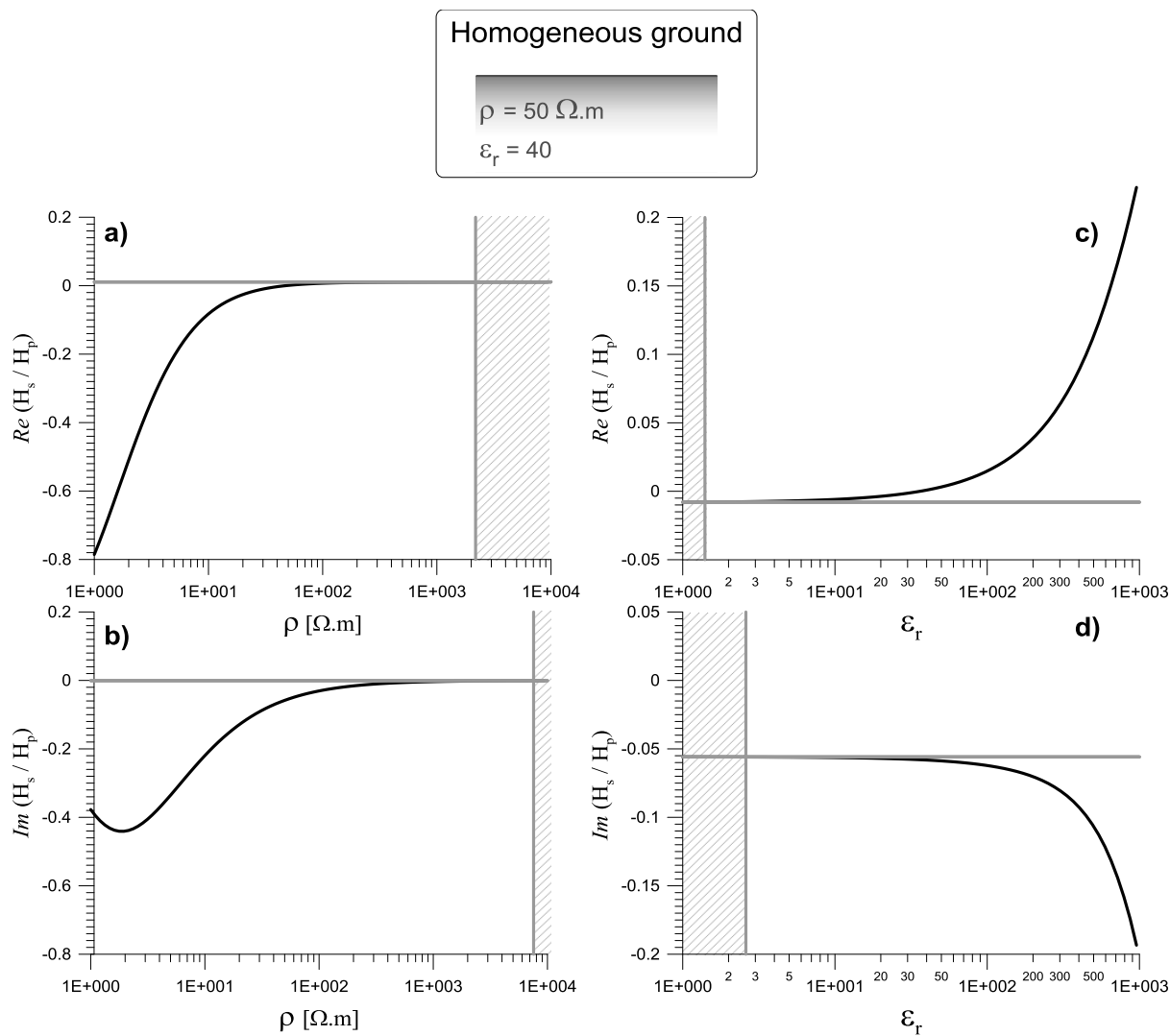
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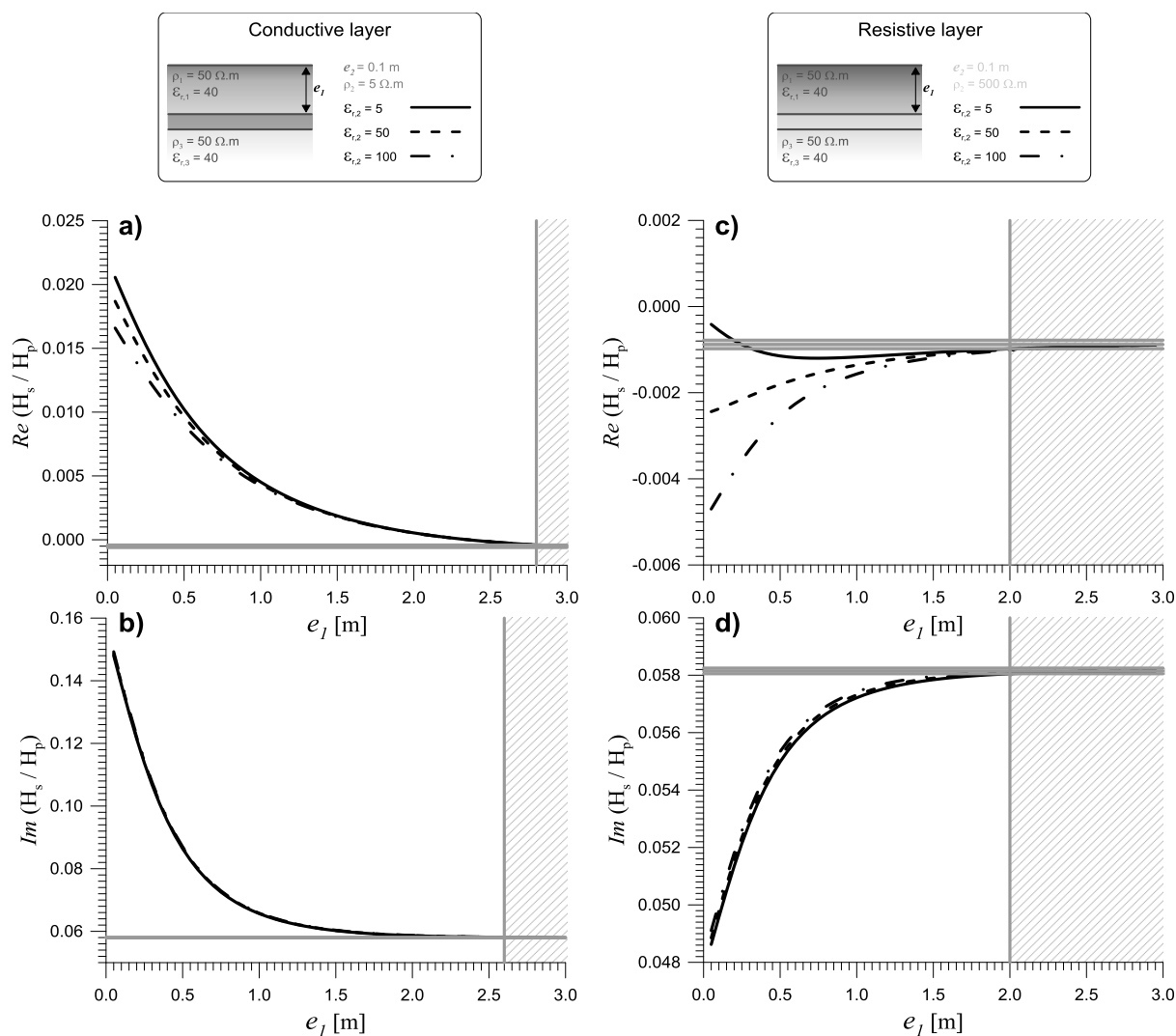


