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1 **Quantifying multiple electromagnetic properties in EMI surveys: a case study of**
2 **hydromorphic soils in a volcanic context – the Lac du Puy (France)**

3

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12

13 **Abstract**

14 We used two different loop-loop electromagnetic induction (EMI) devices to determine
15 the 3D geometry and morphology of the pedo-sedimentary filling and underlying basaltic
16 bedrock of a former wetland in a volcanic soil area, the Lac du Puy depression (Auvergne,
17 France). Electrical conductivity (or resistivity) is usually sufficient for environmental and soil
18 science applications, but the local volcanic context of the survey area results in high values of
19 magnetic susceptibility and possible electrical polarization effects. Therefore we investigated
20 the roles of the four properties: electrical conductivity, magnetic susceptibility, magnetic
21 viscosity and dielectric permittivity. We created models using these four properties for the two
22 coil configurations of each device in order to assess the degree to which each of the properties
23 contributed to the recorded electromagnetic signal. The results show that electrical conductivity
24 controls the quadrature component of the secondary field response but that it can be affected by
25 high values of magnetic viscosity, while magnetic susceptibility controls the in-phase

26 component. Moreover, the low frequencies imply a limited contribution of dielectric
27 permittivity to the in-phase component, except in the cases of higher permittivity or frequency
28 values or greater inter-coil separation. Based on these observations, we propose a way to map
29 the apparent properties from field measurements. We then carried out a 1D inversion, first by
30 considering the electrical conductivity alone and secondly by taking all the electromagnetic
31 properties into account. The results show that there is a marked contrast in the complex
32 magnetic susceptibility between the sedimentary in-fill and the border of the Lac de Puy
33 depression, (stronger than for the electrical conductivity), and that permittivity is unlikely to
34 have a significant influence. The shape and nature of the sedimentary in-fill was thus
35 considerably refined by the second inversion results based on the three other properties. These
36 data, combined with litho-stratigraphic observations from a previous study, allowed the lateral
37 continuity and geometry of the in-fill to be assessed across the whole basin. Results are also
38 consistent with previous interpretations of the depression as a pseudo-sinkhole, a relatively
39 common morphology in volcanic plateaus.

40 Analysis of the magnetic properties also made it possible to characterize the spatial variation of
41 some key features related to hydromorphic processes, such as clayey granularity and the
42 development of iron oxides/hydroxides. This opens up the possibility for using new methods
43 for rapid spatial and pedological characterization of hydromorphic soils and palaeosoils.

44

45

46 **Key words:** EMI, VLF frequency range, conductivity, magnetic susceptibility and viscosity
47 mapping, hydromorphic soils, igneous environment

48

49

50 **1. Introduction**

51 Palaeosols and sedimentary layers can provide valuable records of changing Holocene
52 environmental conditions through careful multi-proxy geo-archaeological and paleo-
53 environmental analysis (e.g. Dotterweich, 2008; Dreibrodt et al., 2010; Henkner et al., 2017).
54 In this context, frequency domain electromagnetic induction measurements have proven to be
55 a useful tool in the first stages of investigation and prior to coring or trenching (Sudduth et al.
56 2005, Saey et al. 2008, Boaga 2017). These techniques can provide information about
57 electromagnetic properties and make it easier to identify the nature, geometry and thickness of
58 superficial formations and sedimentary bodies containing paleo-environmental information.
59 Moreover, once drilling or trenching has been performed, geophysical observations calibrated
60 with field data can be used to extrapolate stratigraphic or sedimentological observations
61 (Bendjoudi et al. 2002, Hendrickx et al. 2002, Triantafilis and Monteiro Santos 2010, Neely et
62 al. 2016).

63 In the framework of a broader geo-archaeological survey of a small pond, the Lac du
64 Puy, situated at the top of the Puy de Corent in central France (Mayoral et al. 2018a), we used
65 two EMI frequency domain instruments commonly used for environmental and soil studies.
66 First the EMP400 (GSSI Ltd, Nashua, NH, USA) where the inter-coil separation, L , equals 1.2
67 m, and secondly the EM31 (Geonics Ltd, Mississauga, Ontario, Canada) where the inter-coil
68 separation equals 3.66 m, both operating with frequencies close to 10 kHz. Their geometry and
69 operating frequency define the domain of electromagnetic induction used. Here it is the Very
70 Low Frequency (VLF, 3-30 kHz) range, in which, regardless of the type of electromagnetic
71 transmitted signal, the electrical conductivity, σ , is the dominant cause of the underground
72 responses. Consequently, for both instruments, only the apparent electrical conductivity is
73 usually considered (Frischknecht et al. 1991). However, four properties are actually involved
74 (Fig. 1): two electrical (electrical conductivity and dielectric permittivity) and two magnetic
75 (magnetic viscosity and magnetic susceptibility):

76 (1) While electrical conductivity represents the global motion of electric charges at the
77 macroscopic scale, another property, permittivity, is required to describe the electrical
78 polarization, which is the oscillations in electrical charge at a microscopic scale (from
79 pore or clay platelet to molecular scales). In the absence of significant changes in salinity
80 or temperature, variations in both properties reflect variations in the granularity, mainly
81 the clay content, or in the soil water content. Both properties can be found in the
82 Maxwell-Ampere equation in the expression, $\sigma + i\omega\epsilon_0\epsilon_r$, where ω is the angular
83 frequency, ϵ_0 the vacuum permittivity, ϵ_r the relative permittivity and $i = \sqrt{-1}$. The
84 relative weighting of the permittivity depends on the frequency: in the low frequency
85 (EMI) domain it can only be strong if ϵ_r is strong (Benech *et al.*, 2016, Simon *et al.*
86 2019).

87 (2) As the acquisition of induced magnetization by a mineral grain is not immediate, there
88 is a delay in acquisition or loss of the induced magnetization (Dabas and Skinner 1993,
89 McNeill 2013, Jordanova 2017). This delay is taken into account by considering that
90 the magnetic susceptibility is a complex quantity, $\kappa = \kappa_{ph} - i\kappa_{qu}$, where κ_{ph} is the in-
91 phase magnetic susceptibility (hereafter simply called magnetic susceptibility) and κ_{qu}
92 is the magnetic viscosity. The magnetic viscosity depends on the size of the magnetic
93 grains. It is strong for small single domain magnetite grains (in the [10 – 30 nm]
94 equivalent diameter range), small for larger single domain grains (around 1 μm) and
95 once again strong for large multi-domain grains (20 μm and greater). These magnetic
96 properties can be used jointly to describe the degree of pedogenesis, as the quantity and
97 size of magnetic grains are directly linked to redox processes that affect iron
98 oxides/hydroxides. Although the presence of organic matter affects these processes
99 (Cuenca Garcia *et al.* 2019), the content of iron oxides of the parent rock plays a key

100 role in the magnitude of soil magnetic susceptibility. In general, high magnetic
101 susceptibility would be expected for basaltic rocks (1000 to 10000 10^{-5} SI).

102 Frequency domain EMI apparatuses with a coil spacing of greater than 3 m and a frequency
103 lower than 30 kHz - such as the EM31- have been used in a wide variety of environmental
104 studies since 1979 (de Jong et al. 1979). Furthermore, over 200 papers have been published
105 using the conductivity measurements obtained with this device (Doolittle and Brevik 2014), but
106 to the best of our knowledge only very few studies look at the other EM property measurements
107 for this instrument. On the other hand, in the field of archaeological prospection, where the
108 separation between the coils remains limited, less than two meters, it has been noted that the
109 magnetic properties play an important part in ground response (Tite and Mullins 1970, Scollar
110 et al. 1990, Simon et al. 2015, De Smedt 2014).

111 In the Puy de Corent pond, the presence of basaltic rocks (basanite) underlying the
112 depression is of particular interest in the study of magnetic properties and electrical polarization
113 phenomena. Such rock types usually contain a high content of stable single domain magnetic
114 grains with high susceptibility (Grison *et al.* 2015), very low viscosity and significant electrical
115 polarizability. Therefore, the purpose of our work was to investigate the four measurable
116 electromagnetic properties rather than using electrical conductivity alone, and to assess their
117 relative abilities to improve interpretation of three-dimensional sedimentary infill (Triantafilis
118 *et al.*, 2013a, Triantafilis *et al.*, 2013b), well documented in Mayoral et al. 2018a but mainly
119 based on direct and spatially limited stratigraphic observations. This non-intrusive approach
120 provides benefits in terms of both time and resources. The raw data is collected by the two
121 instruments and then inverted using point by point 1D modelling, considering first the electrical
122 conductivity alone, and then incorporating the electrical conductivity, the complex magnetic
123 susceptibility and the relative dielectric permittivity in a second round of modelling.

