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# 1 **3D linear inversion of magnetic susceptibility data acquired by frequency domain EMI**

2

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8

## 9 **Abstract**

10 Low induction number EMI instruments are able to simultaneously measure a soil's  
11 apparent magnetic susceptibility and electrical conductivity. This family of dual measurement  
12 instruments is highly useful for the analysis of soils and archaeological sites. However, the  
13 electromagnetic properties of soils are found to vary over considerably different ranges:  
14 whereas their electrical conductivity varies from  $\leq 0.1$  to  $\geq 100$  mSm<sup>-1</sup>, their relative magnetic  
15 permeability remains within a very small range, between 1.0001 and 1.01 SI. Consequently,  
16 although apparent conductivity measurements need to be inverted using non-linear processes,  
17 the variations of the apparent magnetic susceptibility can be approximated through the use of  
18 linear processes, as in the case of the magnetic prospection technique.

19 Our proposed 3D inversion algorithm starts from apparent susceptibility data sets,  
20 acquired using different instruments over a given area. A reference vertical profile is defined  
21 by considering the mode of the vertical distributions of both the electrical resistivity and of  
22 the magnetic susceptibility. At each point of the mapped area, the reference vertical profile  
23 response is subtracted to obtain the apparent susceptibility variation dataset. A 2D horizontal  
24 Fourier transform is applied to these variation datasets and to the dipole (impulse) response of  
25 each instrument, a (vertical) 1D inversion is performed at each point in the spectral domain,

26 and finally the resulting dataset is inverse transformed to restore the apparent 3D  
27 susceptibility variations.

28         It has been shown that when applied to synthetic results, this method is able to correct  
29 the apparent deformations of a buried object resulting from the geometry of the instrument,  
30 and to restore reliable quantitative susceptibility contrasts. It also allows the thin layer  
31 solution, similar to that used in magnetic prospection, to be implemented. When applied to  
32 field data it initially delivers a level of contrast comparable to that obtained with a non-linear  
33 3D inversion. Over four different sites, this method is able to produce, following an  
34 acceptably short computation time, realistic values for the lateral and vertical variations in  
35 susceptibility, which are significantly different to those given by a point-by-point 1D  
36 inversion.

37

38 **Key-words:** Magnetic susceptibility of soils, frequency domain EMI, 3D inversion of in-  
39 phase susceptibility measurements

40

## 41 **Introduction**

42         Soil is produced by various complex processes, to which human activities can make a  
43 significant contribution. A complete, continuous and non-invasive description of a soil's  
44 structure is thus of primary importance in terms of improving our knowledge of ancient  
45 societies, and ensuring more relevant management of the current environment. Geophysical  
46 surveys have thus been recognized as an indispensable tool for subsurface environmental  
47 studies (Butler 2005, Viscarra-Rossel et al. 2010). In addition to its electrical resistivity, the  
48 soil's magnetic properties have sufficient variability, and are sufficiently related to past and  
49 present active pedological processes (namely redox) (Evans and Heller 2003, Liu et al. 2012),  
50 to motivate their utilization in ground prospection campaigns. Magnetic prospection has been

51 the most commonly used technique in archeological applications (Aspinall et al. 2008), in  
52 which spatial variations of the Earth's magnetic field, and thus all variations in the ground's  
53 total magnetization, are measured. However, this technique fails to describe the vertical  
54 layering of a terrain, and is thus less useful for pedological applications in which it is  
55 important to identify the magnetic properties of each horizon; moreover, its ability to detect  
56 lens-like features is very poor (Scollar et al. 1990). These limitations confirm the potential  
57 usefulness of small, frequency-domain electromagnetic (also referred to as Slingram, loop-  
58 loop, or dipole-dipole) instruments, which can simultaneously measure the ground's apparent  
59 electrical conductivity and magnetic susceptibility (Parchas and Tabbagh 1978), and can now  
60 be fitted with a multi-receiver capability (Saey et al. 2012, Bonsall et al. 2013).

61           The present paper focuses on the interpretation of measurements of the  
62 ground's in-phase magnetic susceptibility. Other measurements, such as that of the ground's  
63 magnetic viscosity (Thiesson et al. 2007), or measurements combining both EMI and the  
64 magnetic technique, are reported to be highly advantageous in certain contexts (Benech et al.  
65 2002, Pétronille et al. 2010). The aim of the present study is to assess the performance of a  
66 fast 3D linear interpretation algorithm, which is easy to implement on a laptop computer.  
67 Through the use of the Moment Method (MoM), fast 3D inversion processes have already  
68 been proposed for DC resistivity prospection (Brinon et al. 2012), and for the simultaneous  
69 interpretation of electrical conductivity and magnetic susceptibility EMI data (Benech et al.  
70 2016), whilst this processes is limited to reduced areas in the vicinity of targeted features. In  
71 the following, an inversion technique is proposed for the processing of magnetic susceptibility  
72 variation data derived from the MoM. Since the relative magnetic permeability of the soil  
73 varies only slightly (between 1.0001 and 1.01), it has been verified (Tabbagh 1985) that the  
74 Born approximation can be applied to the analysis of such data, thus paving the way for the  
75 use of linear inversion techniques: this is a sound approximation, and is systematically used in

76 magnetic prospecting when the so-called demagnetizing field is neglected (Grant and West  
77 1965, Scollar et al. 1990). On the other hand, it cannot be applied in the case of DC resistivity  
78 (Dabas et al. 1994, Buvat *et al.* 2013) or conductivity electromagnetic (EM) methods because  
79 the soil's electrical conductivity varies over a wide range, between  $\leq 0.1$  and  $\geq 100$  mS/m. The  
80 implementation of a linear method has the advantage of being more efficient computationally,  
81 thus allowing the entire surveyed surface to be processed in one go.

82 Our proposed interpretation process is divided into two phases. In the first of these, the  
83 usual 1D non-linear inversion scheme is applied, point by point, to determine the vertical  
84 distributions of both electrical conductivity and magnetic susceptibility (Zhang and  
85 Oldenburg 1999). These vertical distributions are often sufficient to allow the terrain's  
86 structure to be characterized. If marked lateral changes require a 3D inversion the statistical  
87 mode of these distributions as a function of depth is taken to be the reference vertical profile.  
88 Then, during the second phase, the interpreter determines the lateral variations in  
89 susceptibility with respect to this profile. Since the response of a contrasting magnetic body  
90 can be assumed to be linear, this process involves successively applying a 2D (horizontal  
91 plane) Fourier transform, non-linearly inverting the resulting spectrum of the 1D vertical  
92 distribution of magnetic susceptibility contrasting with respect to the reference profile, and  
93 finally computing the lateral susceptibility contrast variations by means of an inverse Fourier  
94 transform. The full process is illustrated in Figure 1.

95

#### 96 **Reminder of the 1D inversion process**

97 The EMI instruments under consideration have a transmitting coil and at least one  
98 receiving coil at a metric separation expressed by  $L$ . The coils are located at a height  $d$ , above  
99 ground level. The coil orientations can be adjusted, and various possible configurations have  
100 been defined (Frischknecht et al. 1991) with respect to the plane of the coils. The most

101 commonly used configurations are HCP (horizontal coplanar), VCP (vertical coplanar),  
102 PARA (parallel – inclined at  $55^\circ$  from the horizontal plane), and PERP (perpendicular). The  
103 application of the instrument's primary field over a layered ground generates complex  
104 secondary fields,  $H_s$ , which are expressed by Hankel Transform integrals. The full  
105 development of these expressions, and the definition of the subsequent approximations are  
106 described by Thiesson et al. (2014). The method used to compute these transforms (i.e. the  
107 forward problem) is well known, and is similar to that used for vertical electrical sounding  
108 (Ghosh 1971). The calculation results can be expressed in terms of apparent properties, this  
109 allows an initial approximate evaluation to be made of the soil's properties, thus simplifying  
110 comparisons between different instruments. The apparent magnetic susceptibility,  $\kappa_a$ , is the  
111 susceptibility of a homogeneous terrain that would produce the same results with the same  
112 instrumental geometry ( $L$ , coil orientation, height above the surface).