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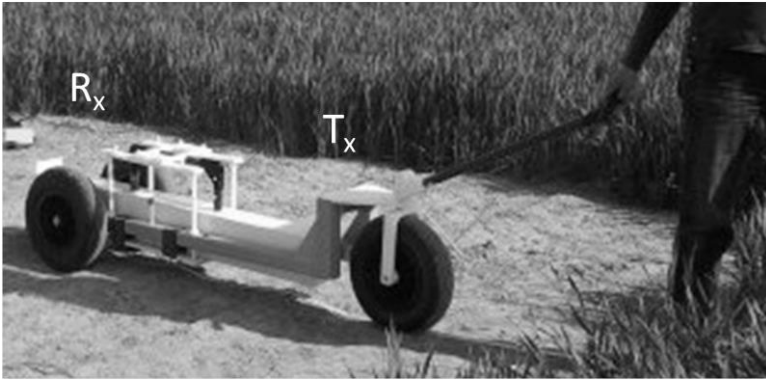
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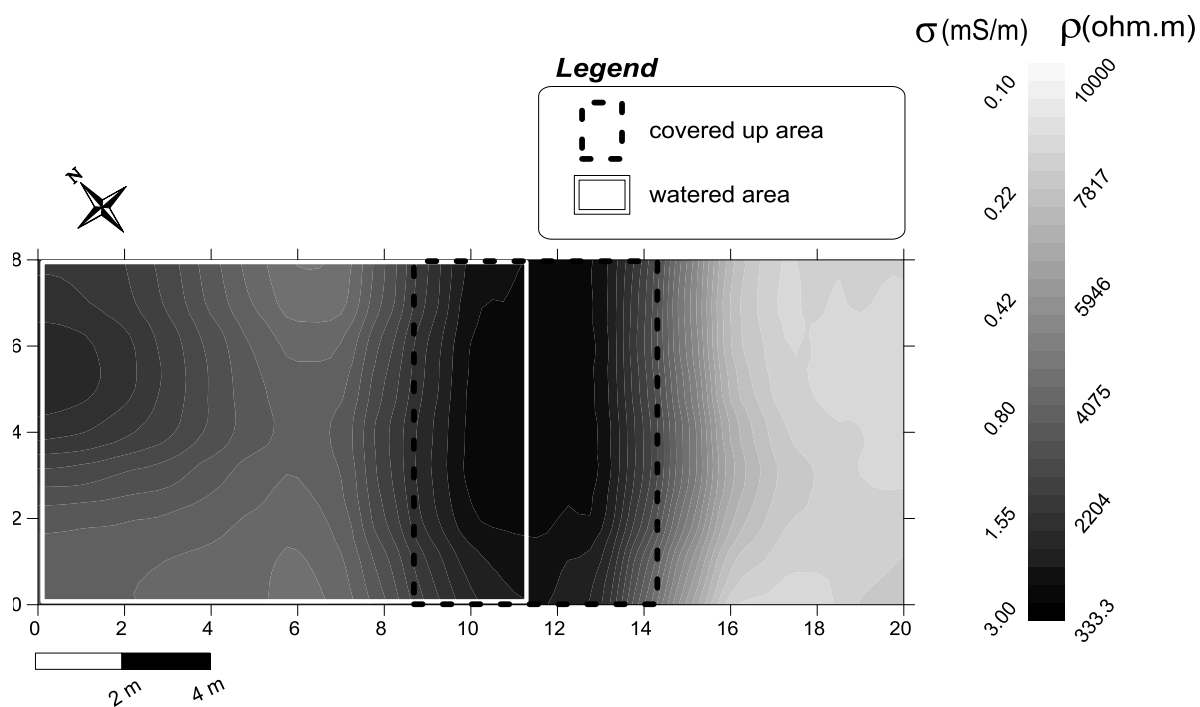
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