124

125 **2. Material and methods**

126 *2-1. Study area and Stratigraphy*

127 The study site is located on top of the Puy de Corent (621 m.a.s.l.), a volcanic plateau
128 dominating the calcareous Limagne Plain in central France. The plateau has been shaped by
129 erosion and topographic inversion of a 3 million year-old scoria cone and an associated basaltic
130 lava flow formed during the Pliocene volcanism of the Massif Central (Greffier, et al., 1980;
131 Nehlig et al., 2003). In the quasi-flat lower part of the plateau, a small circular depression of
132 circa. 2 ha forms a wetland representing a drained pond (Fig. 2). This depression was formerly
133 interpreted as being a secondary crater, but is more likely a pseudo-sinkhole, caused by
134 subsidence phenomena affecting the basaltic lava flow, likely triggered by dissolution of
135 underlying Oligocene sedimentary rocks including marls, limestones and gypsum (Mayoral et
136 al., 2018). Litho-stratigraphic features of the Lac du Puy have already been described in detail
137 in previous work (Mayoral et al. 2018), and are summarized here in Figure 2. The bedrock is
138 basaltic and is formed of the Puy de Corent lava flow. The sedimentary in-fill of the basin is
139 mainly clayey and can reach a thickness of up to 1.8 or 2 m. The lower stratigraphic units have
140 a clay matrix which is very rich in coarse volcanic material (sand to gravel), resulting from
141 detrital input from the plateau and local bedrock weathering and disaggregation. The middle
142 stratigraphic units are dominated by massive, heavy clays which have undergone various phases
143 of pedogenesis since the Neolithic, with dominant hydromorphic features (gleyic and vertic
144 features) and rare coarse particles. The upper units are mainly clayey loams including several
145 basaltic fragments and pottery sherds, and show Roman to present-day soil development.
146 Magnetic susceptibility was measured on two different cores along a trench and is summarized
147 as an average per sedimentary unit. Susceptibility values were measured with the single
148 frequency MS2-E (Bartington Ltd, UK, 1cm spatial resolution, 2 kHz) on the fine soil fraction.

149 This resulted in relatively low susceptibility values (less than $50 \cdot 10^{-5}$ SI), not taking into
150 account the effect of the basaltic and sherd fragments.

151 **2-2. Devices and survey conditions**

152 Two different EMI devices were used on the study site. The EMP400 operates at three
153 frequencies below 16 kHz (5, 8 and 15 kHz were selected). This instrument has one transmitting
154 coil and one receiving coil at a distance of $L=1.21$ m from the transmitting coil. The coils are
155 coplanar, and measurements can be made in either the HCP (horizontal coplanar) or the VCP
156 (vertical coplanar), which is configured by rotating the instrument itself. The depths of
157 investigation for the EMP400 differ between the HCP and VCP, and for the electrical and
158 magnetic properties (Tabbagh 1986b). For the electrical properties, it is generally $0.8L$ in VCP
159 and $1.5L$ in HCP, whereas for the magnetic ones the distances are $0.6L$ in VCP and $0.2L$ in
160 HCP, with a change in the sign of the response for a clearance $h=0.38 L$.

161 The second device, the EM31, has a coplanar configuration, a 3.66 m inter-coil
162 separation and a single frequency of 9.8 kHz. The operator can hold the instrument at shoulder
163 height with $h=1$ m clearance above the ground surface. It can also be pulled using a trolley at a
164 lower clearance. The depths of investigation follow the same general guidelines for L as for the
165 EMP400.

166 The Lac du Puy area was surveyed with the two instruments in both HCP and VCP
167 configurations, in combination with a GNSS positioning system with a sub-decimeter accuracy
168 in order to locate the instrument operator precisely. A profile was collected every two meters
169 with a frequency of data collection of 1 Hz for the EM31 and 10 Hz for the EMP400. Data for
170 both instruments and configurations were collected on October 2015, resulting in eight different
171 independent sets of data: EM31 in HCP, EM31 in VCP, EMP400 in HCP for 5, 8 and 15 kHz
172 and EMP400 in VCP for 5, 8 and 15 kHz. Each was resampled with the same 2 m x 2 m grid

173 meshing in order to enable simultaneous interpretations and inversions using these different
 174 sets.

175

176 **2-3. 1D forward modelling**

177 We present here the 1D forward modelling, which takes the four electromagnetic properties
 178 into account (see also Ward and Homann 1988). It allows us to define the apparent properties
 179 when the ground is assumed to be homogeneous, and to inverse for properties and thicknesses
 180 of the successive layers when a multi-layer model is considered.

- 181 • For horizontal coplanar (HCP), where the transmitter is a vertical magnetic dipole, M_z ,
 182 located at $(0, 0, -h)$ and the receiver a small coil located at $(0, L, -h)$,

$$183 \quad H_z = \frac{M_z}{4\pi} \int_0^{\infty} \lambda^2 R_v(\lambda) e^{-2u_0 h} J_0(\lambda L) d\lambda \quad (1)$$

- 184 • For vertical coplanar (VCP), where the transmitter is a horizontal magnetic dipole, M_x ,
 185 located at $(0, 0, -h)$ and the receiver a small coil located at $(0, L, -h)$,

$$186 \quad H_x = \frac{M_x}{4\pi} \left\{ -\gamma_0^2 \int_0^{\infty} R_H(\lambda) e^{-2u_0 h} J_0(\lambda L) d\lambda + \frac{1}{L} \int_0^{\infty} \frac{R_1(\lambda) e^{-2u_0 h}}{\lambda} J_1(\lambda L) d\lambda \right\} \quad (2)$$

187 In these expressions J_0 and J_1 are the Bessel's function of the first kind, $u_0 = \sqrt{\lambda^2 + \gamma_0^2}$ with

$$188 \quad \gamma_0^2 = -\varepsilon_0 \mu_0 \omega^2, \text{ and } R_v(\lambda) = \frac{\lambda}{\mu_0} \frac{\frac{u_0}{\mu_0} + Y_1}{\frac{u_0}{\mu_0} - Y_1}, \text{ } Y_1 \text{ being recursively calculated by starting at the top}$$

189 of the deepest layer, N , by $Y_N = -\frac{u_N}{\mu_N}$ and using the formula: $Y_i = \frac{u_i}{\mu_i} \frac{Y_{i+1} - \frac{u_i}{\mu_i} \tanh u_i e_i}{\frac{u_i}{\mu_i} - Y_{i+1} \tanh u_i e_i}$. In

190 this formula, e_i is the thickness of the i^{th} layer, and $u_i = \sqrt{\lambda^2 + \gamma_i^2}$ with $\gamma_i^2 = i\sigma_i \mu_i \omega - \varepsilon_i \mu_i \omega^2$

191 and $i = \sqrt{-1}$.

192 $R_1(\lambda) = \gamma_0^2 R_H(\lambda) + u_0^2 R_v(\lambda)$. The function $R_H(\lambda)$ is calculated by $R_H(\lambda) = \frac{\lambda}{u_0} \frac{\frac{u_0}{i\omega\epsilon_0} + Z_1}{\frac{u_0}{i\omega\epsilon_0} - Z_1}$, Z_1

193 being recursively calculated by starting at the top of the deepest layer by $Z_N = -\frac{u_N}{\sigma_N + i\omega\epsilon_N}$

194 and using the formula: $Z_i = \frac{u_i}{\sigma_i + i\omega\epsilon_i} \frac{Z_{i+1} - \frac{u_i}{\sigma_i + i\omega\epsilon_i} \tanh u_i e_i}{\frac{u_i}{\sigma_i + i\omega\epsilon_i} - Z_{i+1} \tanh u_i e_i}$. To get results which are

195 independent of the transmitted power, the secondary field expressions are usually normalized
 196 by the primary amplitude, $H_p = M/(4\pi L^3)$ and the measurements are expressed in terms of H_s/H_p
 197 , in ppm (parts per million) or in ppt (parts per thousand) depending on the device manufacturer
 198 (ppm for the EMP400 and ppt for the EM31, 1ppt=1000 ppm).

199 To illustrate the physical meaning of these complex analytic expressions by showing
 200 the influence of any property or instrument parameter, approximations (Thiesson et al. 2014)
 201 can be calculated based on the range of values of the different properties. The static
 202 approximation ($\omega \rightarrow 0$) establishes that the ratio of the secondary field to the primary field for
 203 a coplanar instrument (HCP or VCP) located at $h=0$ clearance above the surface would be

204 $\frac{H_s}{H_p} \cong -\frac{\kappa_{ph} - i\kappa_{qu}}{2}$. This suggests that the magnetic susceptibility response would be in-phase,

205 the viscosity response in quadrature and their dependence on frequency and coil separation
 206 limited. Furthermore, the Low Induction Number (LIN) approximation, $\sigma\mu\omega L^2 \ll 1$, which

207 corresponds, if $\mu = \mu_0$ and $h=0$, to $\frac{H_s}{H_p} \cong -\frac{i\sigma\mu_0\omega L^2}{4}$ suggests that the conductivity effects would

208 mainly be in quadrature and proportional to the conductivity, the frequency and the square of
 209 the coil separation (this approximation is the one commonly used by most instrument
 210 manufacturers to define ECa).

211 If we take into account the permittivity, this last approximation becomes

212
$$\frac{H_s}{H_p} \cong -\frac{i\sigma\mu_0\omega L^2}{4} + \frac{\varepsilon_0\varepsilon_r\mu_0\omega^2 L^2}{4}$$
, which suggests that the permittivity response would be first

213 order in-phase and would drastically increase with the frequency and coil separation.

214 Consequently, the in-phase response can be dependent on both the magnetic susceptibility and

215 the relative permittivity. Note also that even if the displacement currents are negligible in

216 comparison with conduction ones, $|\sigma| \gg |i\varepsilon_0\varepsilon_r\omega|$, the permittivity response may be significant

217 in comparison with the susceptibility response.

218

219 **2-4. Instrument calibration and sensitivity analysis**

220 At each geometrical configuration and frequency an instrument measures two quantities,

221 the in-phase and quadrature responses, and it is important to understand the influence of each

222 of the four properties (electrical conductivity (or Eca), dielectric permittivity, magnetic

223 susceptibility (or Msa) and magnetic viscosity) on these responses.