113 The inverse problem is usually solved by starting from an *a priori* guess at the values  
114 of the unknown parameters, which are iteratively modified until a good fit between the  
115 computed results and the apparent experimental properties is reached. The number of  
116 parameters is limited by the number of different geometrical configurations which can be  
117 adopted by the instrument (coil orientations and  $L$  distances), since at the studied frequencies  
118 (VLF and LF) and depth ranges, the investigation depth is governed by the instrument  
119 geometry. Although a single parameter inversion can sometimes be useful (Guerin et al.  
120 1996), several instruments (or a multi-coil configuration in the same apparatus) clearly  
121 provide a more detailed description of the terrain's structure.

122 It is important to note that with EMI data inversion, the vertical conductivity profile  
123 must first be determined (using the quadrature out of phase component of the responses),  
124 prior to inversion of the magnetic susceptibility profile because: (1) the conductivity  
125 distribution modifies the total magnetic field distribution in the ground, whereas the terrain's

126 vertical susceptibility distribution has a negligible influence on the total magnetic field  
 127 distribution (Tabbagh 1985) and (2) when high, the conductivity may generate an in-phase  
 128 response (Thiesson et al. 2014) that must be subtracted from the total in-phase response.

129 At the end of the 1D inversion step, the statistical mode of each model parameter is  
 130 adopted, in order to define the reference vertical profile. A susceptibility response  $\kappa_{a0}(d)$  is  
 131 associated with this profile, and is subtracted from the experimental response at each point ( $x$ ,  
 132  $y$ ) of the surveyed area, and for each receiver (at elevation  $d$ ), thereby defining a contrasting  
 133 magnetic susceptibility response  $\delta\kappa_a(x, y, d)$ .

134

## 135 **2D (x,y) inversion using a Fourier transform**

### 136 *Principle*

137 Given  $\delta\kappa(x', y', z')$ , the contrasting magnetic susceptibility distribution inside the  
 138 ground, and since the problem to be solved is linear, the response  $\delta\kappa_a(x, y, d)$  that is added to  
 139 the response of the reference profile can be expressed as a convolution product:

$$140 \quad \delta\kappa_a(x, y, d) = \iiint_{\infty} \delta\kappa(x', y', z') IR(x - x', y - y', d - z') dx' dy' dz' \quad (1),$$

141 where  $IR$  is the ‘impulse response’, the 3D Green function corresponding to the dipole source  
 142 response to the instrumental configuration under consideration (analytical expressions  
 143 corresponding to these functions are presented in more detail in (Tabbagh 1985)). If the  
 144 ground is discretized in the form of  $N$  successive layers having thicknesses  $e_i$  centered at  $z_i$ ,  
 145 and a magnetic susceptibility contrast  $\delta\kappa(x', y', z_i)$ , equation (1) can be approximated by:

$$146 \quad \delta\kappa_a(x, y, d) = \sum_{i=1}^N e_i \iint_{\infty} \delta\kappa(x', y', z_i) IR(x - x', y - y', d - z_i) dx' dy' \quad (2).$$

147 By applying a 2D Fourier transform to Eq. (2) one has:

$$148 \quad \delta\hat{\kappa}_a(u, v, d) = \sum_{i=1}^N e_i \delta\hat{\kappa}(u, v, z_i) R\hat{I}(u, v, d - z_i) \quad (3),$$

149 where a 'circumflex accent' indicates Fourier transformed functions, and  $(u, v)$  are the spatial  
150 frequencies corresponding to  $(x, y)$ . Consequently, at each point  $(u, v)$  the expression for  
151 Eq. (3) corresponding to each level  $z_i$  can be thought of as a single component of an  $N$ -  
152 equation linear system. If the number of different geometric coil configurations  $K$  is smaller  
153 than  $N$ , the system has no solution, however when  $K = N$  it can be solved directly. When  
154  $K > N$  the system can be solved using the least squares method. Knowing  $\delta\kappa(u, v, z_i)$ , it is  
155 straightforward to derive the solution for the problem of 3D susceptibility contrast via the  
156 inverse transformation of  $\delta\hat{\kappa}(x, y, z_i)$ .

157

### 158 *The thin layer solution*

159 Although commercial multi-configuration instruments are now commonly available  
160 and used in field surveys, a considerable volume of data has been acquired over the last forty  
161 years using just one type of configuration. It is thus important to reconsider and enhance the  
162 interpretation of this data. When a single configuration is used, only one layer can be  
163 considered and the resulting thin-layer interpretation is similar to that obtained with potential  
164 methods (Grant and West 1965). In the case of magnetic prospection, this is a valuable  
165 solution (Desvignes et al. 1999) since it allows: (i) the general pattern of the source body to be  
166 restored by correcting for the influence of the Earth's magnetic inclination on the shape of the  
167 anomaly; (ii) the maximum source depth to be assessed, and (iii) the magnetization contrast to  
168 be determined. Similar issues arise when interpreting EMI apparent magnetic susceptibility  
169 data: deformations introduced by the coil configuration, poor accuracy of depth assessments,  
170 and the contrast of any source body. This similarity has made it possible to use  
171 transformations between apparent susceptibility measurements and induced magnetization  
172 anomalies of the Earth's magnetic field, and has opened up significant perspectives for the  
173 simultaneous interpretation of both types of data (Benech et al. 2002). In the present study,



174 our analysis is limited to that of EMI measurements, for which the determination of the depth  
175 of the thin layer raises a specific issue: a relationship clearly does exist between the coil  
176 separation and the depth at which a susceptibility variation can be detected, if the sensitivity at  
177 a depth is too low, then the inversion near that depth will be poor.

178 We thus consider a series of synthetic cases, in which a 2m x 2m slab with a thickness  
179 of 0.2 m and susceptibility contrast equal to  $200 \cdot 10^{-5}$  SI is displaced along the vertical axis.  
180 The apparent susceptibility maps are inverted for each different position (change in depth) of  
181 the slab, and the quality of the inversion is assessed by comparing the susceptibility contrast  
182 produced by the inversion with the original value. Table 1(a) presents the results obtained for  
183 the different depths of the slab and coil separations using VCP configuration. Table 1(b)  
184 provides the results with the PERP configuration, Table 1(c) the results with the HCP  
185 configuration, Table 1(d) the results with the PARA configuration. Four main conclusions can  
186 be drawn for these comparisons:

187 (1) With the VCP configuration, the slab is correctly restored, even for a coil  
188 separation of  $L=2\text{m}$  and shallow slab depths, as well as for smaller coil separations and  
189 greater depths.

190 (2) With the PERP configuration, the results are comparable to those for the VCP  
191 configuration, and (with the exception of shallow slabs with VCP) the inverted values are  
192 generally 10% to 20% higher than the original values. For shallower slabs the outcome can  
193 probably be explained by the more complex lateral variations of the PERP dipole impulse  
194 response, and thus more problematic inversion of PERP data.

195 (3) With the HCP and PARA configurations the sign of the contrast is correctly  
196 restored (the apparent susceptibility anomaly is negative for greater  $d/L$  ratios with HCP) but  
197 not its magnitude (most often significantly amplified)

198 (4) This preceding example, established using synthetic data, shows that good depths  
 199 of investigation can be reached, even for the case of smaller values of  $L$ .

200 However, even for one thin layer, the simultaneous use of several configurations leads  
 201 to slightly better results than the use of a single configuration.