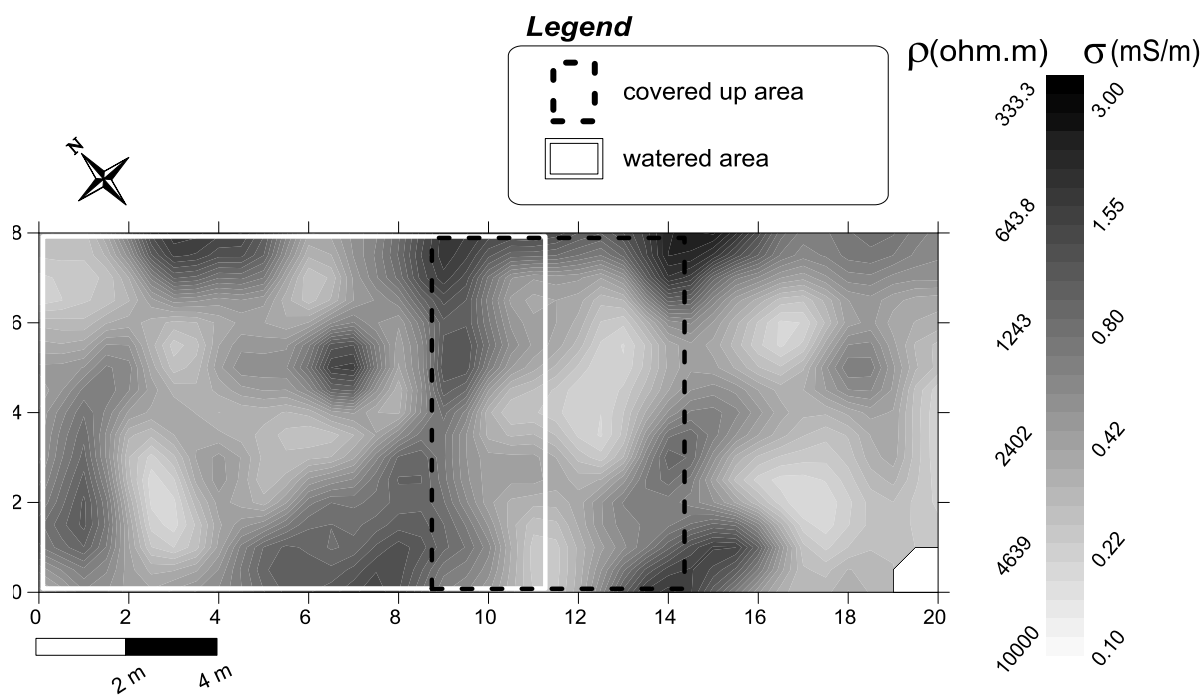
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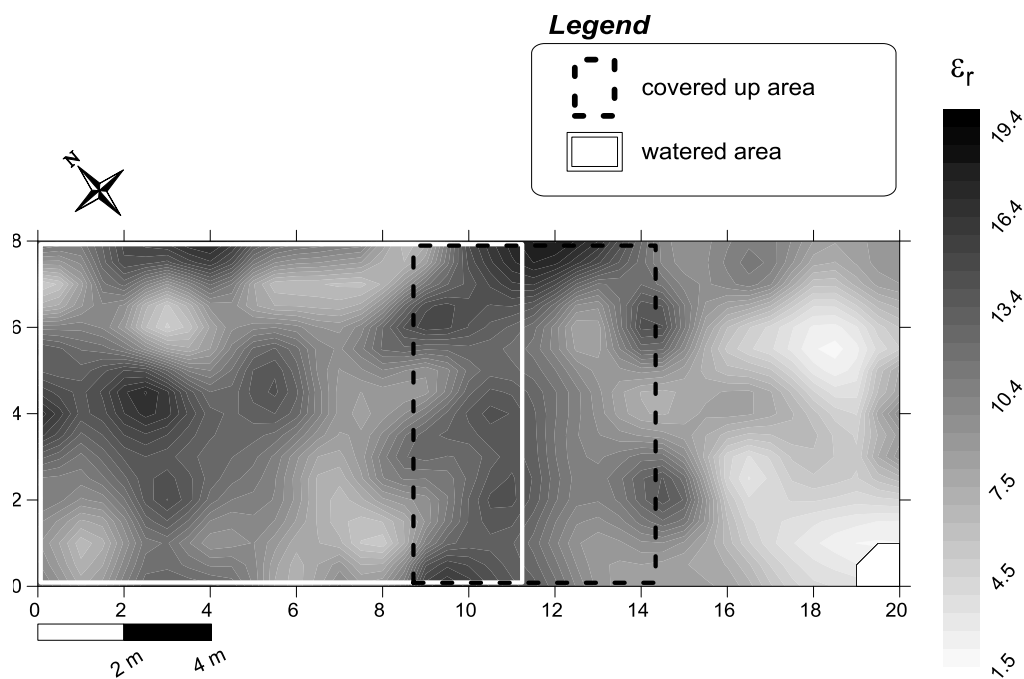
