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Christophe Benech, Michel Dabas, François Xavier Simon, Alain Tabbagh, Julien Thiesson

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1 **Interpretation of shallow EMI resistivity and magnetic susceptibility measurements**  
2 **using rapid 1D/3D inversion**

3

4 **Short title:** Rapid 1D/3D inversion of shallow EMI

5 **Authors:** Christophe Benech<sup>1</sup>, Michel Dabas<sup>2</sup>, François-Xavier Simon<sup>3</sup>, Alain Tabbagh<sup>4</sup>,  
6 Julien Thiesson<sup>4</sup>

7

8 <sup>1</sup> UMR 5133 Archéorient, Maison de l'Orient et de la Méditerranée – Université Lyon 2 F-69365 Lyon

9 <sup>2</sup> Geocarta, 5 rue de la banque F-75002 Paris

10 <sup>3</sup> USR3550, MSH, 4 rue Ledru, F-63000, Clermont-Ferrand

11 <sup>4</sup> Sorbonne Universités, UPMC Paris6, UMR7619, Métis, F-75252 Paris

12

13 Corresponding author: Alain Tabbagh, [alain.tabbagh@upmc.fr](mailto:alain.tabbagh@upmc.fr)

14

15 **Abstract**

16 This paper proposes an inversion process of EMI data based on a two-step approach  
17 with 1D inversion of the entire studied surface and a fast 3D inversion applied over limited  
18 areas. This process is similar to that formerly used in resistivity prospecting. For the study of  
19 soil (environmental, engineering or archaeological explorations) low frequency  
20 electromagnetic instruments (referred to as Slingram EMI, or EMI) have highly useful  
21 specificities. They are light, easy to move in the field, and can simultaneously measure the  
22 ground's electrical conductivity and magnetic susceptibility; they have thus been used to map  
23 these properties over large surface areas, within relatively short periods of time and at  
24 reasonable expense. The possibility of combining several coil geometries has opened up the  
25 potential for multi-depth techniques and systematic 1D inversion, which are found to be  
26 sufficiently revealing to allow larger portions of surveyed areas to be analysed.

27           In the ‘targeted areas’ selected for 3D inversion, the geometries of the 3D features and  
28 the resistivity and/or susceptibility contrasts are determined. This step is based on the method  
29 of moments where only 3D heterogeneities are meshed, and only a small number of major  
30 characteristics, such as contrast, thickness, width, etc., are searched for. This process was first  
31 applied to synthetic data, then to data acquired at an experimental test site, and finally to field  
32 cases. The rapid 3D inversion complements the 1D one by solving a series of issues:  
33 correction for the apparent anisotropy generated by the instrument configuration, multi-arched  
34 anomalies, precise location of lateral changes and determination of the properties contrasts.  
35 The inversion results highlight the importance of the instrument geometry. It is also shown  
36 that apparent magnetic susceptibility data can be more appropriate for the determination of the  
37 volume of man-made features, and is highly complementary to conductivity data.

38

### 39 **Key words**

40 Soil resistivity and magnetic susceptibility, multi-depth EMI prospection, 1D and 3D  
41 successive inversions, archaeological prospection

42

### 43 **Introduction**

44           The application of Slingram electromagnetic induction (EMI) devices to near-surface  
45 studies began during the 1960s in archaeological prospection. The data initially gave rise to a  
46 series of interpretation difficulties, due to the unexpected influence of the ground's magnetic  
47 susceptibility in the measured responses (Scollar et al. 1990). It was later recognized that an  
48 appropriate choice of coil separation and frequency could allow the conductivity response to  
49 be distinguished from that of the magnetic susceptibility (Tite and Mullins, 1970): in cases  
50 where the so-called induction number is sufficiently low, the magnetic susceptibility  
51 generates an in-phase response while the electrical conductivity a quadrature out of phase one.

52 The attractive benefits of this technique have led to considerable research, in an effort to  
53 assess its potential advantages and drawbacks with respect to those of the previously  
54 implemented, conventional magnetic field and DC resistivity techniques. The design of a new  
55 family of EM instruments by Geonics Ltd (Canada) (McNeil 1980) led to large applications in  
56 soil salinity mapping (De Jong et al. 1979), which were then extended to the study of other  
57 soils (Kachanoski et al. 1988).

58 Conductivity measurements are straightforward with an EMI instrument, since it can  
59 be more easily deployed and operated in the field than a DC resistivity array. EMI instruments  
60 have thus experienced considerable developments, for rapid near-surface mapping  
61 applications over extended areas (Bendjoudi et al. 2002, Vitharana et al. 2008, Hoefler et al.  
62 2010). Similarly to the case of airborne electromagnetic measurements (AEM) prospectors  
63 have to face with the complexity of interpreting huge volumes of 3D data (see for example  
64 Huang and Fraser, 1996). The first interpretations involved the application of a 1D point-by-  
65 point inversion, after having outlined the conditions under which this interpretation is relevant  
66 (Guérin et al. 1996). Later, the development of 1D modelling included magnetic susceptibility  
67 and dielectric permittivity in the analysis of EMI data (Huang and Fraser 2002, Farquharson  
68 et al. 2003). Similarly to the case of galvanic resistivity, more sophisticated laterally-  
69 constrained 1D inversions have been applied (Santos 2004, Auken and Christiansen 2004) or  
70 joint inversion has been used with other techniques, magnetic cartography in particular  
71 (Benech et al. 2002).

72 Nowadays, new ground-based multi-coil devices (Saey et al. 2012, Bonsall et al. 2013)  
73 give access to precise multi-depth data, while ensuring accurate collocation of the data fields.  
74 This stimulates the need of inversion procedures that fully exploit the advantages of these  
75 instruments, in terms of imaging both conductivity and susceptibility of subsurface features.  
76 One also wants to take into account the need of a rapid method usable on a laptop allowing

77 easily reconsidering the starting parameters and the extent of the considered area. Compared  
78 with other EM techniques one must note that both the transmitter(s) and the receiver(s) are  
79 moving thus (i) the considered calculations are significantly longer than for fixed sources EM  
80 because the primary field needs to be calculated for each location of the transmitter, but (ii) in  
81 the surveyed field the electromagnetic coupling is negligible between 3D heterogeneities  
82 separated by too great distances (several times the inter-coil separation(s)). To overcome the  
83 difficulties and taking into consideration the practical conditions associated with 3D  
84 inversion, a two-steps efficient approach has been proposed for the processing of multi-depth  
85 DC resistivity data (Brinon et al. 2012). The first step involves defining the 1D structure of  
86 the subsurface. Then the interpreter defines a ‘targeted area’, which is a limited area  
87 surrounding the target(s) of interest and whose surface is several times larger than the range of  
88 investigation of the instruments used. The 3D bodies imbedded in the layered terrain are  
89 characterized by a limited number of parameters: contrast, thickness, width, length,  
90 orientation. This approach is well matched to the characteristics of man-made features that are  
91 searched for in archaeological prospection, or in polluted sites exploration. It is  
92 straightforwardly implemented when using the moment method (MoM) for forward  
93 modelling. MoM combines analytical and numerical calculations, for which only 3D  
94 heterogeneities located in a layered 1D terrain need to be meshed. Its application in EM is less  
95 simple than in DC resistivity but both the conductivity and susceptibility contrasts can be  
96 taken into account (Tabbagh 1985).

97         In the present paper this approach is applied to EMI survey data in order to evaluate its  
98 potential. One first defines the successive steps of the inversion process before inverting  
99 synthetic data, data collected above artificial features on a field test site and finally field data  
100 collected over archaeological sites.

## 102 **Inversion process**

### 103 *Forward modelling*

104 The moment method (MoM) has been applied for more than thirty years in EM  
105 prospection modelling (Raiche 1974, Hohmann 1975, Tabbagh 1985). 3D bodies located in  
106 layered terrain are replaced by an equivalent set of EM dipoles sources. Consequently it  
107 allows meshing to be restricted to heterogeneous bodies, but requires an initial 1D layered  
108 model and analytical calculations of the fields generated by dipole sources in the layered  
109 terrain. These can now be performed very rapidly through the use of convolution calculations  
110 to determine the required Hankel transforms (Guptasarma and Singh, 1997). After having  
111 determined the 1D surrounding model, the heterogeneous body(ies) imbedded in the layers is  
112 (are) meshed, and the intensity of the equivalent secondary sources is determined using a  
113 volume integral equation. These sources are then used to compute the resulting secondary  
114 field at the surface.