202

203 ***Multi-layer inversion***

204 At each point of the spectral domain, the solution  $\delta\kappa(u, v, z_i)$  is represented by an  $N$   
 205 component vector  $\delta\vec{\kappa} = (\kappa_1, \dots, \kappa_N)$ , the solution for the linear equation system. While in  
 206 practice limited to few components, the solution for the  $N$  linear equations system is  
 207 confronted by an instability arising from the fact that an abnormal value in one layer can be  
 208 compensated by another abnormal value, of the opposite sign, in another layer. The solution  
 209 can be stabilized by adding an external constraint, for example by minimizing the norm of the  
 210 solution vector. Although it is also possible to use this constraint to introduce the depth  
 211 sensitivity dependence associated with each coil configuration, this sensitivity tends to be of  
 212 the ‘all or nothing’ type, as shown in Table 1. Following several tests, two options were found  
 213 to be potentially useful: either minimizing the square of the norm of the  $\delta\vec{\kappa}$  vector (constraint  
 214 I):

215 
$$Q = \sum_1^N \hat{\kappa}_i^2, \quad (4),$$

216 or minimizing the sum of the squares of the differences between consecutive components  
 217 (constraint II):

218 
$$Q = \sum_2^N (\hat{\kappa}_i - \hat{\kappa}_{i-1})^2 \quad (5).$$

219 Thus, for  $K$  different instruments the minimized quantity is:

220 
$$\sum_{j=1}^K (\delta\hat{\kappa}_{a,exp,j} - \delta\hat{\kappa}_{a,theo,j})^2 + \lambda Q \quad (6),$$

221 where  $\lambda$  is chosen by the interpreter: for the second option the value  $\lambda=1$  would be set,  
222 whereas with the first option it is more convenient to use the trace of the Jacobian matrix:  
223  $\lambda = \text{trace} / 2$ . With constraint II the stabilization is stronger, the vertical variation of the  
224 magnetic susceptibility contrast minimum.

225 The application of this inversion procedure using synthetic data computed for PERP,  
226 VCP and PARA configurations and inter-coil distances varying between 0.7 and 1.5 m is  
227 presented in Table 2 for the case of constraint II and for  $\lambda=1$ . The body is 2m x 2m x 0.6m  
228 sized, it presents a  $200 \cdot 10^{-5}$  SI susceptibility contrast, it is centered at  $z=0.5$  m and divided in  
229 5 layers (0.12m thick). Equivalently good results were obtained with reduced number of  
230 layers equal to: 3 (0.2 m thickness) or 4 (0.15 m thickness).

231

### 232 **Tests with multi-body synthetic data**

233 We consider a rectangular 25 m x 17 m area, meshed onto a regular 0.5m x 0.5m grid,  
234 containing four different magnetic bodies (Fig. 2) imbedded in a terrain with a homogeneous  
235 resistivity equal to  $70 \Omega\text{m}$ , and susceptibility equal to  $30 \cdot 10^{-5}$  SI. The first body (A) is an L-  
236 shaped ditch with a 1m x 0.4 m cross section, centered at a depth of 0.4 m, the two  
237 perpendicular branches of which are 8 m in length and have a susceptibility contrast of  
238  $120 \cdot 10^{-5}$  SI. The second body (B) is a medium-sized square body with dimensions 2m x 2m x  
239 0.75 m, centered at a depth of 0.6 m and having a susceptibility contrast equal to  $100 \cdot 10^{-5}$  SI.  
240 The third body (C) is a small superficial feature with dimensions 0.4m x 0.4m x 0.2 m,  
241 centered at a depth of 0.3 m depth and having a susceptibility contrast equal to  $100 \cdot 10^{-5}$  SI.  
242 The fourth body (D) is a slim feature with dimensions 0.4m x 0.4m x 1.6 m, centered at a  
243 depth of 1 m and having a susceptibility contrast equal to  $100 \cdot 10^{-5}$  SI. The apparent magnetic  
244 susceptibility maps computed using MoM are shown in Fig. 3, for the seven different  
245 apparatus geometries described in Table 3. For all configurations, the transmitter–receiver

246 line lies parallel to the  $x$  axis. The four features, with their different geometries, can be  
247 recognized in each map. These are characterized by ringing, especially in the case of the  
248 longest coil separations. It should be noted that the shortest apparatus provides the best  
249 description of the four magnetic bodies, in terms of the shape and the magnitude of the  
250 associated anomalies.

251 The seven datasets were inverted together, whilst considering three layers with  
252 different values of magnetic susceptibility, the first centered at  $z_1=0.3$  m with a thickness  
253  $e_1=0.2$  m, the second centered at  $z_2=0.5$  m with a thickness  $e_2=0.2$  m, and the third centered at  
254  $z_3=0.8$  m with a thickness  $e_3=0.4$  m. When 1D inversion is applied (Fig. 4), although the four  
255 features are correctly identified, this inversion fails to correct for their deformed shapes and  
256 for the apparent anisotropy, produced by the different coil orientations. This issue is  
257 particularly pronounced for small features, whose precise locations are difficult to restore. In  
258 addition, ringing with sign changes cannot be eliminated, and is even amplified in the third  
259 layer in which there should be no variations corresponding to the superficial features (A) and  
260 (C). These spurious variations are a consequence of the instrument's low sensitivity to 3D  
261 changes at the depth of these features.

262 The results produced by 3D linear inversion are presented in Fig. 5, showing that the  
263 body's shapes are faithfully restored, and the susceptibility values are in good agreement with  
264 the original values for the first two layers. However, in the case of feature (A) the third layer  
265 is again characterized by greater amplitude variations, resulting from the fact that the  
266 instruments' sensitivities are too low to constrain the solution.

267

## 268 **Interpretation of field data**

269 In order to assess the potential of this approach for data inversion under field  
270 conditions, we analyzed the data acquired using various instrument geometries, at four

271 different archaeological sites characterized by different climatic conditions and soil  
272 environments. In all cases we started from the apparent susceptibility data sets which have  
273 been obtained after checking the instrument calibration (Thiesson et al. 2014) and  
274 transforming the in-phase secondary field measurements. Where the electrical conductivity is  
275 high (Medamud case), the apparent electrical conductivity was first determined using the  
276 quadrature response and then used to calculate the in-phase response which was algebraically  
277 subtracted from the total in-phase response.

278

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

280 The eastern section of this middle-neolithic ‘Passy’ type of funeral enclosure (Mordant  
281 1997) has been the object of multi-method tests. This enclosure was detected using both  
282 electrical (1 m square array) and SH3 prospection (see appendix 1 for the characteristics of  
283 the latter device), but was not detected by magnetic prospection using a fluxgate gradiometer  
284 with  $1 \text{ nTm}^{-1}$  sensitivity (Hesse 1987). This failure was explained by the use of a 3D non-  
285 linear inversion (Bénech *et al.* 2016), applied to a selected zone (indicated by a rectangular  
286 outline in Fig. 6), showing that the SH3 measurements had revealed a 1.4m x 0.4 m cross-  
287 sectional feature, surrounded by gravel, with magnetic susceptibilities of respectively  $51 \times 10^{-5}$   
288 and  $20 \times 10^{-5}$  SI. Using these parameters, the induced magnetization anomaly determined for  
289 a fluxgate vertical gradiometer is less than  $0.5 \text{ nTm}^{-1}$ , and even with the addition of viscous  
290 magnetic remanent magnetization the anomaly cannot clearly overpass  $1 \text{ nTm}^{-1}$ .

291 In the present study we consider just one layer (since only one instrumental dataset was  
292 recorded), of 0.4m thickness and centred at a depth of 0.45m. For the same selected zone, the  
293 following results are obtained:

294 (1) as could be expected, the 1D inversion produces the same image as that generated  
295 using the apparent susceptibility measurements (Fig. 6b),

296 (2) the susceptibility variations are in agreement with the 3D non-linear inversion,  
297 with a magnetic susceptibility of  $40 \cdot 10^{-5}$  SI for the ditch filling, in contrast with a value of  
298  $10 \cdot 10^{-5}$  SI for the immediately surrounding gravel. This calculation was made for the totality  
299 of the 26m x 26 m surface shown in Fig. 6, and required just 7s of computing time, whilst  
300 using the same laptop computer (4 Go RAM, 2.5 GHz) the non-linear inversion over the 2.5m  
301 x 5m area required 267s of computing time.