224 To assess this, the calculated responses, as a function of each of the four properties, are

225 expressed by the ratios of the secondary field to the secondary field of a reference ground, where

226 $\sigma=0.01 \text{ Sm}^{-1}$, $\varepsilon_r=200$, $\kappa_{ph}=100 \cdot 10^{-5} \text{ SI}$ and $\kappa_{qu}=0.06\kappa_{ph}$. In this trial each property is varied from

227 0.1 to 10 times that of the value used in the reference case value. Figure 3 presents the in-phase

228 modelled responses for the EMP400, and Figure 4 those for the quadrature situation for both

229 configurations and each frequency. For the low-frequency instrument, the influence of

230 permittivity is negligible, as illustrated by the flat curve in Figure 3 at all configurations and

231 frequencies. The magnetic susceptibility dominates the in-phase response with a linear

232 dependence (Fig. 3), and conductivity controls the quadrature responses with a quasi-linear

233 dependence (Fig. 4). These characteristics are in complete agreement with all that has already

234 been published (McNeill 1980, Tabbagh 1986a). However, a precise interpretation needs to

235 take the effect of the conductivity on the in-phase response into consideration, which increases,
236 but not in direct proportion to the conductivity (Fig. 3), and the effect of the magnetic viscosity
237 on the quadrature response (Fig. 4). The procedure to determine these properties is presented in
238 Simon et al. (2015).

239 No drift has been observed for the EMP400 (but the temperature changes during the
240 acquisition remained limited). A major drawback of the raw data sets is that they first require
241 the determination of the zero offsets or signal shifts. For in-phase components such shifts are
242 mainly caused by mechanical deformations that modify the direct influence of the primary field,
243 but, surprisingly, offsets also exist in quadrature. For each configuration, this step was achieved
244 by a trial and error process to overcome this problem. In quadrature, the different apparent
245 conductivity values, calculated at each frequency and by considering the differences between
246 each frequency pair, must be as close as possible to each other and positive, while the magnetic
247 viscosity must be positive (Simon et al. 2015). In-phase, the different susceptibility values must
248 be as close as possible and positive. The zero offsets are given in Table 1.

249 Following the same approach as for the EMP400, Figures 5 and 6 show the evolution of the
250 ratio of the in-phase and quadrature secondary fields to those of the reference case for the EM31,
251 in which each property varies from 0.1 to 10 times the value used in the reference case. The
252 dependence of the quadrature response on magnetic viscosity is, in this case ($h=1\text{m}$), quasi null
253 (Fig. 6); therefore, the conductivity determination can be directly achieved with this component
254 at a single frequency. The in-phase component is sensitive to conductivity, permittivity and in-
255 phase magnetic susceptibility (Fig. 5), the permittivity response is illustrated by a quasi-flat
256 curve for all configurations and clearance; it is significantly smaller than those of the
257 susceptibility and conductivity. Determination of the apparent properties thus follows a two-
258 step approach: (1) determination of the apparent conductivity using the quadrature response;
259 (2) taking into account the in-phase electrical conductivity response, determination either of the

260 apparent magnetic susceptibility or of both the permittivity and the susceptibility if both HCP
261 and VCP configurations are available. This last step follows the linear process described in
262 Benech et al. (2016).

263 With EM31, no zero offset correction is necessary for the quadrature part of the signal
264 because of the good field calibration of the device achieved by the manufacturer and of the
265 large coil spacing which increases the signal/noise ratio. On the other hand, the zero offset
266 corrections for the in-phase part of the signal must be evaluated (this component is used in metal
267 detection). Here, following the same the calibration protocol as for the EMP400, in-phase signal
268 offsets were established at 56 ppt for HCP (56000 ppm) and 64 ppt (64000 ppm) for VCP by a
269 trial and error process. These high values correspond to a significant uncertainty regarding the
270 exact offset value, but not for the spatial variations of the properties.

271

272 **3- Results**

273 **3-1. *Apparent property maps***

274 Each apparent property is defined here as the property of homogeneous flat ground that
275 would give the same response as that obtained with the considered instrument.

276 The maps resulting from the EMP400 measurements are presented in Figure 7 for the
277 apparent conductivity, and in Figure 8 for the apparent magnetic susceptibility. As the magnetic
278 viscosity, the conductivity and the depth of investigation are independent of the frequency, the
279 difference in quadrature responses between the 15 kHz and 5 kHz frequencies allowed us to
280 remove the magnetic viscosity effect (Simon et al. 2015). To determine the electrical
281 conductivity we thus compared these differences to the corresponding theoretical reference
282 curves calculated from equations (1) for HCP, or (2) for VCP. We also used theoretical
283 reference curves for each frequency to determine the electrical conductivity using the

284 quadrature responses. Using this electrical conductivity value, it is then possible to extract the
285 magnetic viscosity value, which is shown for the VCP and HCP configurations in Figure 9.

286 As illustrated in Figure 7, the maps of electrical conductivity at the different frequencies
287 show identical results, in complete agreement with the values of the Induction Number that
288 establish the similarity in depths of investigation. This result corroborates the solution adopted
289 for the computation of magnetic viscosity. The HCP and VCP maps for apparent conductivity
290 are also very similar. The HCP configuration exhibits a greater range of values, and lower
291 values at the edge of the depression, in agreement with an investigation at greater depth. In the
292 center, the values are higher than 0.04 S.m^{-1} and, as expected, confirm the clayey nature of the
293 filling and clearly delineate the topographic trough.

294 For magnetic properties, reference curves deduced from equations (1) and (2) are used
295 to determine the apparent magnetic susceptibility, taking into account the estimated electrical
296 conductivity at each point. The HCP and VCP susceptibilities are globally very high, between
297 300 and $3,800 \cdot 10^{-5} \text{ SI}$, in agreement with the presence of a basaltic rock substratum (Trigui and
298 Tabbagh 1990). The differences between results for the three frequencies are small, as predicted
299 by the theory. The strong similarity confirms the efficiency of the correction of the induction
300 effect on the in-phase signal for HCP and VCP configurations, respectively. However, the
301 sediment in-fill has lower susceptibility values than the border, at around $700 \cdot 10^{-5} \text{ SI}$. The
302 horizontal delineation is in complete agreement with that of the conductivity. The magnetic
303 viscosity is relatively low and its lateral distribution differs from that of the susceptibility. In
304 HCP the magnetic viscosity (depth of investigation of $0.2 L$) is higher than in VCP (depth of
305 investigation: $0.6 L$) which suggests that it is stronger for the superficial layer of the depression.
306 This observation is in complete agreement with the field observations. The uppermost 45-50
307 centimeters, of slightly varying thickness, contain many sherds and are very different to the
308 deeper layer (Mayoral et al. 2018a). The ratio $\frac{\kappa_{qu}}{\kappa_{ph}}$ values, being higher than 4% inside the

309 topographic trough and lower than 1% at the border, confirm that the basalt mainly contains
310 stable single-domain magnetic grains (high susceptibility and low magnetic viscosity) while the
311 in-fill has been enriched by pedogenic processes - such as redoximorphic processes or alteration
312 of mineral grains (Mayoral et al. 2018) - into smaller single-domain grains closer in volume to
313 the superparamagnetic range (Maher and Taylor 1988). By comparison, a ratio of 6% or more
314 is expected for common non-hydromorphic soils (Dabas and Skinner 1993). As only a single
315 frequency device (MS2-E) was used on the laboratory soil sample measurements, no direct
316 comparison in terms of frequency variation for the susceptibility can be carried out for this field
317 observation.

318 HCP and VCP conductivity maps obtained from the EM31 quadrature signal (Figure
319 10) confirm the horizontal distribution shown by the EMP400 maps. As expected, given that
320 the investigation depth is greater, the conductivity values are about one and a half times lower
321 than for the EMP400.

322 For the in-phase signal, due to the longer coil separation, the effects of both the magnetic
323 susceptibility and the relative permittivity should be considered. The raw data variability is
324 presented in Table 2. The sensitivities of EM31 to the homogeneous ground properties are given
325 in Table 3. The lower sensitivity to κ_{ph} of the HCP response is due to the instrument's clearance,
326 $h=1$ m, because this elevation is close to the change in sign which occurs in the HCP
327 configuration for magnetic responses (at $h=1.39$ m for a coil separation of 3.66 m). If we
328 calculate the apparent magnetic susceptibility from the in-phase responses without considering
329 the relative permittivity, the discrepancy between HCP and VCP results is marked (Figure 11):
330 the spatial distributions are significantly different with a higher dynamic in HCP (in the range
331 7,500 to 50,000 10^{-5} SI), and a lower dynamic in VCP (in the range 2,500 to 18,000 10^{-5} SI).
332 As potentially imperfect offset corrections would increase this effect, the significant difference

333 between the two configurations can probably be explained by the sensitivity to susceptibility
334 distribution in relation to the depth.

335 The maps presented in Figure 12 show the results with both the permittivity and the
336 susceptibility taken into account to define the homogeneous half-space properties using both
337 HCP and VCP in-phase values (Benech et al. 2016). In these apparent property maps, the
338 susceptibility variations remain similar to those observed in Figure 11, whereas the permittivity
339 variations are huge, with a 140,000 interquartile deviation and a big gap for the zero offset. The
340 range of values looks unlikely and it can only be assumed that the basalt border has lower values
341 than the sedimentary in-fill in the depression. The high susceptibility values agree with the
342 presence of a basaltic substratum underlying the sedimentary in-fill and are logically greater
343 than the values delivered by the EMP400. The permittivity values logically result from the low
344 sensitivity presented in Table 3. Considering the high magnetic context and the unlikely
345 apparent permittivity values, the intervention of a permittivity response looks unrealistic. This
346 conclusion will be reconsidered later on when considering a layered terrain.