### 115 *Inversion*

116 The aim of an inversion process is to determine the unknown quantities representing  
117 physical properties of interest. In the present case, these correspond to the electrical resistivity  
118 and magnetic susceptibility values, and the geometrical boundaries of selected layer(s) and  
119 body(ies). The inversion is achieved by starting with an *a priori* set of values, representing  
120 each of the different inversion parameters, and then iteratively modifying these in order to  
121 achieve a sufficiently good fit between the results of the forward model and the experimental  
122 data. The Levenberg-Marquardt algorithm (Marquardt, 1963) is used to achieve a linearized  
123 iterative process, in which the cost function includes both the Euclidian distance (L2 norm)  
124 between the model results and the data, as well as the intensities of the model parameter  
125 increments, multiplied by a damping factor the weight of which is reduced during the course  
126 of the iterative process.

127 In the present case the total inversion process thus follows two steps. The first of these  
 128 determines, over the entire studied area, an optimised 1D structure that is fitted (point by  
 129 point, or with a lateral constraint) to the apparent resistivities and susceptibilities measured by  
 130 the various instruments. In this step, if vertical electrical sounding results are not available,  
 131 one generally fixes the number of layers at 3 and chooses the *a priori* resistivity and thickness  
 132 values by considering the apparent resistivity and magnetic susceptibility values as well as the  
 133 depth of investigation of each EMI configuration used.

134 The algorithm is the following. We called  $\mathbf{m}$  the vector of the parameters,  $\mathbf{m}_0$  the  
 135 corresponding *a priori* starting values,  $\mathbf{d}$  the vector of the data and  $\mathbf{G}$  the operator of the  
 136 forward calculation. As the problem is non-linear, it is iteratively solved by calculating at  
 137 iteration,  $i$ ,  $\mathbf{G}$  and its Jacobian  $\mathbf{J}$  using  $\mathbf{m}_{i-1}$  parameters and then deducing the increment  
 138  $\Delta\mathbf{m}=\mathbf{m}-\mathbf{m}_{i-1}$  by derivation of the cost function:

$$139 \quad \mathbf{S}=\Delta\mathbf{p}^T\Delta\mathbf{p}+\lambda\Delta\mathbf{m}^T\Delta\mathbf{m} \quad (1)$$

140 Where

$$141 \quad \Delta\mathbf{p}=\mathbf{d}-\mathbf{G}\mathbf{m}_{i-1}-\mathbf{J}\Delta\mathbf{m} \quad (2)$$

142 The solved equation is thus:

$$143 \quad \mathbf{J}^T\mathbf{J}+\lambda\mathbf{I})\Delta\mathbf{m}=\mathbf{J}^T\Delta\mathbf{p} \quad (3)$$

144 Where  $\mathbf{I}$  is the identity matrix and  $\lambda$  the regularisation parameter.  $\lambda$  has a starting value  
 145 equal to the double of the trace of the  $\mathbf{J}^T\mathbf{J}$  matrix divided by the number of parameters and,  
 146 after, is divided at each iteration  $i$  by  $i^{1.5}$ . The number of iteration depends on the  $\mathbf{m}_0$  choice  
 147 but remains lower than 10.

148 Where a 3D approach is required, the second step begins by defining, over the  
 149 ‘targeted area’ surrounding the body(ies), the 1D reference or ‘background’ model. We adopt  
 150 the statistic mode of each value of the layer’s parameters in that area. Then the parameters

151 characterising the 3D heterogeneous body(ies) are determined. The *a priori* starting values of  
152 the horizontal limits the body(ies) are defined by considering the full width half maximum of  
153 the anomaly, that of the resistivity by dividing by two the background resistivity if the body is  
154 more conductive and by multiplying by two the background resistivity if the body is more  
155 resistive. To verify the influence of these *a priori* values they can also be freely fixed by the  
156 interpreter. In 3D inversion the starting value of regularisation parameter,  $\lambda$ , equals the fifth of  
157 the trace of the matrix divided by the number of parameters. The susceptibility contrast is  
158 linearly inverted.

159         The electrical resistivity and magnetic susceptibility are nevertheless two independent  
160 properties, but whereas the resistivity distribution modifies the ‘primary’ field distribution  
161 seen by the magnetic grains inside the layered terrain (which could be significantly different  
162 from the free space distribution), the susceptibility (and the susceptibility contrast) is  
163 sufficiently small for its influence on the primary field to be considered as negligible  
164 (Tabbagh 1985). This means that the resistivity distribution must be known before the  
165 susceptibility distribution can be inverted, whereas the converse does not apply. In both the  
166 1D and 3D inversion steps, we thus proceed by initially inverting the resistivity distribution  
167 and the geometrical limits, before searching for the susceptibility distribution.

#### 168         *Tests of rapid 1D/3D inversion on synthetic data*

169         Although the 1D inversion of apparent resistivity data maps is well known and has  
170 been used and published for more than twenty years (Guérin *et al.* 1996), the 3D inversion of  
171 data raises new issues. The first difficulty, of major importance for the prospector, is to assess  
172 the optimal number of independent in-phase and quadrature out of phase measurement maps  
173 needed to determine the required resistivity and susceptibility contrasts as well as the  
174 geometrical parameters of the body(ies). Although this problem is complex and probably has



175 no general solution, the analysis of a synthetic example can contribute to an improved  
176 understanding of this process.

177 We consider a 3D elongated body 3 m in length, 1 m in width and 1 m in thickness  
178 (which could correspond to a ditch) embedded in the second layer of a three-layer ground  
179 having a resistivity of 20  $\Omega\text{m}$  (50  $\text{mSm}^{-1}$  conductivity) and a susceptibility of  $80 \times 10^{-5}$  SI.  
180 The top of the body is located 0.3 m below the ground. The first layer (corresponding to the  
181 topsoil) has a resistivity of 100  $\Omega\text{m}$  (10  $\text{mSm}^{-1}$ ), a susceptibility of  $30 \times 10^{-5}$  SI, and a  
182 thickness equal to 0.2 m. The second layer is characterised by the same parameters with the  
183 values: 200  $\Omega\text{m}$  (5  $\text{mSm}^{-1}$ ),  $20 \times 10^{-5}$  SI and 2m, and the third layer is characterised by the  
184 values: 50  $\Omega\text{m}$  (20  $\text{mSm}^{-1}$ ) and  $10 \times 10^{-5}$  SI. The synthetic data are calculated for three  
185 different Slingram EMI devices: a) a 0.6 m coil separation with HCP (horizontal coplanar)  
186 and VCP (vertical coplanar) coil configurations, an operating frequency equal to 27.96 kHz,  
187 and measurements recorded at 0.08m above the ground; b) a 1.0 m coil separation with HCP  
188 and VCP coil configurations, an operating frequency equal to 14.6 kHz, and measurements  
189 recorded at 0.08m above the ground; c) a 1.5 m separation with a PERP (perpendicular) coil  
190 configuration, an operating frequency equal to 8 kHz, and measurements recorded 0.15 m  
191 above the ground. We thus have ten independent data sets, of which five correspond to in-  
192 phase measurements expressed by apparent susceptibility values (Figure 1b) and five  
193 correspond to quadrature measurements expressed by apparent resistivity values (Figure 1a),  
194 calculated with a fine  $0.25 \times 0.25 \text{ m}^2$  mesh over a  $8 \times 8 \text{ m}^2$  surface area, corresponding to a  
195 total of 1089 measurement points.