302

### 303 *Neolithic settlement of Perdika 2 (Central Greece)*

304 This neolithic settlement, in this region referred to as a *magoula*, is located on the  
305 eastern Thessalian plain of Greece and was surveyed using different methods in the frame of  
306 the IGEAN project (Innovative Geophysical Approach for the study of Early Agriculture  
307 villages of Neolithic Thessaly) (Simon et al., 2015). The magnetic survey revealed a complex  
308 system of enclosures (Fig. 7). In order to acquire a better description of what is thought to be  
309 an enclosure entrance, a 40m x 40m area was prospected using the CMD instrument (see  
310 Appendix I for its characteristics). The ditches are more clearly discernible by their magnetic  
311 susceptibility contrast than by their electrical conductivity. The resistivity variations are  
312 relatively small, lying within a moderate range of values: a 150  $\Omega$ m layer of topsoil, and  
313 subsoil variations ranging between 30 and 100  $\Omega$ m. As the magnetic susceptibility data  
314 acquired with the shorter coil separation ( $L=0.32$ m) was too noisy for suitable interpretation,  
315 we made use of four data sets for the inversion (Fig. 8): HCP with 0.71 m and 1.18 m  
316 separations, and VCP with 0.71 m and 1.18 m separations. The topsoil layer was assumed to  
317 be homogeneous. In order to assess the vertical extent of the archaeological features, we  
318 chose to divide the subsoil into two contiguous layers of 0.5 m thickness, with the first lying  
319 between 0.2 and 0.7 m, and the second between 0.7 and 1.2 m. The images produced by  
320 point-by-point 1D inversion and by 3D linear inversion of the data are presented in Figs. 9a

321 and 9b, respectively. In the 1D inversion, the second layer reveals some features that are  
322 different to those found in the first layer, which is characterised by strong susceptibility  
323 variations. Also performed using constraint I, see equation (4), the 3D linear inversion shows  
324 that the ditches are shallow, and that different features appear at greater depths, but with  
325 smaller variations in susceptibility.

326

### 327 *Middle Kingdom Kôm of Medamud (Egypt)*

328 The site of Medamud is located 4 km to the north of Karnak, and was occupied for a  
329 long period of time, from the Middle Kingdom of Egypt until the Roman era (Relats-  
330 Montserrat 2016(a)). The geophysical survey initiated by the IFAO tended to characterize a  
331 Middle Kingdom pottery workshop area. The survey was carried out with the CMD (see  
332 Appendix I) instrument in a VCP configuration, in order to simultaneously describe the soil's  
333 electrical conductivity and magnetic susceptibility. In the area under consideration the fine-  
334 grained, thick archaeological layer present just below the surface has a very low resistivity,  
335 centred on 16  $\Omega\text{m}$ , for which a correction is required to eliminate the in-phase component of  
336 the conductivity response

337 In the present study we consider a 44m x 60m zone from this site. Fig. 10 shows three  
338 apparent susceptibility maps, produced using inter-coil distances of 0.32, 0.71 and 1.18 m,  
339 respectively. Fig. 11 shows the results of the inversions when two layers are considered, with  
340 the first situated between 0.05 and 0.35 cm, and the second between 0.35 and 0.65 m: Fig. 11a  
341 and Fig. 11b show the results of the 1D and 3D inversions (both using constraint I),  
342 respectively. Both inversions show that the magnetic features have a significant vertical  
343 extent (which probably exceeds the range of the instrument), and that their susceptibilities are  
344 high. However, comparisons between these different results underscore the fact that when 1D  
345 inversion is used, the second layer has higher values, in the range [350 – 1250]  $10^{-5}$  SI,

346 whereas the first layer remains close to a modal value of  $200 \cdot 10^{-5}$  SI, which is the same as that  
347 found for both layers with the 3D inversion. Again in this case, the second layer of the 3D  
348 inversion is characterised by a narrower range of variations ( $[180 - 225] \cdot 10^{-5}$  SI) than the first  
349 layer ( $[130 - 330] \cdot 10^{-5}$  SI).

350         These maps clearly show the presence of a mud brick wall which corresponds to lower  
351 apparent susceptibilities. By comparing these results with measurements (MS2D Bartington  
352 Ltd) taken over another feature we obtain values in the range  $[60 - 90] \cdot 10^{-5}$  SI for the mud  
353 bricks and a modal value of  $178 \cdot 10^{-5}$  SI for the surrounding magnetic soil (Relats-Montserrat  
354 et al. 2016(b)). When applying a full 3D inversion to the rectangular 12m x 3 m area (marked  
355 in Figure 11b) we obtain, by considering a wall of 0.6m thickness and 4m width, a  
356 susceptibility contrast of  $-92 \cdot 10^{-5}$  SI with the surrounding soil. These results are in fair  
357 agreement with the results mapped in Figure 10b and with the 3D linear inversion using one  
358 layer of 0.6m thickness which gives a  $-100 \cdot 10^{-5}$  SI susceptibility contrast.

359

### 360 *Destroyed medieval city of Théroutanne (Pas-de-Calais, France)*

361         Théroutanne was originally a Gallic, then an important Gallo-roman city, and during  
362 medieval times was one of the main centres of the Picardie region in France. In 1553 it was  
363 besieged and totally levelled by Charles Quint. This location was settled again as a small  
364 village, only at the end of the XIX<sup>th</sup> century. The aim of the survey was to identify the  
365 remains of the ancient medieval city, through a series of EMI and electrical prospection  
366 campaigns. The test area considered here covers a surface area of 180m x 40m, and was  
367 surveyed using the DualEM instrument (see Appendix I) in both HCP and VCP base  
368 configurations. From this archaeological survey, we produced six different apparent magnetic  
369 susceptibility maps, derived from the instrument's in-phase recordings made with the HCP  
370 1m, HCP 2m, PERP 1.1m, PERP 2.1m, VCP 1m and VCP 2m configurations. In the present



371 analysis, the longest inter-coil separations of 4 m and 4.1m were not used, and the HCP 1m  
372 and PERP 2m channels produced corrupted data. Thus, only four independent magnetic  
373 susceptibility maps could be used, as shown in Fig. 12.

374         The electrical resistivity maps of the terrain reveal a 70  $\Omega$  m topsoil layer, followed by  
375 a conductive subsoil layer with a resistivity between 10 and 60  $\Omega$ m, suggesting a significant  
376 clay content (the salt spread under the order of Charles Quint was probably leached out well  
377 before the time of the prospection campaign). The apparent magnetic susceptibility is  
378 generally high, and higher for the PERP 1m and HCP 2m measurements than for both VCP  
379 configurations (different susceptibility scales are used in Fig. 12). The change in sign of the  
380 susceptibility response for the HCP 2m measurement, at approximately 0.75m, suggests that  
381 most of the observed features have shallow locations. Three layers were considered for the  
382 inversions: the first between 0.25 and 0.75 m; the second between 0.75 and 1.25 m; and the  
383 third between 1.25 and 2.25 m. The results of the 1D point-by-point inversion are presented in  
384 Fig. 13, and those of the 3D linear inversion are shown in Fig. 14. Constraint I was applied for  
385 both inversions. Although the mean values of susceptibility decrease slightly with depth in the  
386 1D inversion, the lateral variations have the same aspect and reproduce those of the four  
387 apparent susceptibility maps. A large, 40 m diameter semi-circular feature, centred 18m to the  
388 north of the image centre, can be seen in all three layers, thus suggesting that it has a  
389 substantial vertical extent. In the 3D inversion, the first layer is clearly more magnetic than  
390 the remaining two layers (the scales are different in Fig. 14), and the large semi-circular  
391 feature is less noticeable in the deepest layer.