347 From the apparent property mapping, it can be seen that the filling is more conductive
348 and possibly more polarizable than the surrounding basalt. Its conductivity indicates that it is
349 dominated by fine particles. It has a lower magnetic susceptibility with respect to the
350 surrounding weathered basalt, but a higher magnetic viscosity. Taking all this into account, the
351 electromagnetic properties can provide an accurate description of magnetic behavior in addition
352 to the electrical properties. We are then able to describe not only the clay filling of the
353 depression but also some pedogenetic phenomena, and even provide further details about the
354 lateral and horizontal variations in the hydromorphic soils in a volcanic context, which is poorly
355 revealed by a single electrical conductivity mapping based approach.

356

357 ***3-2 1D inversion processing using quadrature data***

358 Based on the 1D forward modelling (Gu erin et al. 1996), we carried out 1D inversions,
359 firstly considering the electrical conductivity alone, then taking all the electromagnetic
360 properties of the soil into account. Due to the quality of the data, it was not necessary to select
361 a lateral smoothing inversion process, as it was possible to achieve this point by point. The
362 forward operator, \mathbf{G} , uses equation (1) for HCP data, and equation (2) for VCP data. At each
363 point, an iterative damped least square linearization was applied, which started from the \mathbf{m}_0
364 vector of the *a priori* values of the conductivity and/or thickness and calculated $\Delta\mathbf{m}$, the solution
365 of the equation, $(\mathbf{J}^T \mathbf{J} + \lambda \mathbf{I}) \Delta\mathbf{m} = \mathbf{J}^T (\mathbf{d} - \mathbf{G}\mathbf{m}_{i-1})$, \mathbf{m}_{i-1} being the vector solution at the (i-1)th
366 iteration, \mathbf{d} the vector of the data, \mathbf{I} the identity matrix, \mathbf{J} the Jacobian of \mathbf{G} , and λ the
367 regularization parameter. λ has a starting value equal to half of the trace of the $\mathbf{J}^T \mathbf{J}$ matrix.

368 To carry out a more in depth characterization of the sedimentary in-fill, we attempted to
369 reconstruct the depth to the bedrock using a 1D inversion in a two-step approach. In the first
370 step, we only considered the HCP and VCP quadrature responses by using the differences
371 between 15 kHz and 5 kHz for the EMP400 quadrature data, and the quadrature data at 9.8 kHz
372 for the EM31. In the second step, we considered the four properties using eight independent
373 sets of data: quadrature and in-phase. For the conductivity profile, following comparison with
374 the field data (Mayoral et al. 2018), we used a three-layer model (see Figure 2) with a superficial
375 soil layer (the two top clay loam layers), a second layer corresponding to the sedimentary in-
376 fill (massive heavy clay layer), and a third layer corresponding to the possibly weathered
377 basaltic rocks (sandy bottom and weathered basaltic rock layers). As an initial model of the
378 parameters, the superficial layer had a conductivity of $\sigma_1=20$ mS.m⁻¹ (or 50 Ω .m resistivity) and
379 a thickness of $e_1=0.15$ m; the sedimentary in-fill a conductivity of $\sigma_2=83.3$ mS.m⁻¹ (or 12 Ω .m
380 resistivity) (a little bit higher than the EMP400 minimum) and a thickness of $e_2=1$ m; and the
381 basement a conductivity of $\sigma_3=3.33$ mS.m⁻¹ (or 300 Ω .m resistivity) (lower than any of the
382 EM31 HCP measurements). The conductivities and thicknesses of the different layers were

383 tested and it was observed that the parameters of the uppermost layer had only a very limited
384 influence. EMI inversions were also subject to so-called ‘cases of equivalence’: in the case of
385 a conducting layer between two more resistive ones (H type for vertical electrical soundings),
386 the conductive layer can be exchanged for any other layer with the same $\frac{e^2}{\rho}$ ratio (Guérin et
387 al. 1996). Finally, by allowing only e_2 and σ_1 to vary, and keeping the other parameters fixed,
388 the thickness distribution presented in Figure 13 was obtained.

389 These results suggest that the 0.75 m thickness value corresponds to the contour of the
390 depression itself, due to a thickness contrast with the surrounding second layer. This thickness
391 variation is in complete agreement with the profile published by Guillemoteau (2016) when
392 interpreting DualEM421 results and with the field observation (Mayoral et al. 2018). We also
393 carried out a control of the inversion results by comparing field observations with the results of
394 the inversion using the quadrature part of the signal. Figure 14(a) shows that the estimations of
395 the thicknesses of the three layers made it possible to clearly describe the depth of the high clay
396 content layers filling the depression. Only one of the logs (log 3) located in the central trench
397 of the site (Figure 14), does not fit the inversion results. This difference could derive from the
398 1D interpretation which leads to a smoothed model of the bottom of the second layer where
399 there is in reality a local rise in the basalt.

400

401 **3-3 1D inversion using both quadrature and in-phase data sets**

402 Using the three-layer model obtained by 1D modelling of the conductivity results, the
403 other EM properties for each layer were determined point by point. The same issue as above
404 recurs: is it possible to determine both the susceptibility and permittivity or can the influence
405 of the permittivity be neglected? In other words, which hypothesis gives the more realistic

406 results with respect to the geological/pedological context and the external information available
407 describing the depression as having an irregular base shaped into several alteration zones?

408 When the permittivity is neglected, the magnetic susceptibility obtained for the second
409 layer by using four sets of in-phase data is presented in Figure 15. The permittivity for the three
410 layers is fixed at an ordinary value of: $\epsilon_{r1}=\epsilon_{r2}=\epsilon_{r3}=200$, and with $\kappa_{ph1}=500 \cdot 10^{-5}$ SI and $\kappa_{ph3}=2000$
411 10^{-5} SI. The map is in agreement with the apparent susceptibility maps in terms of the lateral
412 distribution and the parameter's magnitude (Figures 8 and 11).

413 Figure 16 presents the results for the case where the permittivity of the second layer is
414 variable. These results are obtained with $\epsilon_{r1}=\epsilon_{r3}=2000$ but are practically independent of the
415 first and third layer fixed permittivity values. The susceptibility is reduced by a factor close to
416 two and, again, the permittivity values are very high and unrealistic. For a permittivity of 10^6
417 (median value obtained), the quantity $\omega\epsilon_r\epsilon_0$ would equal 0.54 Sm^{-1} , seven times greater than the
418 conductivity itself ($83 \text{ mS}\cdot\text{m}^{-1}$). Considering this extremely high and unlikely estimated range
419 of values of dielectric permittivity, the second hypothesis, where the variations of the
420 permittivity are not characterized for the EMP400 and EM31 instruments, and where the in-
421 phase results correspond to magnetic susceptibility only, must be adopted.

422 A comparison with the susceptibility observed at a scale of 1 cm in the cores ('U-
423 Channel' cores), which is summarized in Figure 14, shows a significant discrepancy between
424 the magnitude of inverted in-field susceptibility values and the laboratory ones (MS2-E) for the
425 in-fill of the depression. This discrepancy is explained if one considers that the presence of
426 basalt gravels and pebbles (with around $12000 \cdot 10^{-5}$ SI susceptibility) is taken into account by
427 in-field measurements rather than laboratory one on the cores. These coarse particles would
428 correspond to one fourth or one fifth of the sediment volume at a metric scale.

429

430 **4 Conclusion**

431 This case study confirms the relevance of this type of light EMI apparatus for the rapid
432 exploration of superficial sedimentary/pedological formations, and will increase the reliability
433 of future sediment sampling at the Lac du Puy. Two different single receiver instruments were
434 used, although a multi-receiver/multi-frequency apparatus would produce the same results and
435 be easier to use.

436 The highly magnetic context due to the basaltic substrate led us to look at the in-phase
437 measurements and try to describe the magnetic susceptibility and magnetic viscosity of the in-
438 fill. This process is more common for shorter separation instruments, but nothing has yet been
439 published about this usage for the EM31. The superficial soil and the depression in-fill have a
440 lower magnetic susceptibility and a higher magnetic viscosity than the surrounding weathered
441 basalt and their spatial distribution is slightly different to that of the sediment thickness. Due to
442 the improbable magnitude of the inverted permittivity results, no role can be attributed to the
443 dielectric permittivity variations and the full signal can be attributed to the complex magnetic
444 susceptibility and electrical conductivity. Further studies should be done in the future to assess
445 the effect of permittivity on the in-phase EM31 signal. In this volcanic substrate case study,
446 magnetic susceptibility responses outweigh the electrical polarization when using the EM31. It
447 would be worth doing further investigations in order to assess the potential for this type of
448 instrument in other environments, such as coastal areas or salt-rich soils.

449 In conjunction with the field characterization of the sedimentary accumulation,
450 measurements of the quadrature and in-phase components of the H_s/H_p ratio using the HCP
451 and VCP configurations for both instruments provided a clear description of the conductivity
452 variations. It enabled the Lac du Puy sedimentary in-fill to be identified, by mapping the shape
453 and morphology of the bedrock, lending support to the hypothesis that the depression is a
454 pseudo-sinkhole (Mayoral et al 2018a).

455 The analysis of a combination of magnetic properties allowed the 3D morphology of the
456 sedimentary in-fill to be determined across the basin, and provided stratigraphic and
457 sedimentological information. In addition, selected magnetic properties provided information
458 on the spatial variation of some key features related to hydromorphic processes, in particular
459 clayey granularity and the development of iron oxides/hydroxides. These findings, which will
460 be further tested and refined in other parental rocks, could provide new means of rapid spatial
461 and pedological characterization of hydromorphic soils and palaeosoils, with useful
462 applications for palaeoenvironmental studies.