#### 196 *1D inversion results*

197 Here the inversion bears over one single unknown parameter, the resistivity  
198 (respectively susceptibility of the second layer) in order to be able to compare the results of  
199 the different configurations. As expected from theory (Tabbagh 1986), for the apparent

200 resistivity measurements VCP configurations give the best results, with a full width half  
201 maximum corresponding to the width of the body, and a minimum reaching  $60 \Omega\text{m}$  ( $16.7$   
202  $\text{mSm}^{-1}$ ) for a 1 m VCP, whereas the latter parameter is determined as  $100 \Omega\text{m}$  ( $10 \text{mSm}^{-1}$ ) for  
203 a 1m HCP configuration, and  $97 \Omega\text{m}$  ( $10.3 \text{mSm}^{-1}$ ) for the PERP 1.5 m instrument. When the  
204 five sets of data are inverted together, the resulting image is less informative than when the  
205 VCP configuration is used alone, and the resistivity minimum is determined to be  $84 \Omega\text{m}$   
206 ( $11.9 \text{mSm}^{-1}$ ). It can thus be understood that it is not necessarily relevant to use several  
207 datasets due to its unavoidable ‘averaging’ effect. However, the difference between the 1D  
208 results and the resistivity of the body ( $20 \Omega\text{m}$ ) always remains high.

209 The 1D inversion of apparent susceptibility datasets produces similar results, except  
210 that, as in the apparent susceptibility maps (Figure 1b), the shapes of the anomalies fit the  
211 shape of the body more accurately. Similarly to the case of the resistivity, the VCP  
212 configuration produces the best result: the VCP 1m thus leads to a  $55 \times 10^{-5}$  SI maximum,  
213 whereas the HCP 1m leads to  $45 \times 10^{-5}$ SI, the PERP gives  $52 \times 10^{-5}$  SI and all five datasets  
214 also find  $52 \times 10^{-5}$  SI for the predefined  $80 \times 10^{-5}$  SI susceptibility of the body.

### 215 *3D inversion results*

216 Using the full width half maxima, it is relatively straightforward to determine the  
217 shape of the body in the horizontal plane. In the following, we focus on assessing the  
218 suitability of various instrument geometries/configurations for the determination of three  
219 parameters: the body's vertical extent, its resistivity/conductivity contrast, and its  
220 susceptibility contrast. The vertical extent of a body is known to be the most difficult  
221 parameter to asses, using the DC resistivity method. The inversion is based on the data  
222 corresponding to a small area, i.e. the selected targeted area comprising  $5 \times 21$  measurement  
223 points centred on the body (thus a  $1 \times 5 \text{m}^2$  area, Figures 1a and 1b). The results obtained with  
224 each dataset (corresponding to 5 different instrumental configurations), and with the

225 combined datasets, are presented in Table 1. These include results based on both apparent  
226 resistivity measurements, and apparent susceptibility measurements. It can be seen that the  
227 computed results are close to the real values (provided in the first line of this table), with the  
228 exception of the vertical extent of the body, determined by inverting the apparent resistivity  
229 data, which has uncertainties as high as 20%. The most accurate results, obtained using the  
230 apparent susceptibility data, can be explained by the stronger geometrical correspondence  
231 between the shape of the anomaly and the shape of the causative body. In this example, the  
232 VCP 1m configuration appears to produce the best inversion results. The most inaccurate  
233 resistivity inversion is determined with the PERP instrument (probably as a result of its  
234 greater 1.5m inter-coil separation), and the most inaccurate susceptibility inversion is  
235 determined with the HCP (probably because it has the smallest anomaly). It is important to  
236 note that this conclusion is valid even in the case of the smallest inter-coil separation, in  
237 agreement with previously published experimental results (Thiesson *et al.* 2009). Again there  
238 is no clear advantage in using the five data sets together, two of the one data sets giving better  
239 results.

240

#### 241 **Field test over an artificial feature**

242 A field test over artificial features has several advantages when compared to (physical  
243 or numerical) modelling: 1) it makes use of real in-field measurements, associated with the  
244 usual errors arising from uncertainties in measurement locations, external sources of EM  
245 noise, etc., 2) even when the anomalous bodies are built very carefully, the homogeneity of  
246 the filling material is never perfect, thus leading to real variability in the body properties, 3)  
247 the surrounding medium may also be inhomogeneous, and be characterised by significant  
248 natural changes in the immediate vicinity of the body.

249           The artificial feature we studied is located at the Garchy laboratory (Nièvre, France). It  
250 consists of a dual-branch ditch, dug into a silty superficial weathered formation above the  
251 Jurassic limestone: the two branches have respectively N-S and E-W alignments, and both  
252 have the same dimensions: a  $0.8 \times 0.8 \text{ m}^2$  section, and a length of 8 m. The ditch is filled with  
253 exogenous topsoil, and thus has a higher magnetic susceptibility than the surrounding soil. Its  
254 resistivity contrast is low. EMI measurements were carried out in 1999 (Benech 2000), using  
255 three different devices: the MS2B magnetic susceptibility probe (Bartington, Ltd), the EM38  
256 (Geonics ltd), which can in principle be used in both VCP and HCP configurations, and the  
257 SH3 (a laboratory prototype, (Parchas and Tabbagh 1978)). The MS2 has a 0.18m diameter  
258 coincident loop and thus a small depth of investigation, equal to approximately 0.1m,  
259 allowing the susceptibility determination to be restricted to the topsoil. The EM38 has a 1m  
260 coil separation and is operated at 14.6 kHz. The SH3 has a PARA coil orientation (the two  
261 coils have parallel axes at  $35^\circ$  from vertical so that their direct coupling is null in free space),  
262 a 1.5m coil separation, and is operated at 8.04 kHz. The dimensions of the studied area were  
263  $20 \times 20 \text{ m}^2$ , and this was surveyed using a  $1 \times 1 \text{ m}^2$  measurement mesh. This mesh was however  
264 too coarse to allow changes in sign of the anomaly measured with the EM38 HCP  
265 configuration to be correctly monitored. All HCP data was thus excluded from the  
266 interpretation process. The measurements were carried out along North-South profiles, with  
267 the EM38 and SH3 being aligned with this profile (the line joining the transmitter to the  
268 receiver was parallel to the profile).

269           The three apparent magnetic susceptibility maps shown in Figure 2, and the two  
270 apparent resistivity maps shown in Figure 3, were processed by median filtering over a  $3 \times 3$   
271 points moving window. Even for the topsoil, the two branches of the ditch exhibit a greater  
272 magnetic susceptibility than the surrounding terrain, and the global shape of the feature can be  
273 recognized. In the apparent resistivity maps, the presence of the ditch is less well defined; it

274 appears to be slightly more resistive than the surrounding layer, and is clearly visible on the  
275 EM38-VCP map. However, the SH3 map reveals the natural variations of the medium, rather  
276 than those of the feature. This can be explained by the greater depth of investigation of this  
277 instrument. The apparent anisotropy effect associated (Guérin *et al.* 1996) with the  
278 configuration and orientation of the EM38-VCP may also have affected the measurements.

### 279 ***1D inversion results***

280 In accordance with the electrical sounding carried out in the area nearby, the data were  
281 inverted by considering a three-layer ground comprising: a topsoil layer with 70  $\Omega\text{m}$   
282 resistivity ( $14.3 \text{ mSm}^{-1}$  conductivity), variable magnetic susceptibility, and 0.15 m thickness;  
283 a second layer having a variable resistivity and magnetic susceptibility and 1 m thickness; and  
284 a third layer, the sound limestone, having a resistivity of 300  $\Omega\text{m}$  ( $3.33 \text{ mSm}^{-1}$ ) and a  
285 magnetic susceptibility of  $20 \cdot 10^{-5}$  SI. The resistivity of the second layer,  $\rho_2$ , was first inverted  
286 using EM38-VCP and SH3 apparent resistivity data. Then, the topsoil and second layer  
287 magnetic susceptibilities,  $\kappa_{p1}$  and  $\kappa_{p2}$ , were inverted using the MS2B, EM38-VCP and SH3  
288 apparent magnetic susceptibility data. The resulting maps are shown in Figures 2 and 3. As  
289 could be expected from the apparent resistivity maps, the exact shape of the ditch cannot be  
290 discerned on the  $\rho_2$  map (Figure 2), but both branches appear to be more resistive, with  
291 apparent resistivity values reaching 100  $\Omega\text{m}$  ( $10 \text{ mSm}^{-1}$ ). As expected, in view of the  
292 instrument's shallow depth of investigation, the  $\kappa_{p1}$  map reproduces the MS2B map in shape  
293 and magnitude. The  $\kappa_{p2}$  map confirms the presence of a zone of significant magnetic contrast  
294 below the topsoil layer. All of the results reveal the inhomogeneity of both the material filled  
295 into the ditch, and the natural surrounding medium.