392

### 393 **Conclusion**

394         The new linear inversion technique presented here has been tested on synthetic and  
395 field data. When compared with the original model, or with the complete 3D MoM inversion

396 technique, it provides reliable results for the shape of the sought features, as well as the  
397 magnitude of the contrasts. It is shown to be highly efficient for the correction of anomalous  
398 deformations, caused by the instrument's geometry, of a feature's geometrical outlines. By  
399 using the instrument's dipole impulse response in the analysis, this technique takes the  
400 influence of the real instrumental geometry into account, including that of the coil  
401 orientations. Its results are thus significantly different to those obtained with 1D point-to-  
402 point inversions, in terms of susceptibility variations as a function of depth, making it possible  
403 to improve the identification of the vertical boundaries of a given feature.

404         It should be underlined, however, that this technique is limited by the number of  
405 different available instrument geometries: in practice the magnetic susceptibility contrasts of  
406 only a rather small number of layers at a limited number of depths can be inverted. It is very  
407 valuable to have even this limited information on depth and susceptibility and where  
408 necessary the prospector has the possibility to increase the number of instruments geometries  
409 by considering measurements acquired at several altitudes with the same device.

410         Compared to 3D complete MoM inversion, the rapidity of this technique not only  
411 leads to a significant gain in time, but also provides the interpreter with the ability to test  
412 several stabilization process options, such as the choice of the number of layers or layer  
413 thicknesses. This also makes it possible to assess the probable vertical extent of the different  
414 features, through the use of a vertically translated thin layer.

415

416

417

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495 **Appendix I** Characteristics of the devices used for field studies

496

497 **SH3:** this apparatus is a laboratory prototype designed in 1977 (Parchas and Tabbagh 1978).

498 It has a PARA coil orientation (the two coils have parallel axes aligned at  $35^\circ$  from the  
499 vertical, such that their direct coupling is null in free space), a 1.5 m coil separation, a coil  
500 center height of  $d=0.2$  m, and is operated at 8.04 kHz.

501

502 **CMD:** this apparatus is a multi-receiver EMI (Gf Instruments, Ltd, Brno) comprising one  
503 transmitter coil and three receiver coils, located at distances of 0.32, 0.71 and 1.18 m from the  
504 transmitter. All the coils are coplanar, allowing the instrument to be used in either HCP or  
505 VCP configurations. The instrument's operating frequency is 30 kHz, and it can be used in a  
506 continuous recording mode by a mobile operator in the field, with an above-ground clearance  
507 of  $d=0.12$  m.

508

509 **DualEM 421S:** this apparatus is a multi-receiver EMI (DualEM Ltd, Milton) operated at  
510 9 kHz. It associates one horizontal transmitter loop with three pairs of receivers. In each pair,  
511 the first receiver is horizontal, allowing HCP measurements to be made. By rotating the entire  
512 apparatus, VCP configuration measurements can also be made. The second receiver of each  
513 pair is oriented in a radial direction from the transmitter, allowing PERP configuration  
514 measurements to be used. The receivers of the first pair are located at respectively 1m and  
515 1.1m from the transmitter, those of the second pair at 2m and 2.1 m, and those of the third  
516 pair at 4m and 4.1m. However, in the archaeological surveys presented here, data from the  
517 third pair were not considered. Data from the VCP 1m, VCP 2m, HCP 1m, HCP 2m, PERP  
518 1.1m and PERP 2.1m are used in the present study.

519

520 **Figure captions**

521 Figure 1: Flowchart demonstrating the full process with both a 1D non-linear inversion and a  
522 3D linear inversion over the variations.

523 Figure 2: Description of the different bodies used to generate synthetic data

524 Figure 3: Apparent magnetic susceptibility maps calculated using the method of moments and  
525 the characteristics of the seven devices under consideration.

526 Figure 4: Results of the 1D inversion when three layers are considered: the first is centered at  
527  $z_1=0.3$  m and has a thickness  $e_1=0.2$  m, the second is centered at  $z_2=0.5$  m and has a thickness  
528  $e_2=0.2$  m, and the third is centered at  $z_3=0.8$  m and has a thickness  $e_3=0.4$  m.

529 Figure 5: Results of the 3D linear inversion when three layers are considered (using the same  
530 geometries as in Fig. 3), and the norm of the  $\kappa$  vector is minimized using  $\lambda=trace/2$

531 Figure 6: Balloy neolithic enclosure: (a) SH3 apparent magnetic susceptibility, the relatively  
532 high level is explained by the high susceptibility of the upper layer of soil (approx.  $100 \times 10^{-5}$   
533 SI), and the inverted magnetic susceptibility of a layer situated between the depths of 0.25 m  
534 and 0.65 m, derived from the 1D inversion (b) and from the 3D linear inversion (c). The  
535 rectangles indicate the contour of the targeted area used for 3D non-linear inversion.

536 Figure 7: Perdika2 (Central Thessaly, Greece) magnetic map: pseudo-gradient of the vertical  
537 component of the Earth's magnetic field. The area surveyed using the CMD is colored orange.

538 Figure 8: Perdika2 site, apparent magnetic susceptibility maps measured using the CMD  
539 instrument.

540 Figure 9: Perdika2 site, (a) inverted magnetic susceptibility of the 0.2 – 0.7 m and 0.7 – 1.2 m  
541 layers using the 1D inversion, (b) inverted magnetic susceptibility of the 0.2 – 0.7 m and 0.7 –  
542 1.2 m layers using the 3D linear inversion.



543 Figure 10: Medamud site (Egypt), three apparent magnetic susceptibility maps measured  
544 using the CMD instrument over the 44m x 60 m survey area.

545 Figure 11: Medamud site, (a) inverted magnetic susceptibility of the 0.05 – 0.35 m and 0.35 –  
546 0.65 m layers using the 1D inversion, (b) inverted magnetic susceptibility of the 0.05 – 0.35 m  
547 and 0.35 – 0.65 m layers using the 3D linear inversion. The white rectangles indicate the  
548 contour of the targeted area used for 3D non-linear inversion.

549 Figure 12: Th rouanne (Pas-de-Calais, France) site, four apparent magnetic susceptibility  
550 maps.

551 Figure 13: Th rouanne site, inverted magnetic susceptibility of the 0.25 – 0.75 m, 0.75 –  
552 1.25 m, and 1.25 – 2.25 m layers using the 1D inversion.

553 Figure 14: Th rouanne site, inverted magnetic susceptibility of the 0.25 – 0.75 m, 0.75 –  
554 1.25 m, and 1.25 – 2.25 m layers using the 3D linear inversion.

555

556

557 **Table captions**

558 Table 1: Inverted susceptibility contrast (in  $10^{-5}$  SI) as a function of the slab's depth of the  
559 slab,  $z$ , and the separation between transmitting and receiving coils,  $L$  (the original value  
560 being  $200 \cdot 10^{-5}$  SI), (a) VCP configuration, (b) PERP configuration (the symbol X means that  
561 the shape of the slab is not correctly restored and unidentifiable), (c) HCP configuration and  
562 (d) PARA configuration

563

564 Table 2: Inverted susceptibility contrast when a  $2\text{m} \times 2\text{m} \times 0.6\text{m}$  body, of  $200 \cdot 10^{-5}$  Si  
565 susceptibility contrast is divided into 5 thin layers of  $0.12\text{m}$  thickness, determined using  
566 respectively five, six and seven different instrumental configurations (constraint II is used in  
567 the inversion).

568 Table 3: Characteristics of seven instrumental configurations used to interpret inversion  
569 processes with synthetic data.