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570 **Figure captions**

571 Figure 1: Schematic view of the relationship between the soil properties, the geophysical
572 properties and the resulting dataset process during 1D inversions.

573 Figure 2: a) Site location in Central France, b) Aerial view of the Plateau de Corent and the Lac
574 du Puy area, c) Ortho-photography of the depression with cross-section location marked,
575 d) Cross-section showing the main sedimentary units and their respective average
576 magnetic susceptibility measurements (MS2-E, Bartington Ltd, device).

577 Figure 3: EMP400 ($L=1.21$ m, $h=0.25$ m) ratio of the in-phase secondary field to the in-phase
578 secondary field of the reference model for relative permittivity (a), magnetic susceptibility
579 (b) and electrical conductivity (c), for the three frequencies used (5 kHz in red, 8 kHz in
580 green and 15 kHz in blue), for HCP (solid lines) and VCP (dashed lines) configurations.

581 Figure 4: EMP400 ($L=1.21$ m, $h=0.25$ m) ratio of the quadrature secondary field to the
582 quadrature secondary field of the reference model for magnetic viscosity (a), and electrical
583 conductivity (b), for the three frequencies used (5 kHz in red, 8 kHz in green and 15 kHz
584 in blue), for HCP (solid lines) and VCP (dashed lines) configurations.

585 Figure 5: EM31 ($L=3.66$ m, $f=9.8$ kHz) ratio of the in-phase secondary field to the in-phase
586 secondary field of the reference model for relative permittivity (a), magnetic susceptibility
587 (b) and electrical conductivity (c), for HCP (solid lines) and VCP (dashed lines)
588 configurations at $h=1$ m (in red) and $h=0.3$ m (in blue) clearances.

589 Figure 6: EM31 ($L=3.66$ m, $f=9.8$ kHz) ratio of the quadrature secondary field to the quadrature
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591 conductivity (b), for HCP (solid line) and VCP (dashed line) configurations at $h=1$ m (in
592 red) and $h=0.3$ m (in blue) clearances.

593 Figure 7: EMP400 apparent conductivity maps: determined using the difference in quadrature
594 response between 15 kHz and 5 kHz (Simon et al. 2015) (above), and at each frequency
595 (5, 8 and 15 kHz) (below).

596 Figure 8: EMP400 apparent magnetic susceptibility maps, κ_{ph} , at the three frequencies used (5,
597 8 and 15 kHz), for HCP (left) and VCP (right) configurations.

598 Figure 9: EMP400 apparent magnetic viscosity map κ_{qu} for HCP (left) and VCP (right)
599 configurations.

600 Figure 10: EM31 apparent electrical conductivity maps for HCP (left) and VCP (right)
601 configurations.

602 Figure 11: EM31 apparent magnetic susceptibility, κ_{ph} , maps determined without taking the
603 relative permittivity, ϵ_r , response into account for the HCP and VCP configurations.

604 Figure 12: EM31 maps of the apparent magnetic susceptibility, κ_{ph} , and of the apparent relative
605 permittivity, ϵ_r , deduced from both in-phase HCP and VCP responses.

606 Figure 13: Thickness of the second layer, e_2 , resulting from a 1D inversion when σ_1 and e_2 are
607 variable: a) thickness map of e_2 , b) oblique view of the 3D representation of e_2 .

608 Figure 14: a) comparison of field observations and results based on the estimation of the
609 thickness of each layer for the 3-layer model, b) location of the trench and log observation,
610 c) Value of the magnetic susceptibility measurement of the MS2-E (Bartington Ltd)
611 carried out on a 'U-channel' core from log 3.

612 Figure 15: Inversion of the magnetic susceptibility of the second layer, ignoring permittivity
613 variations.

614 Figure 16: Inversion of both the magnetic susceptibility and the dielectric permittivity of the
615 second layer.

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618 **Tables :**

619 Table 1: EMP400 zero offset corrections in ppm

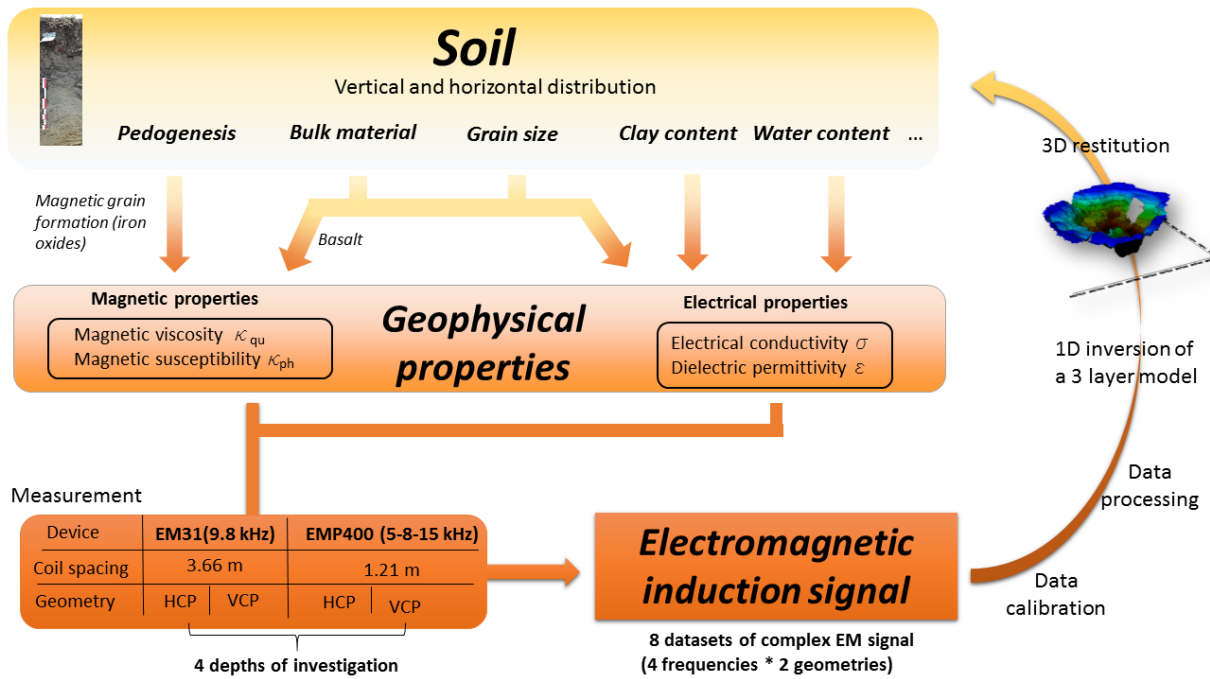
620 Table 2: Variabilities of the in-phase raw data from EM31

621 Table 3: Sensitivities of the EM31 in-phase responses to homogeneous ground susceptibility
622 and permittivity when $h=1$ m