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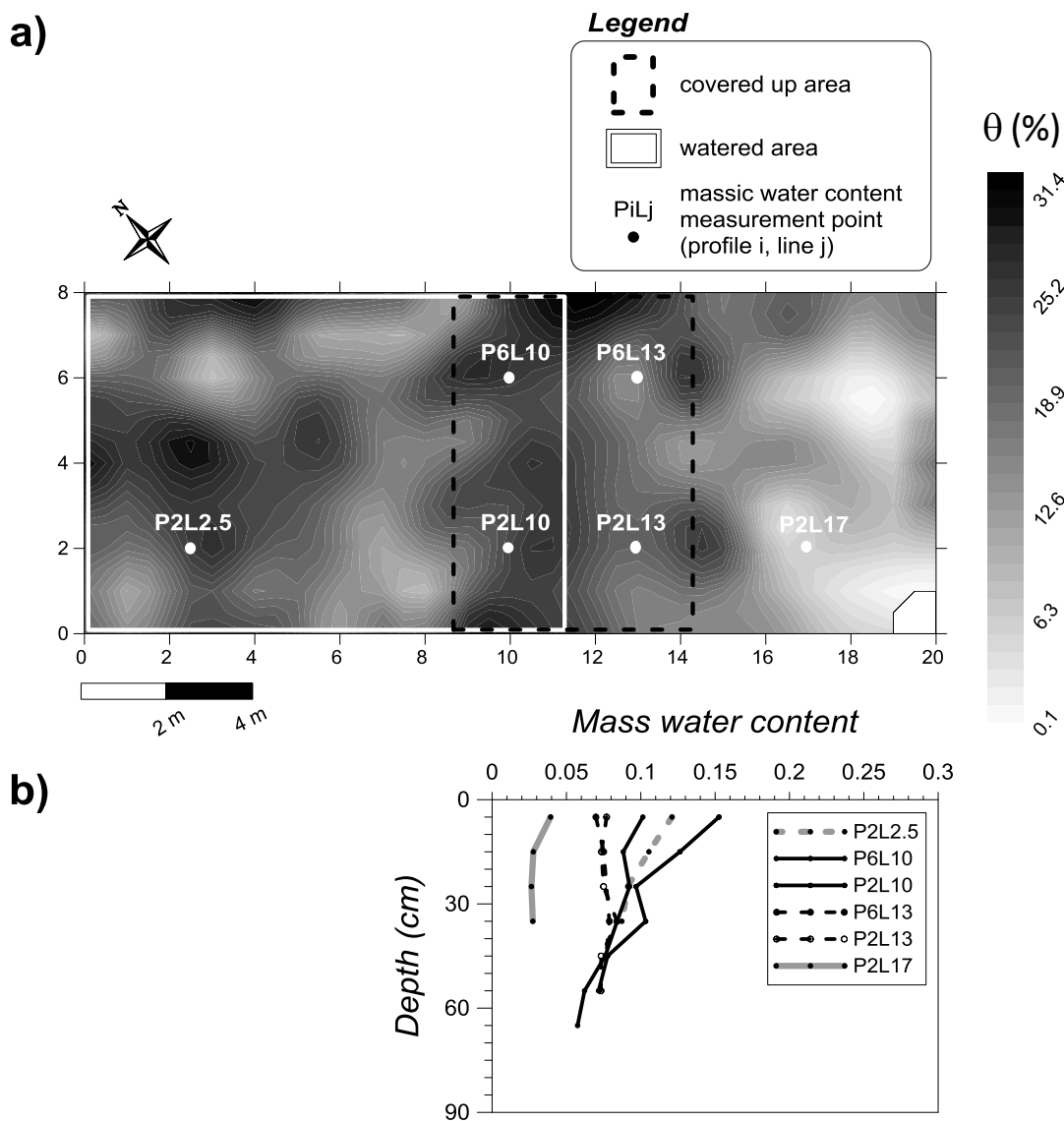
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