### 296 ***3D inversion results***

297 The data inversion was applied over two small, separate targeted areas that are  
298 delineated by dotted rectangles in Figures 2 and 3. The values of contrast between the two

299 branches and the surrounding terrain, determined in terms of conductivity and magnetic  
300 susceptibility, are summarized in Table 2.

301 When the data produced by the EM38-VCP and SH3 instruments are used in the  
302 inversion, a conductivity contrast close to  $-10\text{mSm}^{-1}$  is obtained, corresponding to an absolute  
303 resistivity of  $100\ \Omega\text{m}$  ( $10\ \text{mSm}^{-1}$ ) for the ditch filling material, as opposed to about  $50\ \Omega\text{m}$   
304 ( $20\ \text{mSm}^{-1}$ ) for the surrounding terrain. The computation time took 29 mn for the NS branch  
305 and 32 mn for the EW one with a 4Go RAM and 2.5 GHz laptop computer.

306 When the inversion results are considered for each instrument separately, the contrasts  
307 are very different: as could be expected from the apparent resistivity maps, the EM38-VCP  
308 maps are comparable for the two branches and are characterised by a negative contrast (the  
309 feature is less conductive); conversely, with the SH3 the contrast is positive (the feature looks  
310 more conductive) but null and very low, and in fact the ditch is not detected. Thus, SH3  
311 measurements do not contribute to the results of the two-instrument 3D inversion, which is  
312 totally dominated by the data from the EM38-VCP.

313 When the magnetic susceptibility is considered, the values obtained for both branches  
314 reveal a generally stronger magnetic feature. The absolute value of the ditch fill material lies  
315 between  $50$  and  $150 \times 10^{-5}$  SI. Again, the results obtained with the EM38-VCP and SH3  
316 instruments are significantly different in magnitude: with the EM38-VCP, the values of  
317 contrast determined for the two branches are quite similar, whereas with the SH3 clearly  
318 different results are found, approximately  $40 \times 10^{-5}$  SI for the N-S branch, and approximately  
319  $110 \times 10^{-5}$  SI for the E-W branch. This difference remains difficult to explain, because the  
320 anisotropy associated with the direction of the applied magnetic field is normally taken into  
321 account in the 3D inversion process.

322 Globally, the experiment conducted over these artificial ditches shows that the  
323 inversion results obtained with different instruments can be significantly different, and that

324 the coil configuration plays an important role in EMI instrument responses. In conclusion, it  
325 can be judicious to use several instrumental configurations when the depths of anomalous  
326 features are not known.

327

## 328 **Field tests over two archaeological sites**

### 329 *Gallo-roman site of Vieil-Evreux (Eure, France)*

330 The test was carried out in the *fanum* area of this site, called Gisacum during the  
331 Roman era. This is a religious centre, located 7 km east of the capital city of Aulerques  
332 Eburovices (now Evreux in Normandy) (Guyard and Lepert 1999). Several new surveying  
333 techniques and different devices (Flageul et al. 2013) have already been tested in this area,  
334 such that a series of control data was available. The soil resistivity was mapped using a three-  
335 depth multipole array ARP© (Automatic Resistivity Profiling) so that both the pattern of the  
336 different features and the resistivity ranges of the different materials are known. The site is  
337 located in the geological context of a flint-clay plateau, resulting from the weathering of the  
338 cretaceous chalk. Above this clay, which has a resistivity of approximately 15  $\Omega$ m, the  
339 archaeological remains have a variable thickness and can exceed 100  $\Omega$ .m in resistivity. In the  
340 *fanum* area, the thickness of the archaeological layer is approximately 90 cm. The tests were  
341 carried out using the DualEM 421S instrument, a multi-receiver EMI (DualEM sensor manual  
342 2010) operated at 9 kHz. It associates one horizontal transmitter loop with three pairs of  
343 receivers. In each pair, the first receiver is horizontal, allowing HCP measurements to be  
344 made. By rotating the entire apparatus, VCP configuration measurements can be made. The  
345 second receiver of each pair is oriented in a radial direction from the transmitter, allowing  
346 PERP configuration measurements to be used. The receivers of the first pair are located at  
347 respectively 1m and 1.1m from the transmitter, those of the second pair at 2m and 2.1 m, and  
348 those of the third pair at 4m and 4.1m. However, in the present test data from the third pair

349 were not considered, and only HCP 1m, HCP 2m, PERP 1.1m and PERP 2.1m data was used  
350 for the 1D/3D inversion. The data was acquired at a high sampling rate, by towing the  
351 instrument (with a quad bike) 0.1m above the ground. Each data point was located using a  
352 dGPS system, thus allowing the resulting map to be produced on a fine,  $0.3 \times 0.3 \text{ m}^2$  mesh.  
353 The apparent resistivity maps obtained with the four configurations are shown in Fig. 4. The  
354 approximately 10m x 10m square *cella* can be seen at the centre of each of these images, and  
355 on the east and west sides the external walls of the *fanum*. The global apparent resistivity is  
356 found to have lower values with the PERP 2.1m and HCP 2m instrument configurations, than  
357 for shorter coil separations. This is due to the greater influence of the underlying flint-clay  
358 layer. In both HCP images, the anomalies generated by walls correspond to three parallel,  
359 resistive/conductive/resistive strips; this experimental result is in full agreement with the  
360 theory (Tabbagh 1986), and was achieved thanks to the fine mesh used for this survey.  
361 However, such anomalies with this coil configuration can lead to misinterpretation, if the  
362 experimental results are not compared with the theoretical model. The wall anomalies are  
363 more pronounced on the PERP 1.1m map than on the HCP 1m map, and the ability of the  
364 former to image the wall pattern appears to be equivalent to that of the electrical method  
365 (Dabas et al. 2015).

366 The 3D interpretation allows these different points to be more thoroughly investigated.  
367 To this aim, a limited  $4.8 \times 3.6 \text{ m}^2$  targeted area was defined, including the external wall ,  
368 which is delineated by a rectangle in Fig. 5 (the *cella* itself appears to be more complicated, it  
369 probably has deeper underground sub-structures). In this zone, 3D interpretation of the  
370 electrical data acquired with the ARP© indicates that the wall has a section of  $1.00 \times 0.88 \text{ m}^2$   
371 and a resistivity of  $70.7 \text{ } \Omega\text{m}$  ( $14.1 \text{ mSm}^{-1}$ ), which is in contrast with the second, surrounding  
372 layer with a resistivity of  $32 \text{ } \Omega\text{m}$  ( $31.2 \text{ mSm}^{-1}$ ). The conductivity contrast characterizing the  
373 wall is thus  $-17.1 \text{ mSm}^{-1}$ . Table 3 presents the conductivity contrast between the wall and



374 surrounding layer, computed using the same geometrical parameters (to define the wall's  
375 location and section), based on the data provided by each configuration alone, and on the  
376 combined data from all four configurations. In all cases, the contrast is found to be lower than  
377 that obtained with DC resistivity measurements. The conductivity contrast determined with  
378 the combined data is not greater than the contrast computed from the data produced by each  
379 individual instrument. The two configurations giving a qualitatively correct contrast, i.e.  
380 PERP 1.1m and HCP 2m, are those which also produce the clearest apparent resistivity maps.  
381 The near absence of contrast obtained with the PERP2 configuration, with no detection of the  
382 wall, can be explained by the depth of investigation of this configuration. The sign inversion  
383 obtained with the HCP 1m is a consequence of the three arched anomalies, and confirms that  
384 the use of a HCP configuration can lead to considerable interpretation difficulties in the case  
385 of small resistive features. These observations again emphasize the advantage and drawback  
386 associated with the simultaneous use of several configurations.