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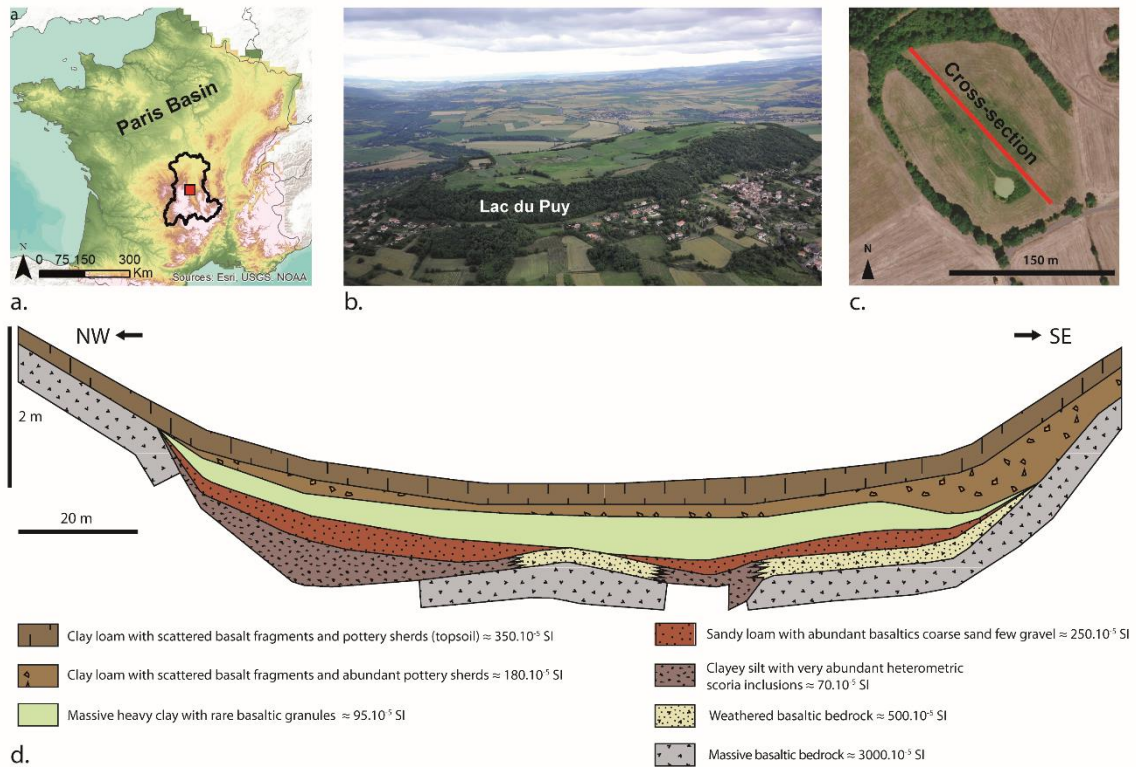
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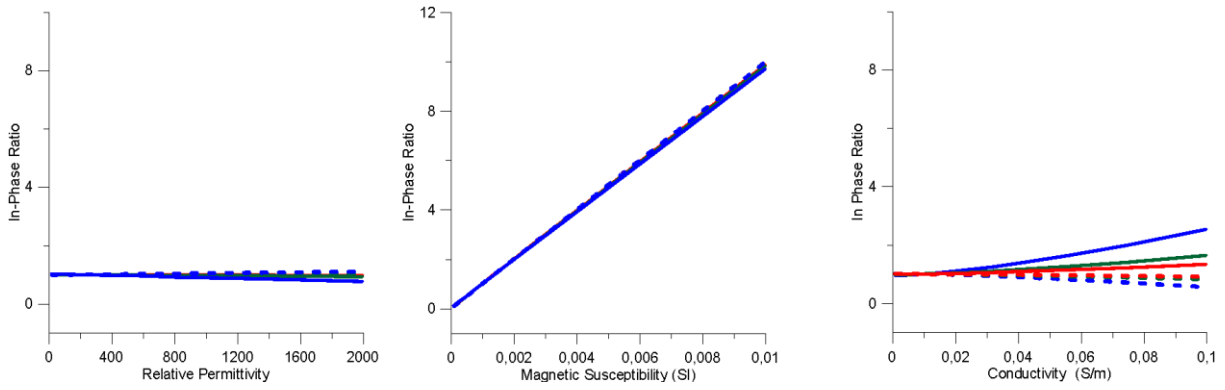
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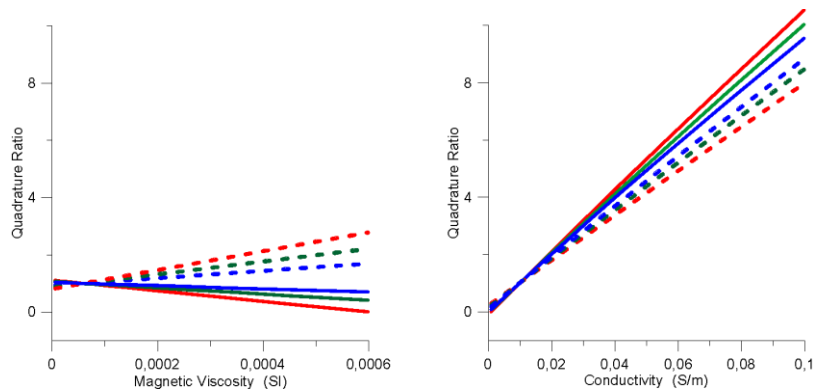
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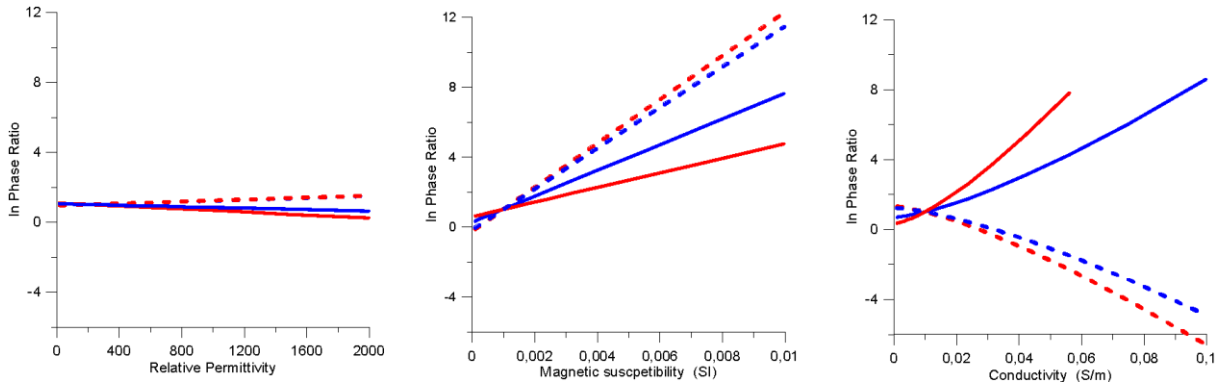
641
 642 Figure 3: EMP400 ($L=1.21$ m, $h=0.25$ m) ratio of the in-phase secondary field to the in-phase
 643 secondary field of the reference model for relative permittivity (a), magnetic susceptibility
 644 (b) and electrical conductivity (c), for the three frequencies used (5 kHz in red, 8 kHz in
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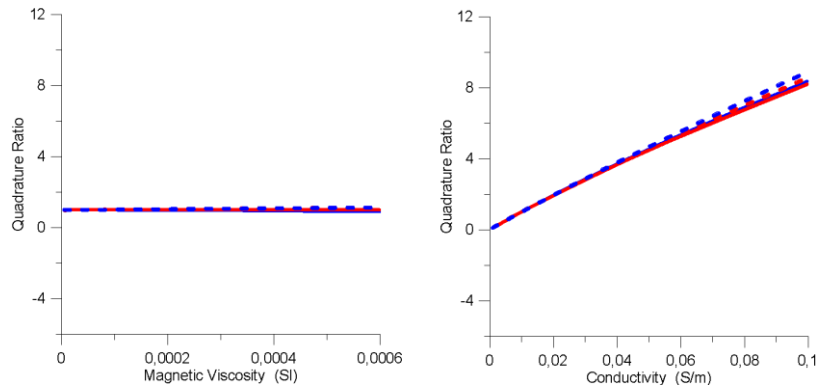


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654 Figure 5: EM31 ($L=3.66$ m, $f=9.8$ kHz) ratio of the in-phase secondary field to the in-phase
 655 secondary field of the reference model for relative permittivity (a), magnetic susceptibility
 656 (b) and electrical conductivity (c), for HCP (solid lines) and VCP (dashed lines)
 657 configurations at $h=1$ m (in red) and $h=0.3$ m (in blue) clearances.

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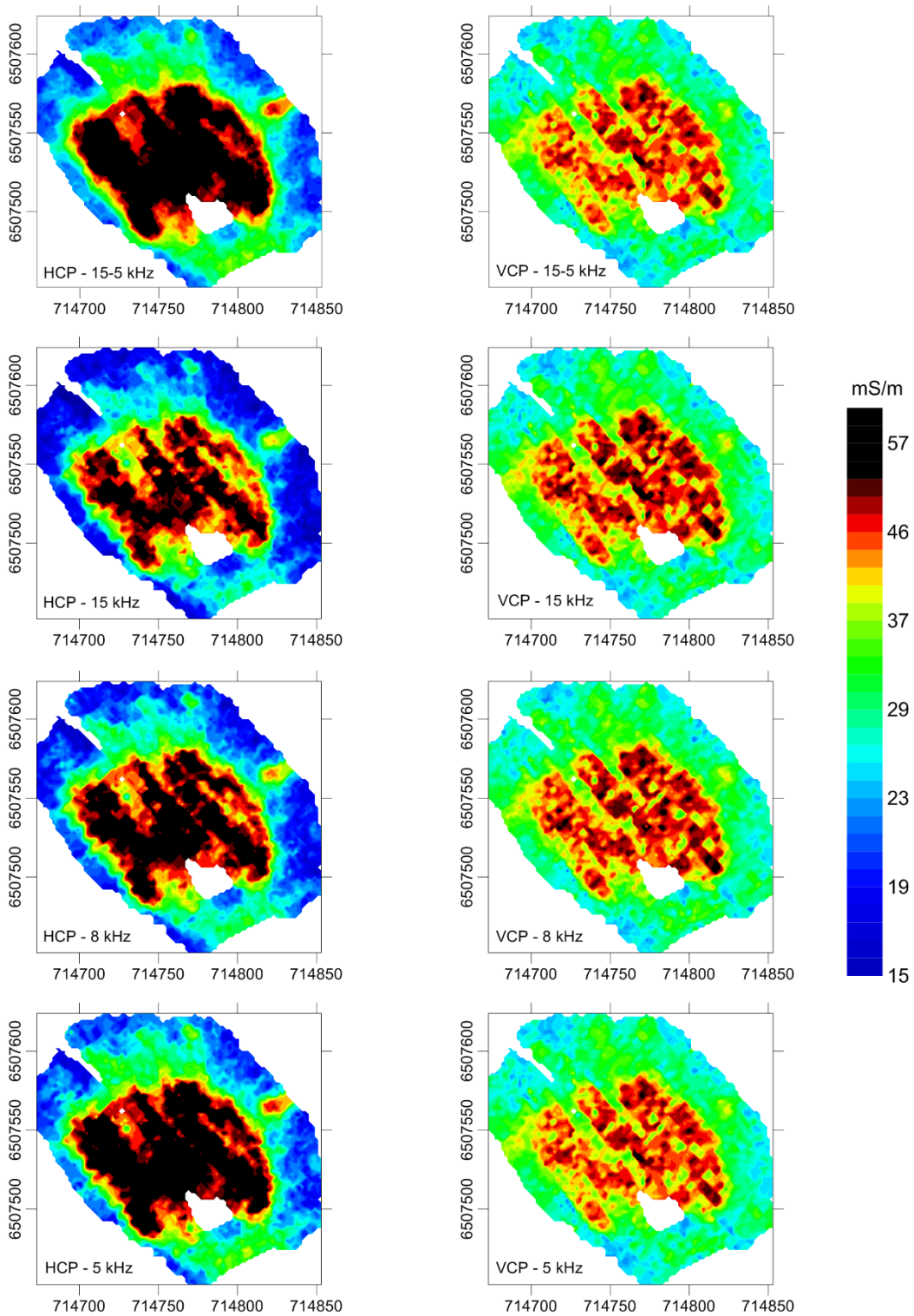