570

	$L=0.5\ m$	$L=0.7\ m$	$L=1\ m$	$L=1.5\ m$	$L=2\ m$
$z=0.3\ m$	195	187	153	169	153
$z=0.5\ m$	227	224	209	226	200
$z=0.7\ m$	245	235	221	236	234
$z=1\ m$	242	241	239	241	229
$z=1.5\ m$	250	226	219	249	205

571 Table 1(a)

572

	$L=0.5\ m$	$L=0.7\ m$	$L=1\ m$	$L=1.5\ m$	$L=2\ m$
$z=0.3\ m$	206	258	183	X	X
$z=0.5\ m$	235	244	217	259	219
$z=0.7\ m$	242	240	233	253	228
$z=1\ m$	252	245	252	248I	230
$z=1.5\ m$	X	X	X	249	193

573 Table 1(b)

574

	$L=0.5\ m$	$L=0.7\ m$	$L=1\ m$	$L=1.5\ m$	$L=2\ m$
$z=0.3\ m$	296	120	240	225	X
$z=0.5\ m$	271	221	215	233	302
$z=0.7\ m$	266	304	257	224	284
$z=1\ m$	271	282	263	292	276
$z=1.5\ m$	277	279	249	280	248

575 Table 1(c)

576

	$L=0.5\text{ m}$	$L=0.7\text{ m}$	$L=1\text{ m}$	$L=1.5\text{ m}$	$L=2\text{ m}$
$z=0.3\text{ m}$	217	205	185	222	224
$z=0.5\text{ m}$	318	247	249	255	241
$z=0.7\text{ m}$	289	280	258	272	276
$z=1\text{ m}$	280	287	260	283	275
$z=1.5\text{ m}$	273	277	179	311	284

577 Table 1(d)

578

579

Different instrument configurations used	Inverted susceptibility contrast ( $\times 10^{-5}$ SI) for 5 layers
5 configurations : PERP 1 m, PERP 1.5 m, VCP 0.7 m, VCP 1 m and PARA 1.5 m	Layer 1 (centered et 0.26m) 219.5 Layer 2 (centered at 0.38 m) 219.8 Layer 3 (centered at 0.50 m) 220.2 Layer 4 (centered at 0.62 m) 220.4 Layer 5 (centered at 0.74 m) 220.5
6 configurations : PERP 0.7 m, PERP 1 m, PERP 1.5 m, VCP 0.7 m, VCP 1 m and PARA 1.5 m	Layer 1 217.6 Layer 2 218.0 Layer 3 218.3 Layer 4 218.5 Layer 5 218.6
7 configurations : PERP 0.7 m, PERP 1 m, PERP 1.5 m, VCP 0.7 m, VCP 1 m, VCP 1.5 m and PARA 1.5 m	Layer 1 219.1 Layer 2 219.5 Layer 3 219.8 Layer 4 220.4 Layer 5 220.5

580 Table 2

581

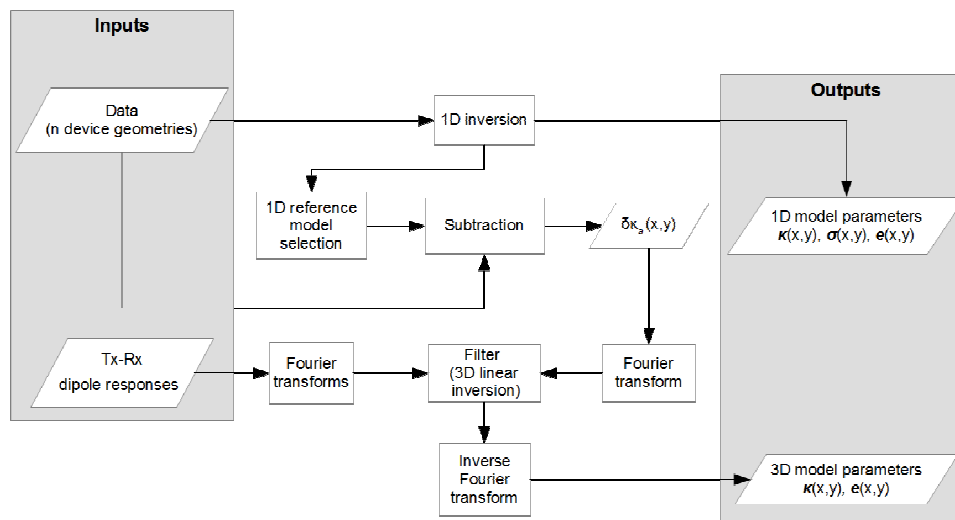
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583

Apparatus	Geometrical configuration	Inter-coil separation (m)	Frequency (kHz)	Height of the coils (m)
SH3	PARA	1.5	8.0	0.2
PRP6	PERP	0.6		
PRP10	PERP	1.0		
PRP15	PERP	1.5		
VCP6	VCP	0.6		
VCP10	VCP	1.0		
VCP15	VCP	1.5		

584 Table 3

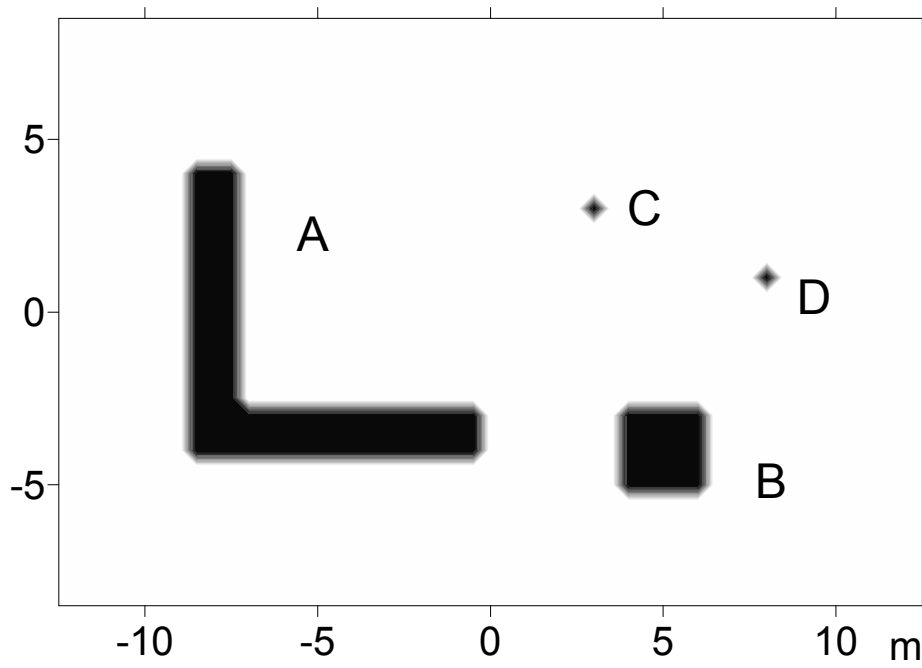
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587 Fig. 1