### 387 *Neolithic enclosure at Balloy (Seine et Marne, France)*

388 The study of this middle Neolithic enclosure provides an interesting example of the  
389 usefulness of 3D inversion. The eastern section of this 'Passy' type of funeral enclosure  
390 (Mordant 1997) has been the object of multi-method tests. This enclosure was detected by  
391 both electrical (square array of 1m side) and SH3 prospection, but not by magnetic  
392 prospection using a fluxgate gradiometer with 1nT sensitivity (Hesse 1987) and it is important  
393 to explain this failure. The apparent magnetic susceptibility map of this enclosure is shown in  
394 Fig. 5. On this site, the cultivated topsoil layer has a susceptibility of  $100 \times 10^{-5}$  SI, a  
395 resistivity of  $70 \Omega\text{m}$  and a thickness of 0.25 m. This layer covers a highly resistive gravel  
396 formation ( $300 \Omega\text{m}$ ) with a low susceptibility, equal to  $20 \times 10^{-5}$  SI.

397 3D interpretation was applied to a targeted area in which the ditch can be clearly  
398 distinguished (see contours in Figure 5). It shows that the ditch fill material, which contrasts

399 with the gravel, is thin, i.e. has a section of  $1.4 \times 0.4 \text{ m}^2$ , and has a relatively low magnetic  
400 susceptibility of  $51 \times 10^{-5} \text{ SI}$ . Using these parameters, the magnetic anomaly determined with  
401 a fluxgate vertical gradient is not more than  $0.5 \text{ nT/m}$ . Both the limited thickness and the  
402 limited contrast explain why no magnetic anomaly was observed, even with the addition of  
403 viscous magnetic remanent magnetization, and confirm the usefulness of EM susceptibility  
404 measurements over thin features.

405

## 406 **Conclusion**

407 1D interpretation allows underground structures to be more clearly delineated, and  
408 permits a better assessment of variations in the soil's physical properties than simple mapping  
409 of apparent properties. The complementary 3D inversion allows solving a series of issues:  
410 correction for the apparent anisotropy generated by the instrument configuration, multi-arched  
411 anomalies, precise location of lateral changes and determination of the contrasts between the  
412 considered body and its surrounding medium.

413 When applied to EMI data, the rapid 1D/3D inversion process we have proposed not  
414 only allows an (expected) improvement in interpretation to be achieved, but also emphasizes  
415 the importance of the instrument's geometry, which should be optimally matched with the  
416 objectives of the survey. This inversion process is shown to be useful for the assessment of  
417 multi-configuration instrument capabilities. In particular, it confirms the difficulties  
418 encountered with the use of an HCP configuration, and the conclusions of early theoretical  
419 studies of this technique.

420 Since the analytical and numerical (MoM) calculation method presented in this study  
421 is the same as the one already used with the DC resistivity technique, 1D/3D inversion will  
422 offer the possibility of combining DC and EMI data in a joint inversion. This would be useful

423 to surveyors because EMI is faster for in-field mapping, while DC is more reliable for the  
424 determination of electrical resistivity contrasts of resistive features.

425         Although interpretations of both electrical conductivity and magnetic susceptibility  
426 measurements are presented in this study, it is important to note that contrary to the electrical  
427 resistivity which most often belongs to the [1, 10,000  $\Omega\text{m}$ ] interval, the range of relative  
428 magnetic permeability values is very narrow: between 1.00 and 1.01. Consequently it is  
429 sufficiently small for the ‘magnetic’ EMI responses to be considered as linear. This means  
430 that a wide range of linear techniques, such as linear filtering, can be applied to the  
431 interpretation of apparent magnetic susceptibility maps. Further research is needed, to  
432 evaluate potential developments and applications for these techniques.

433

434

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516

517 **Figure captions**

518 Figure 1: Synthetic data for three different Slingram devices, recorded above an elongated, 3D  
519 body (resistivity =  $20 \Omega\text{m}$ , susceptibility =  $80 \times 10^{-5}$  SI) of dimensions: length=3 m,  
520 width=1m, thickness=1 m, embedded in the second layer of a three layer ground, the top of  
521 which is located 0.3 m below the ground surface (first layer  $100 \Omega\text{m}$ ,  $30 \times 10^{-5}$  SI and 0.2m,  
522 second layer  $200 \Omega\text{m}$ ,  $20 \times 10^{-5}$  SI and 2m, third layer  $50 \Omega\text{m}$  and  $10 \times 10^{-5}$  SI). The  
523 rectangular dotted line indicates the contours of the targeted area used for 3D interpretation

524 (a) Apparent resistivity maps for in-line

525 (b) Apparent magnetic susceptibility maps for in-line measurements, and vertical section  
526 of the feature.

527 Figure 2: Apparent magnetic susceptibility maps of the artificial L-shaped feature at the  
528 Garchy site and first and second layer susceptibility variations after 1D inversion. The two  
529 dashed rectangles indicate the contours of the two targeted areas used for 3D inversion.

530

531 Figure 3: Apparent resistivity maps of the artificial L-shaped feature at the Garchy site and  
532 second layer resistivity variations after 1D inversion

533

534 Figure 4: Apparent resistivity maps of the Fanum area at Vieil-Evreux, corresponding to  
535 quadrature measurements using DualEM HCP 1m, HCP 2m, PERP1.1m and PERP2.1m  
536 configurations. The rectangles indicate the contour of the targeted area on which 3D  
537 interpretation is applied.

538

539 Figure 5: Apparent magnetic susceptibility map of the Neolithic funeral enclosure at Balloy  
540 (Seine et Marne, France), using in-phase SH3 measurements. The rectangles indicate the  
541 contour of the targeted area used for 3D inversion.



542

543 **Table captions**

544 Table 1: Numerical values obtained after 3D inversion of synthetic data. First four columns:  
545 resistivity, conductivity and vertical extent of the body and relative RMS error, based on  
546 apparent resistivity data inversion. Last three columns: magnetic susceptibility, vertical extent  
547 of the body, and relative RMS error based on apparent magnetic susceptibility inversion. The  
548 definition of the relative RMS error is the

549 following:  $RMS = \sqrt{\frac{1}{N_{app}N_{point}} \sum_{i=1}^{N_{app}} \sum_{j=1}^{N_{point}} \left( \frac{M_{i,j} - R_{i,j}}{R_{i,j}} \right)^2}$  where  $N_{app}$  is the number of apparatus,

550  $N_{point}$  the number of points,  $M_{i,j}$  the measurement with the  $i$  apparatus at the point  $j$  and  $R_{i,j}$  the  
551 theoretical measurement with the  $i$  apparatus at point  $j$ .

552

553 Table 2: Electrical conductivity and magnetic susceptibility contrasts and inversion relative  
554 RMS error obtained from 3D inversion, using each instrument separately, and using both  
555 instruments together. The starting a priori values adopted for conductivity are indicated in  
556 parentheses.