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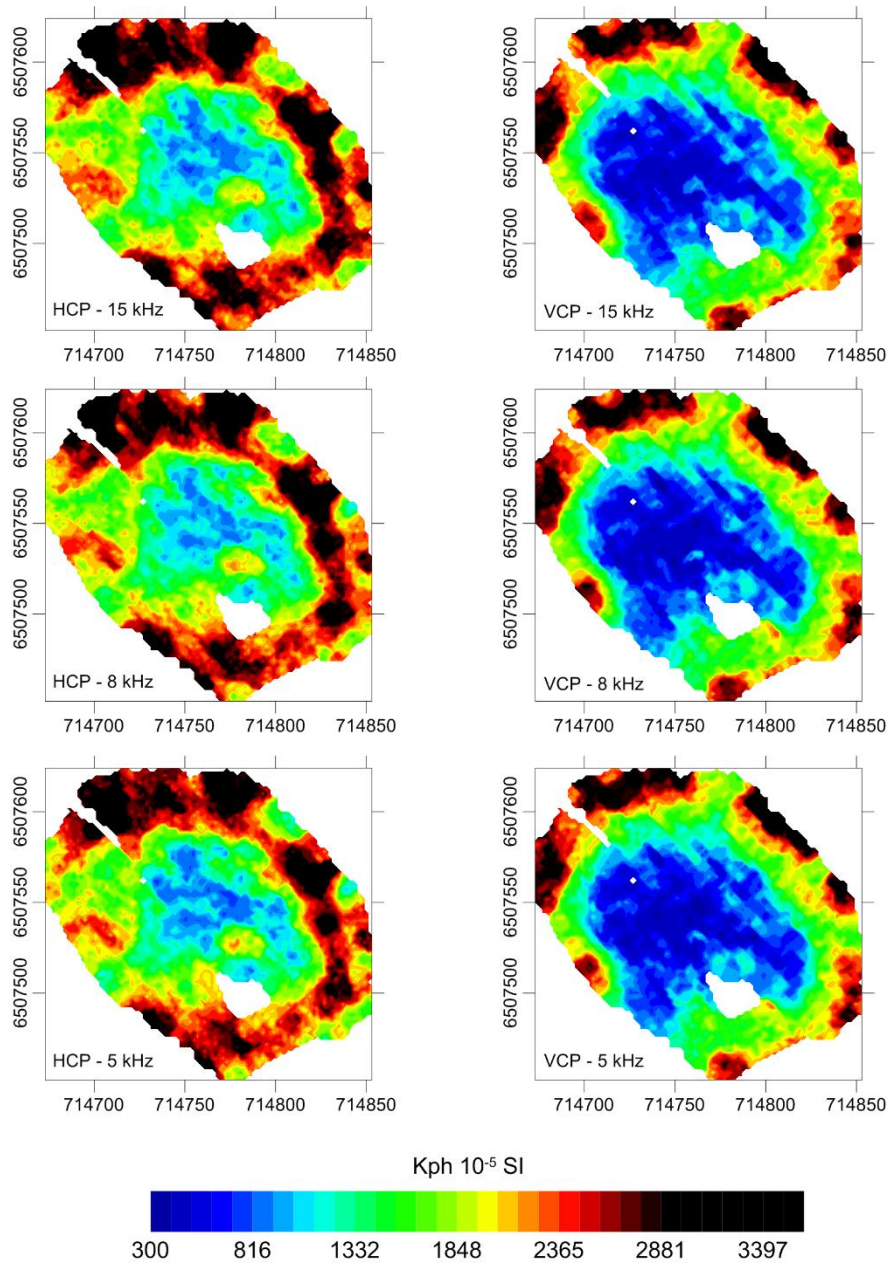
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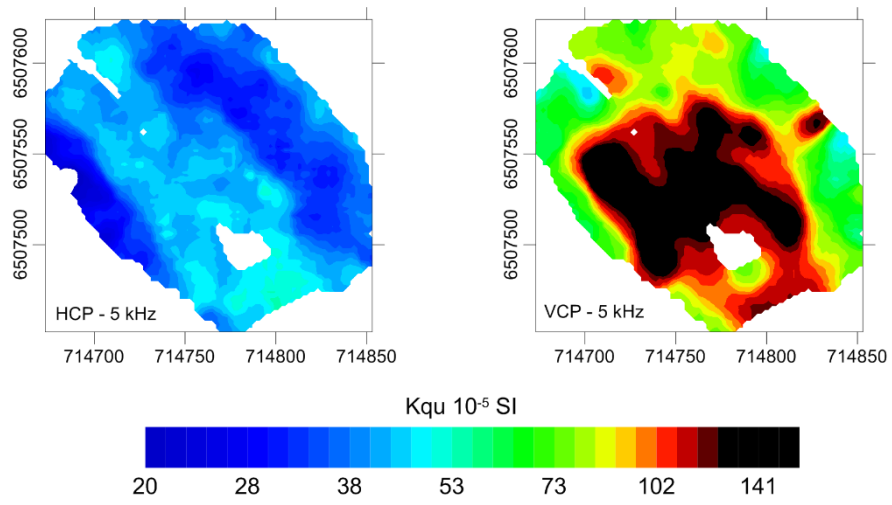
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685 Figure 9: EMP400 apparent magnetic viscosity map κ_{qu} for HCP (left) and VCP (right)

686 configurations.

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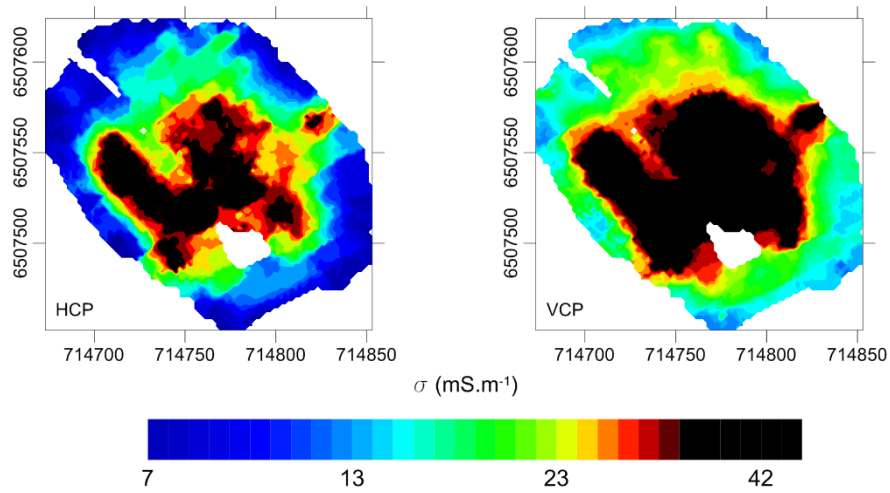
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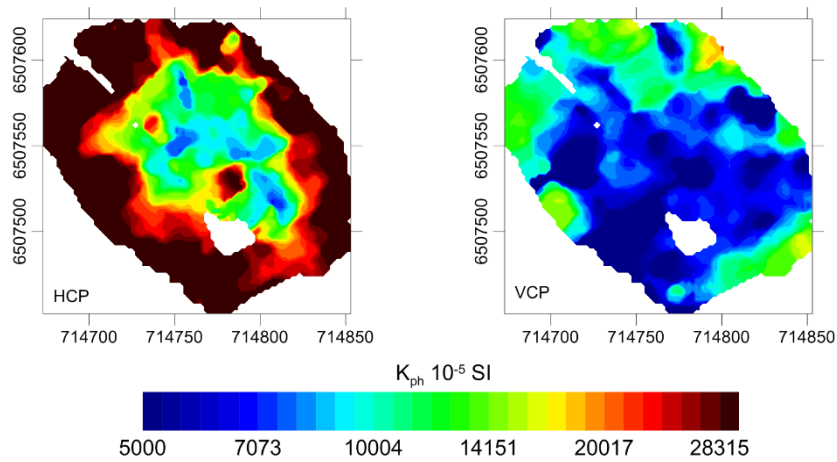


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700 Figure 10: EM31 apparent electrical conductivity maps for HCP (left) and VCP (right)

701 configurations.

702

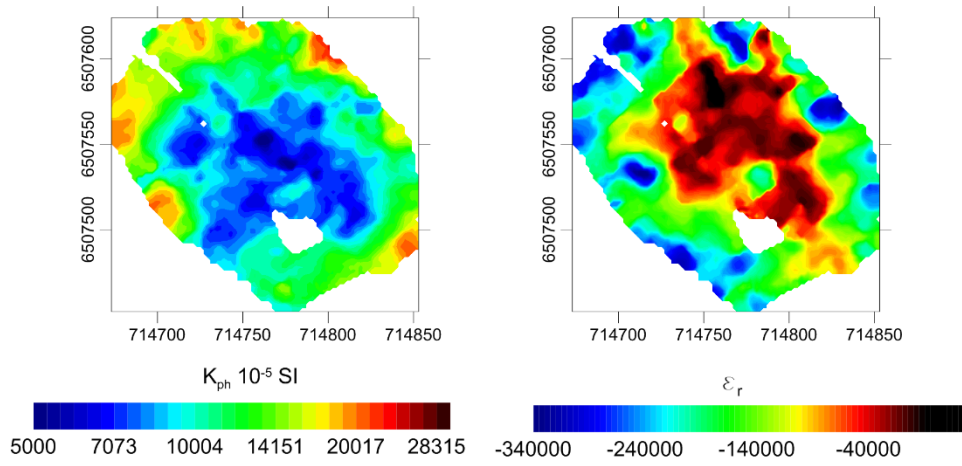


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704 Figure 11: EM31 apparent magnetic susceptibility, κ_{ph} , maps determined without taking the

705 relative permittivity, ϵ_r , response into account for the HCP and VCP configurations.