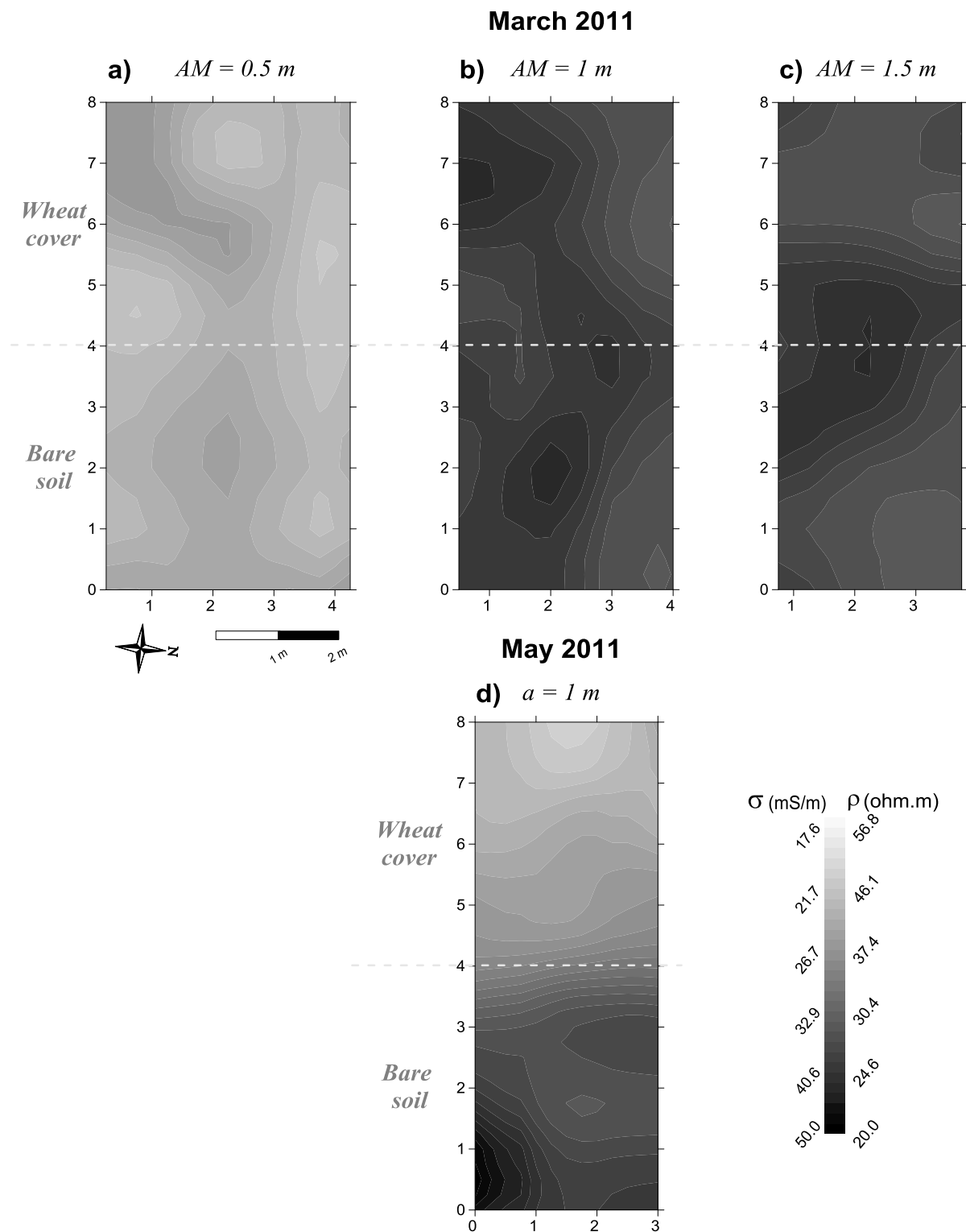
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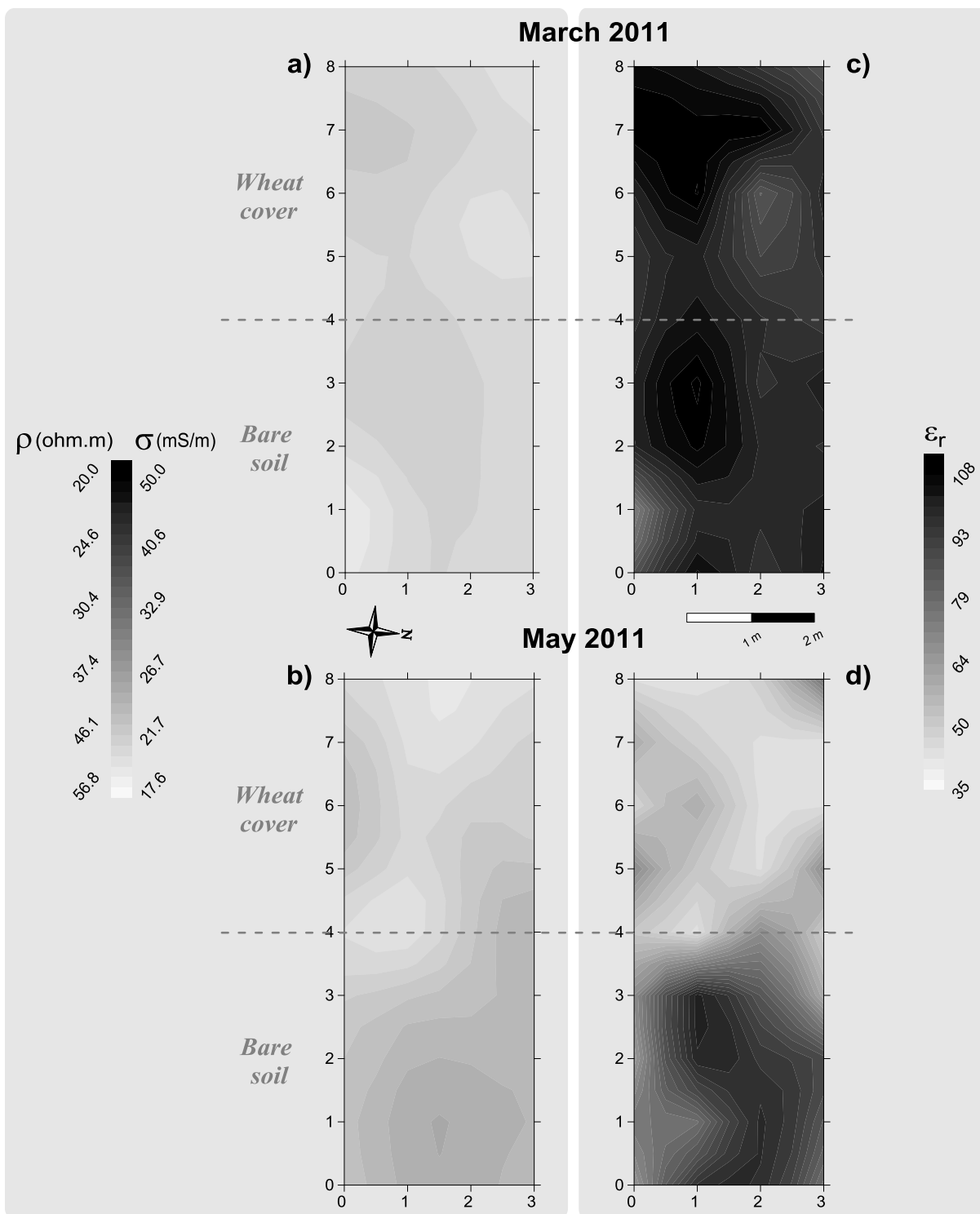