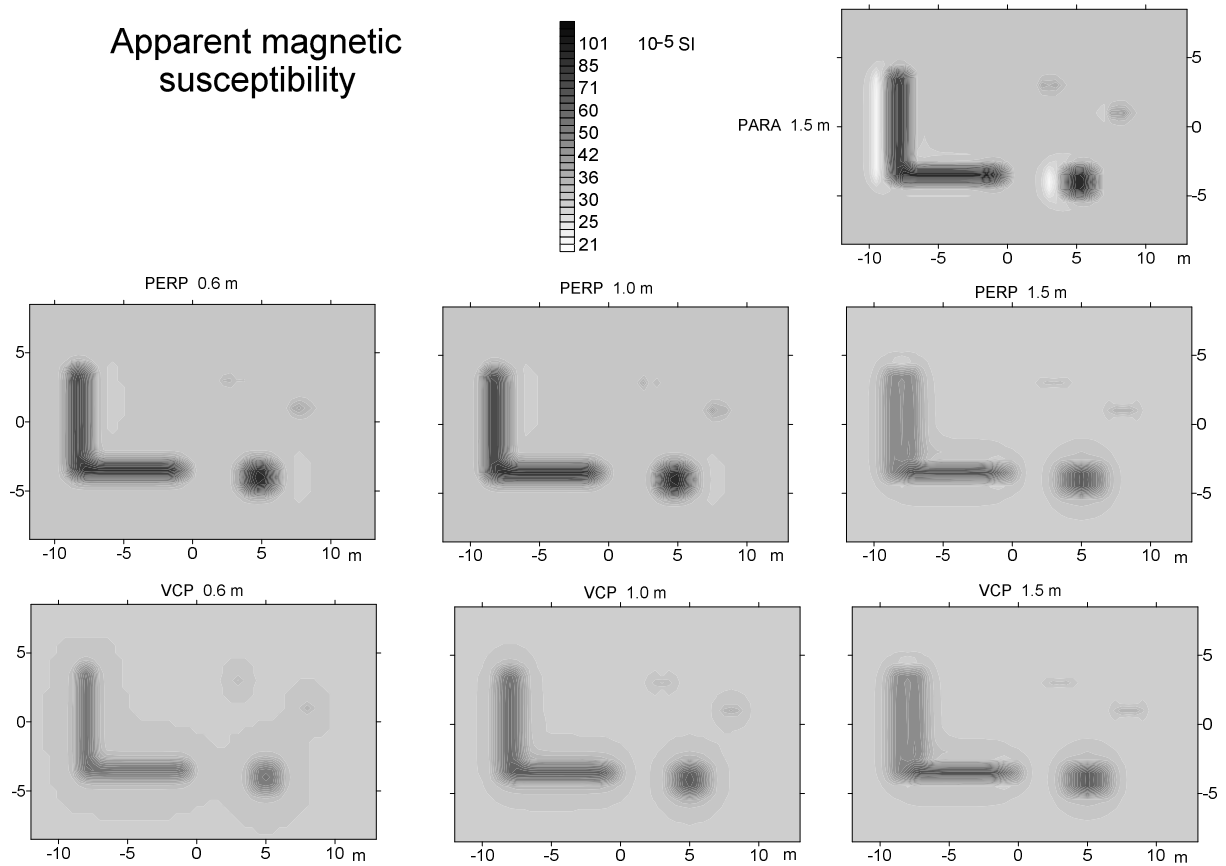
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591 Fig. 2

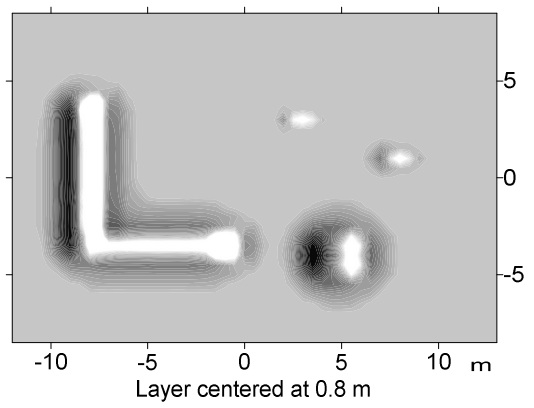
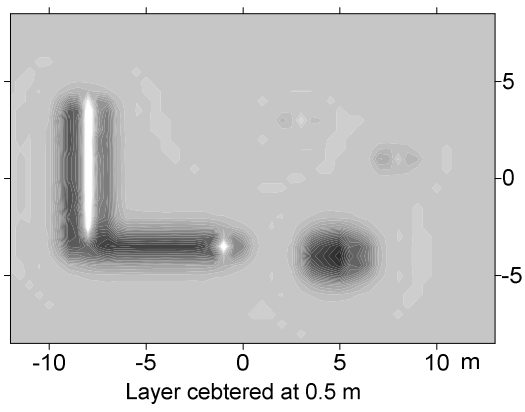
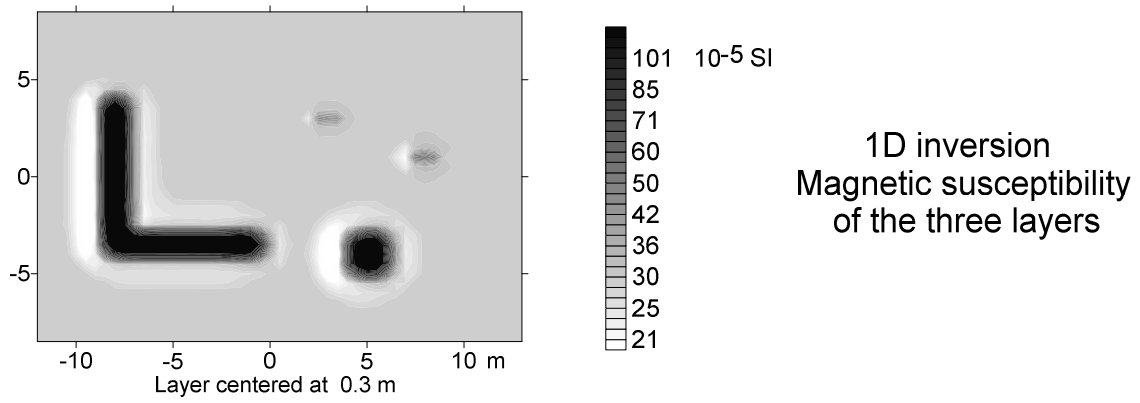
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594 Fig. 3

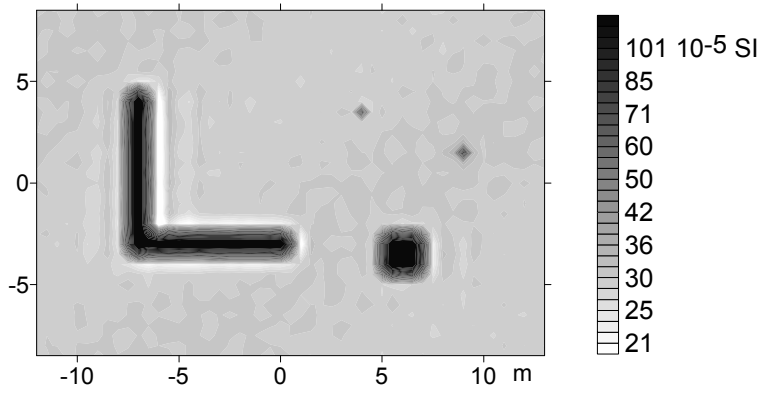
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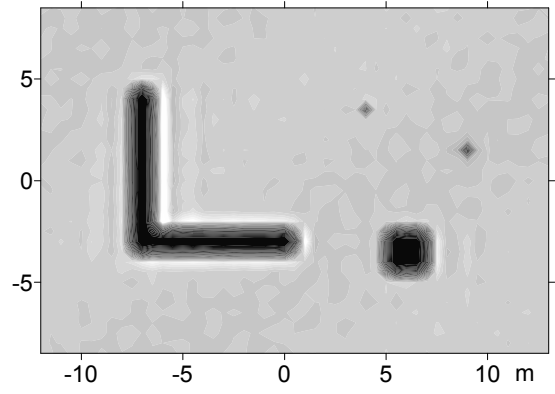
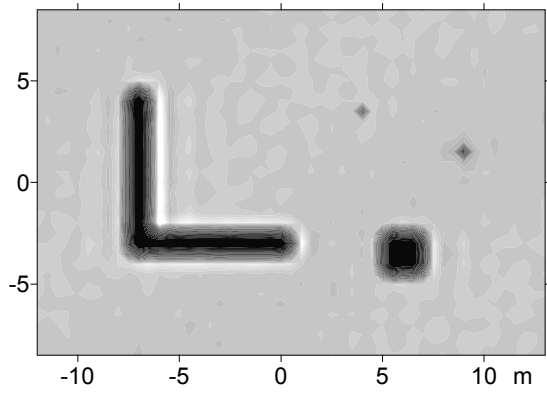
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597 Fig. 4