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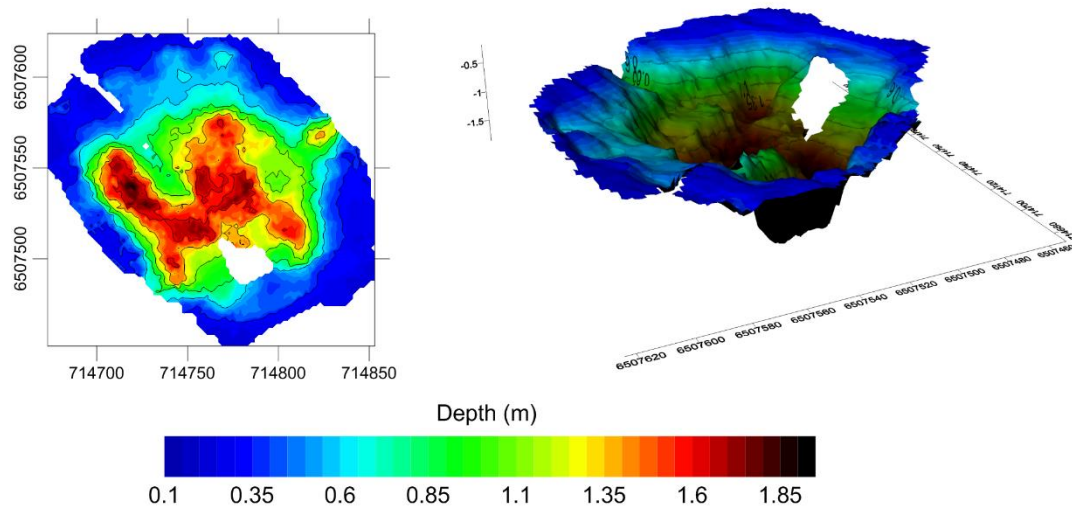
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708

709 Figure 12: EM31 maps of the apparent magnetic susceptibility, κ_{ph} , and of the apparent relative

710 permittivity, ϵ_r , deduced from both in-phase HCP and VCP responses.

711



712

713 Figure 13: Thickness of the second layer, e_2 , resulting from a 1D inversion when σ_1 and e_2 are

714 variable: a) thickness map of e_2 , b) oblique view of the 3D representation of e_2 .

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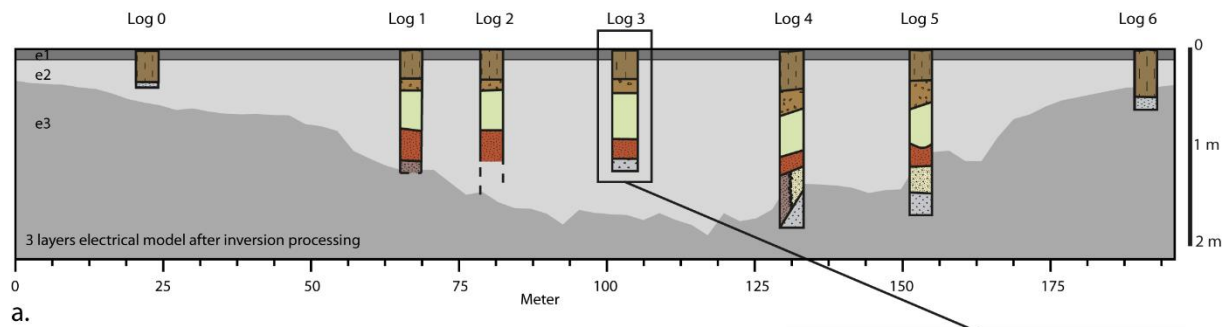
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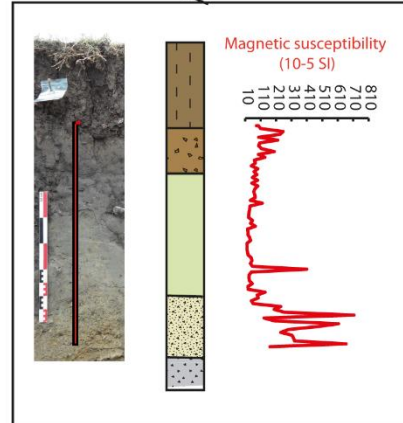
725



a.



b.



c.

- | | | | |
|--|--|--|---|
| | Clay loam with scattered basalt fragments and pottery sherds (topsoil) | | Clayey silt with very scoria inclusions |
| | Clay loam with scattered basalt fragments and abundant pottery sherds | | Weathered basaltic bedrock |
| | Massive heavy clay with rare basaltic granules | | Massive basaltic bedrock |
| | Sandy loam with abundant basaltics coarse sand and few gravel | | |

726

727 Figure 14: a) comparison of field observations and results based on the estimation of the
 728 thickness of each layer for the 3-layer model, b) location of the trench and log observation,
 729 c) Value of the magnetic susceptibility measurement of the MS2-E (Bartington Ltd)
 730 carried out on a 'U-channel' core from log 3.

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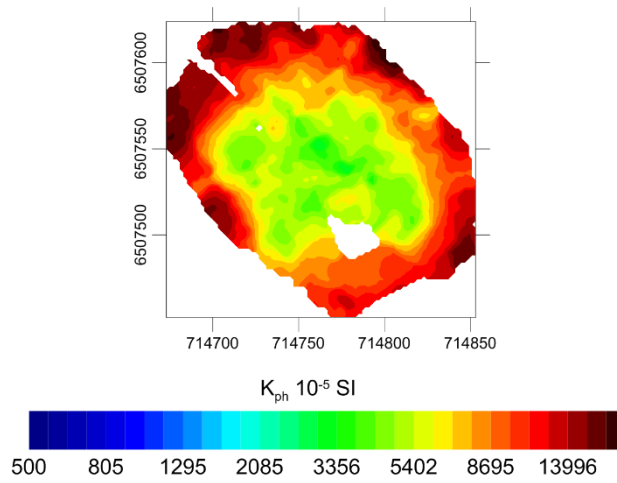
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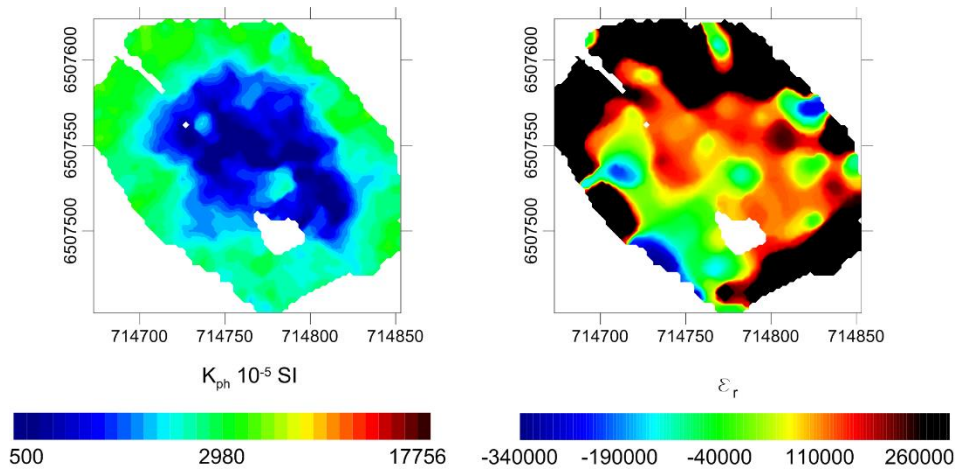


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741

742 Figure 15: Inversion of the magnetic susceptibility of the second layer, ignoring permittivity
743 variations.

744



745

746 Figure 16: Inversion of both the magnetic susceptibility and the dielectric permittivity of the
747 second layer.

748

EMP400	15 kHz		8 kHz		5 kHz	
	Phase	Quadrature	Phase	Quadrature	Phase	Quadrature
HCP	12500	-217	1260	20	-1300	35
VCP	-22000	-1540	-7000	-750	-3610	-500

749

750 Table 1: EMP400 zero offset corrections in ppm

751

752

In-phase EM31	1 st quartile	median	3 rd quartile
VCP	75.7 ppt	82,0 ppt	93.1 ppt
HCP	32.4 ppt	42,1 ppt	52.6 ppt

753

754 Table 2: Variabilities of the in-phase EM31 raw data

755

756

EM31 ($h=1\text{m}$)	HCP	VCP
$\frac{\partial \left(\frac{H_s}{H_p} \right)}{\partial \epsilon_r}$	$C_{HE} = 0.110 \text{ ppm}$	$C_{VE} = 0.077 \text{ ppm}$
$\frac{\partial \left(\frac{H_s}{H_p} \right)}{\partial \kappa_{ph}}$	$C_{HK} = -1.044 \text{ ppm}/1 \cdot 10^{-5} \text{ SI}$	$C_{VK} = 3.36 \text{ ppm}/1 \cdot 10^{-5} \text{ SI}$

757

758 Table 3: Sensitivities of the EM31 in-phase responses to a homogeneous ground susceptibility
759 and permittivity when $h=1 \text{ m}$

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