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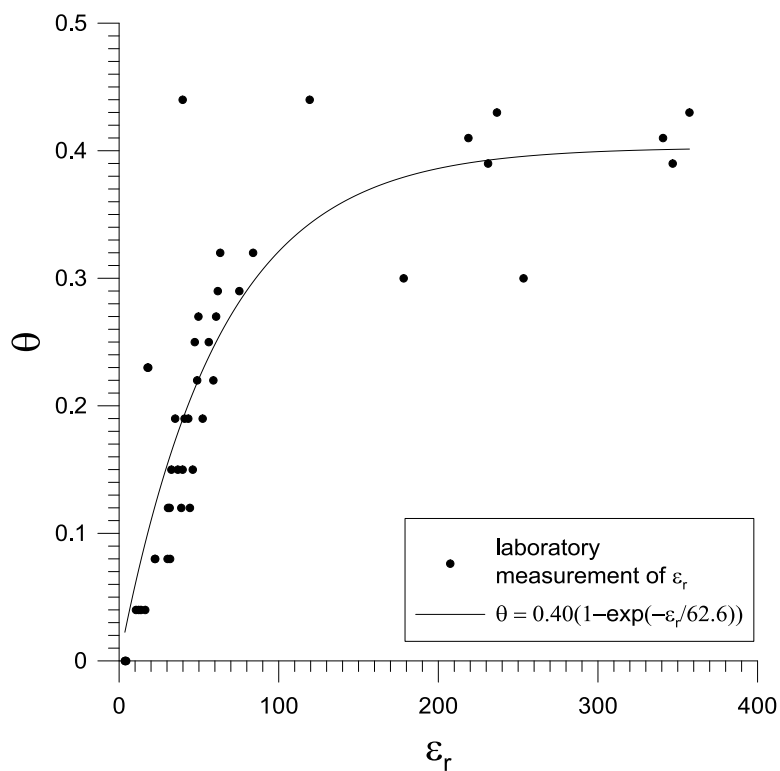