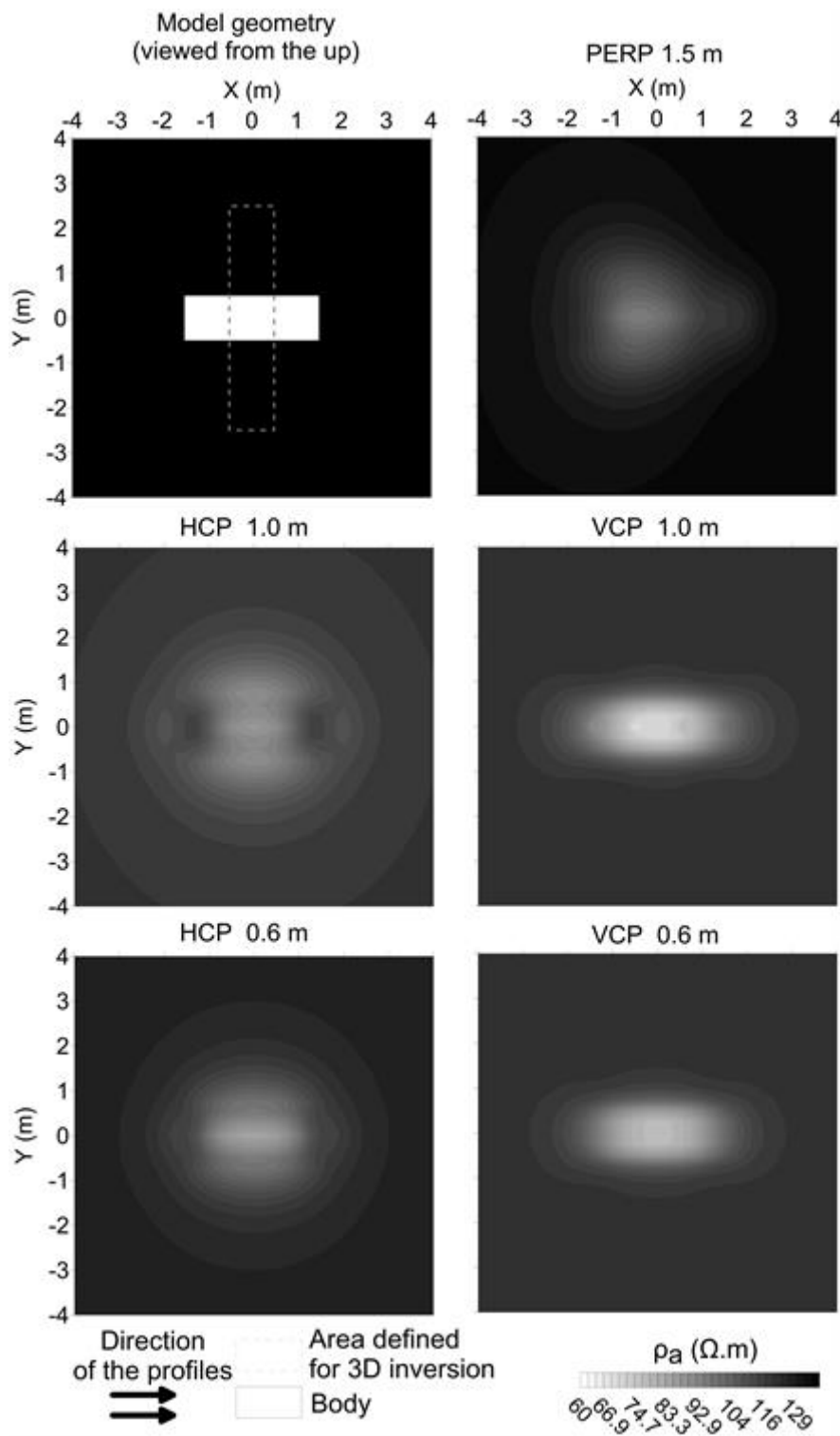
557

558 Table 3: Conductivity contrasts and inversion relative RMS error obtained between the  
559 external *fanum* wall and the surrounding layer (the wall has a 1.00 x 0.88 m<sup>2</sup> section and is  
560 centred at 0.70m depth). The starting a priori values adopted for conductivity are also  
561 indicated.

562

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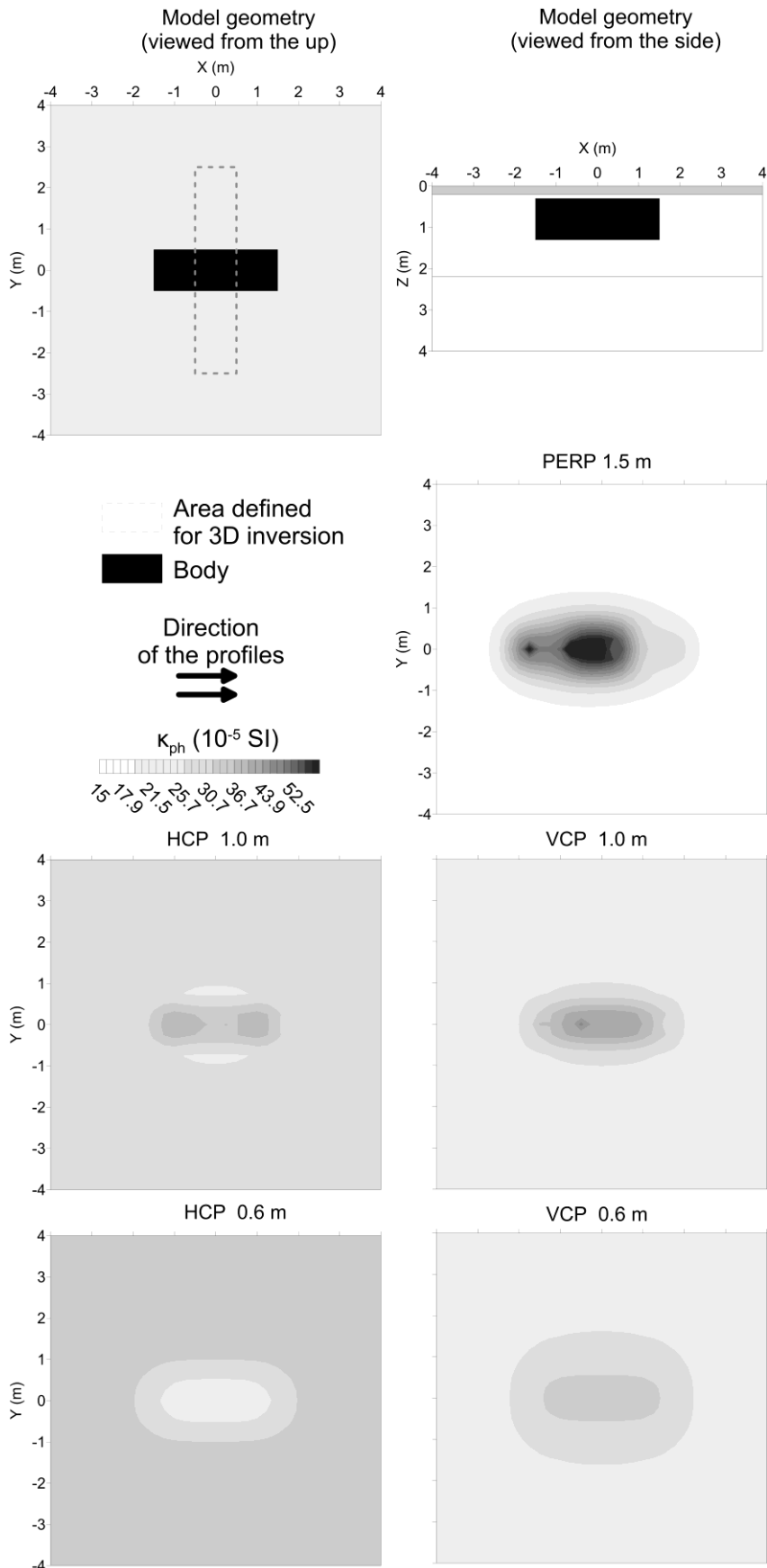
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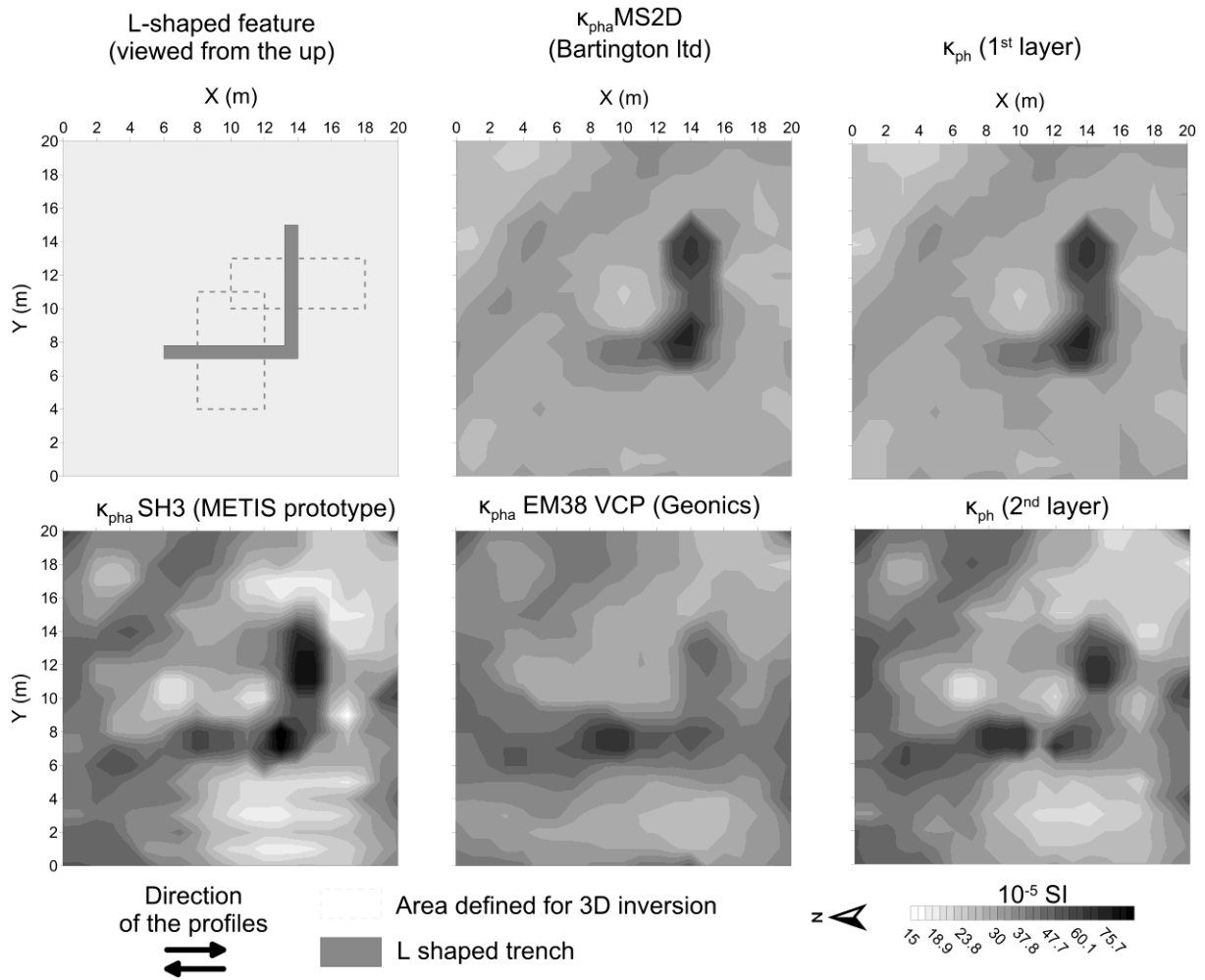
566 Fig. 1a