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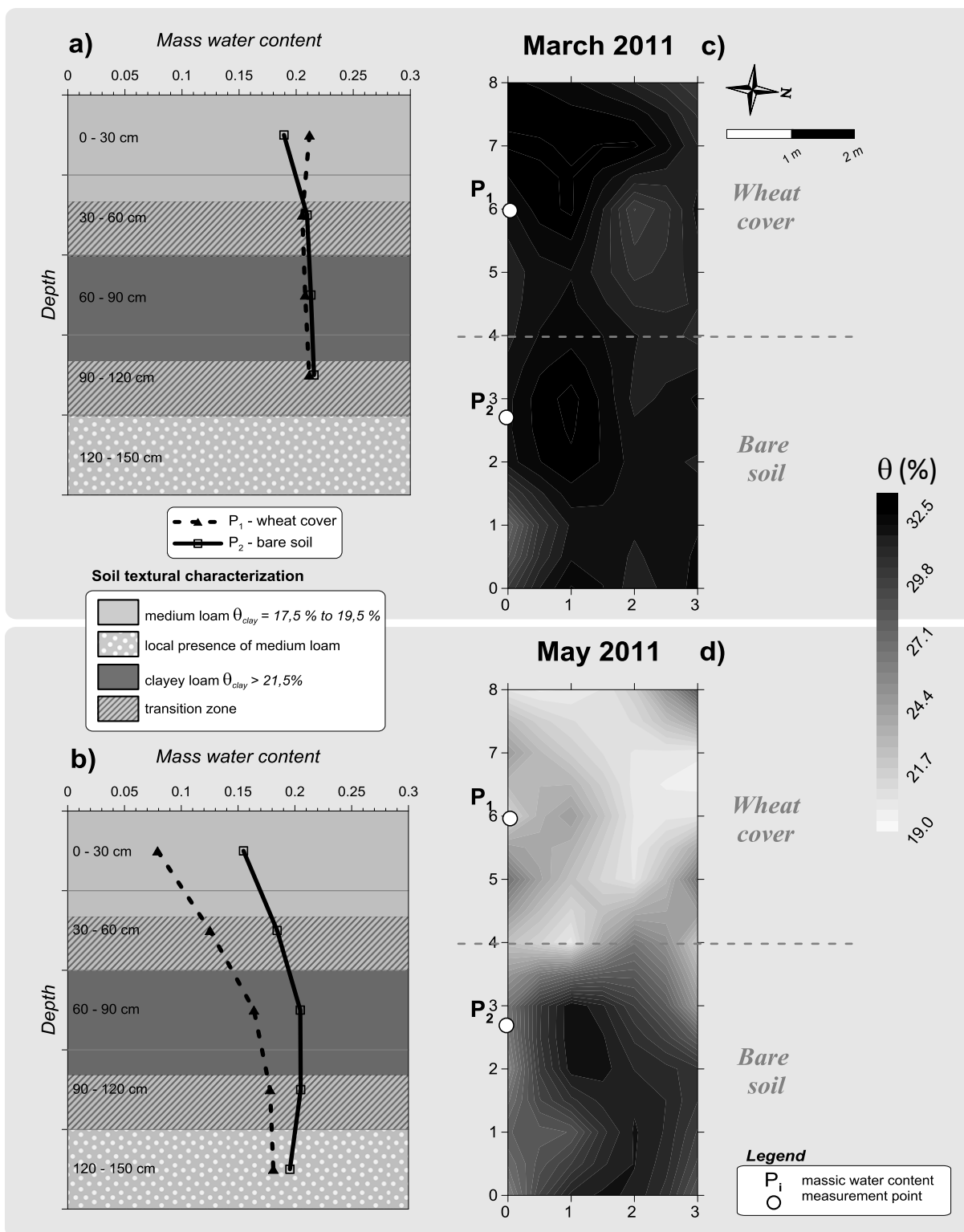
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