567



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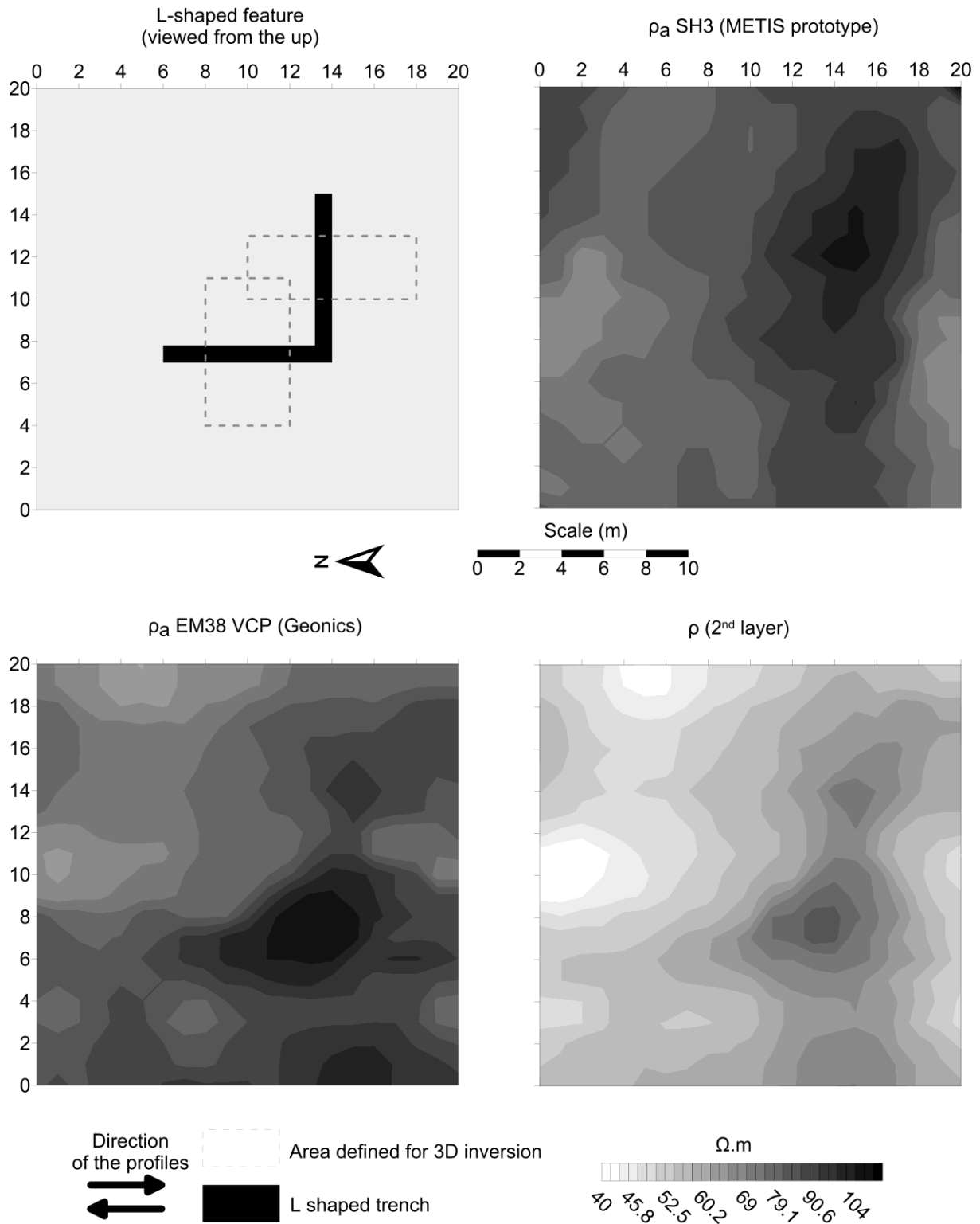
569 Fig. 1b



570

571 Fig. 2

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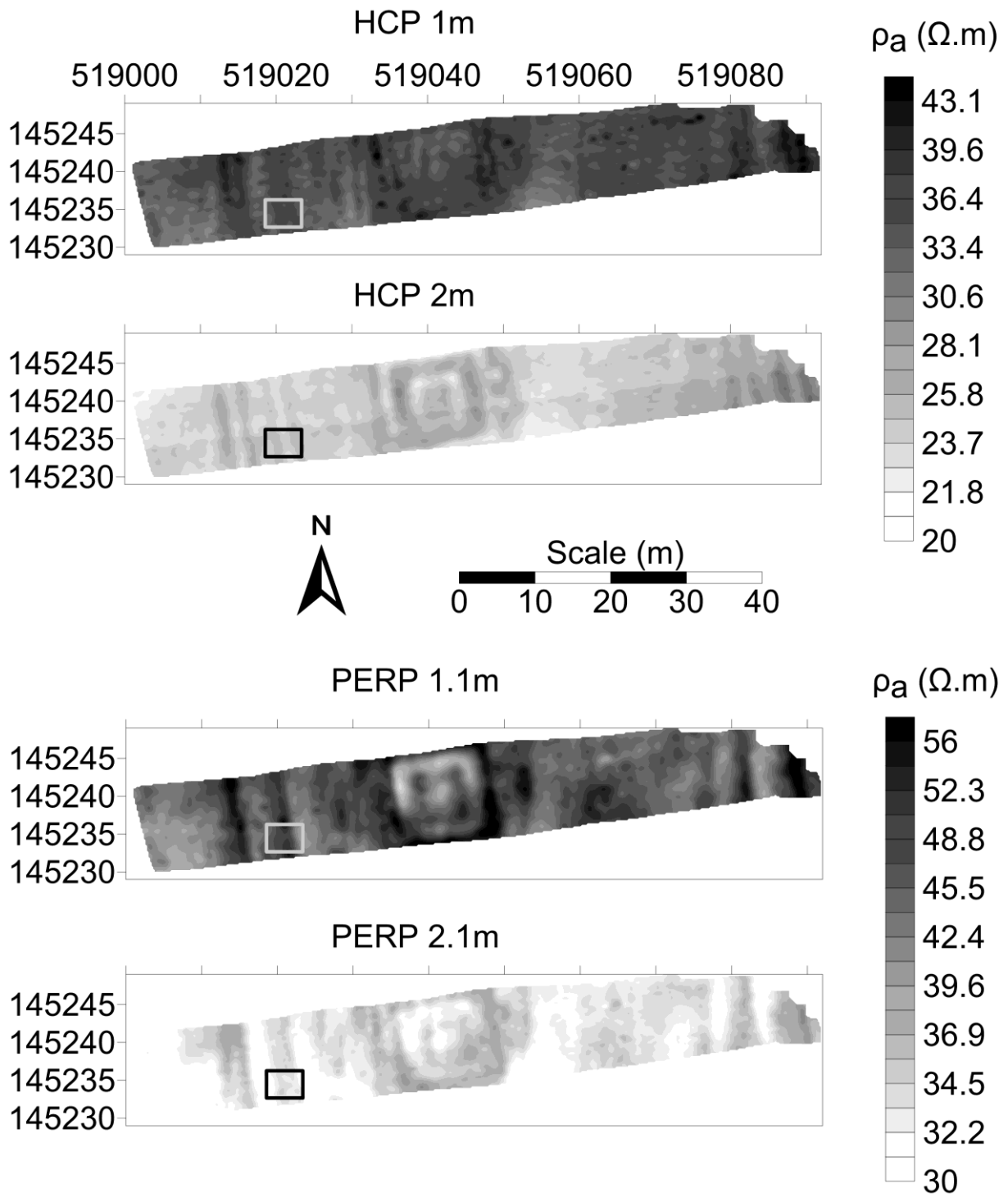


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575 Fig. 3

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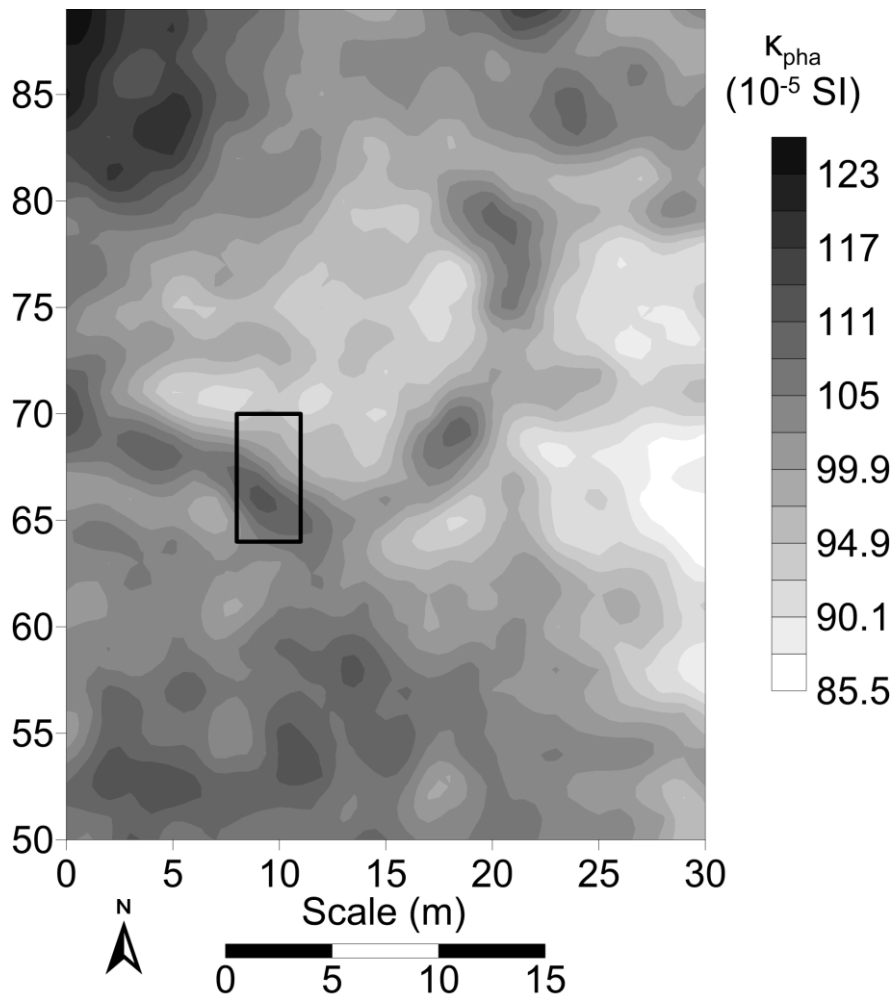


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578 Fig. 4

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581

582 Fig. 5

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585

	$\rho_b$ (20 $\Omega\text{m}$ )	$\sigma_b$ (50 $\text{mSm}^{-1}$ )	ZI (1m) Using the resistivity map	Relative RMS error	$\kappa_b$ (80 $10^{-5}$ SI)	ZI (1m) Using the susceptibility map	Relative RMS error	$\kappa_b$ (80 $10^{-5}$ SI)
VCP 0.6 m	20.9	47.8	0.84	0.028	76.5	0.98	0.030	76.5
HCP 0.6 m	22.3	44.8	0.82	0.021	77.5	0.95	0.094	77.5
VCP 1 m	19.4	51.5	0.85	0.038	80.1	1.00	0.031	80.1
HCP 1 m	22.9	43.7	0.80	0.034	66.8	0.96	0.056	66.8
PERP 1.5 m	23.5	42.6	0.81	0.043	81.3	1.02	0.059	81.3
5 configurations	21.4	46.7	0.82	0.039	79.8	0.98	0.036	79.8

586 Table 1

587

588

	N-S Branch	Relative RMS error	E-W Branch	Relative RMS error
	Electrical conductivity contrast (in $\text{mSm}^{-1}$ ) with starting a priori value		Electrical conductivity contrast (in $\text{mSm}^{-1}$ ) with starting a priori value	
EM38-VCP (Quadrature)	-10.0 (a priori at -6.2)	0.126	-13.9 (a priori at -6.2)	0.071
SH3 (Quadrature)	0.0 (a priori at -14.9)	0.058	1.75 (a priori at -12.0)	0.092
EM38-VCP & SH3 (Quadrature)	-8.4 (a priori at -9.0)	0.102	-9.6 (a priori at -8.6)	0.097
	Magnetic susceptibility contrast (in $10^{-5}$ SI)		Magnetic susceptibility contrast (in $10^{-5}$ SI)	
EM38-VCP (in-Phase)	64.5	0.076	50.5	0.170
SH3 (in-Phase)	39.5	0.140	108.5	0.150
EM38-VCP & SH3 (in-Phase)	47.4	0.077	109.7	0.084

589 Table 2

590

591



592

	Conductivity contrast starting a priori values (in $\text{mSm}^{-1}$ )	Inverted conductivity contrast (in $\text{mSm}^{-1}$ )	Relative RMS error
HCP 1m + HCP 2m + PERP 1.1m +PERP 2.1m	-23.3	-0.32	0.021
HCP 1m	-28.5	+10.5	0.003
HCP 2m	-30.8	-3.5	0.002
PERP 1.1m	-28.5	-8.0	0.005
PERP 2.1m	-28.5	0.34	0.002

593 Table 3

594