598



3D linear inversion  
 Magnetic susceptibility  
 of the three layers

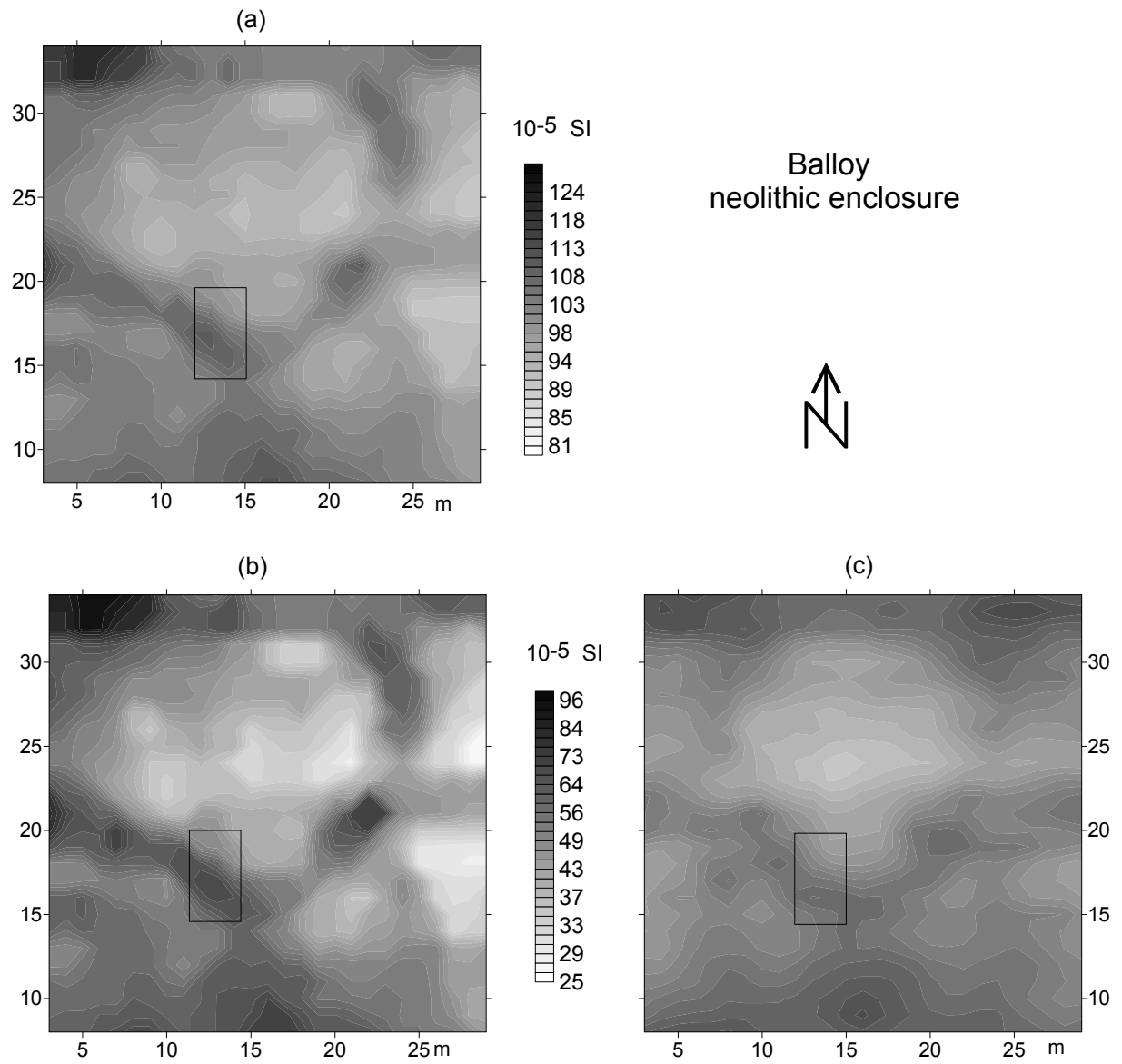


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600 Fig. 5

601





602

603 Fig. 6

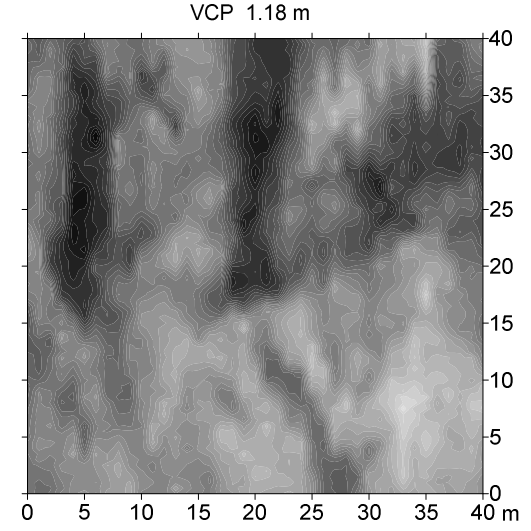
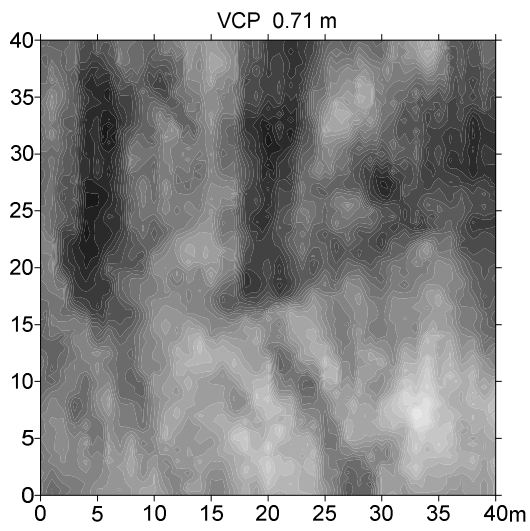
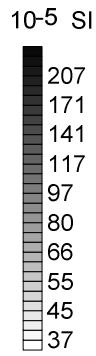
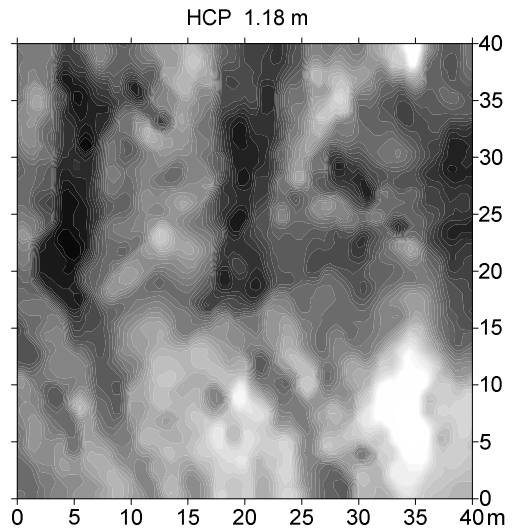
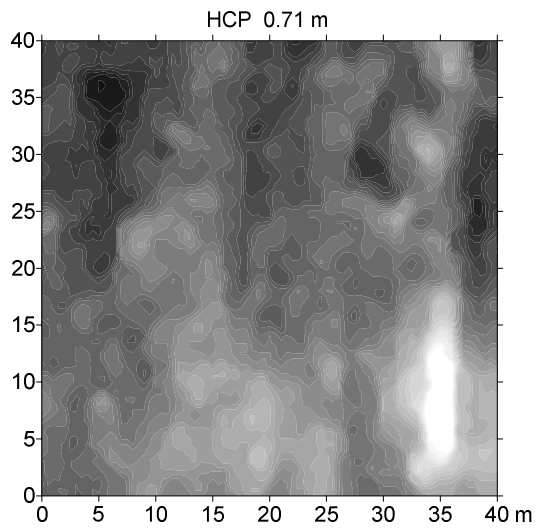
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606 Fig. 7

607

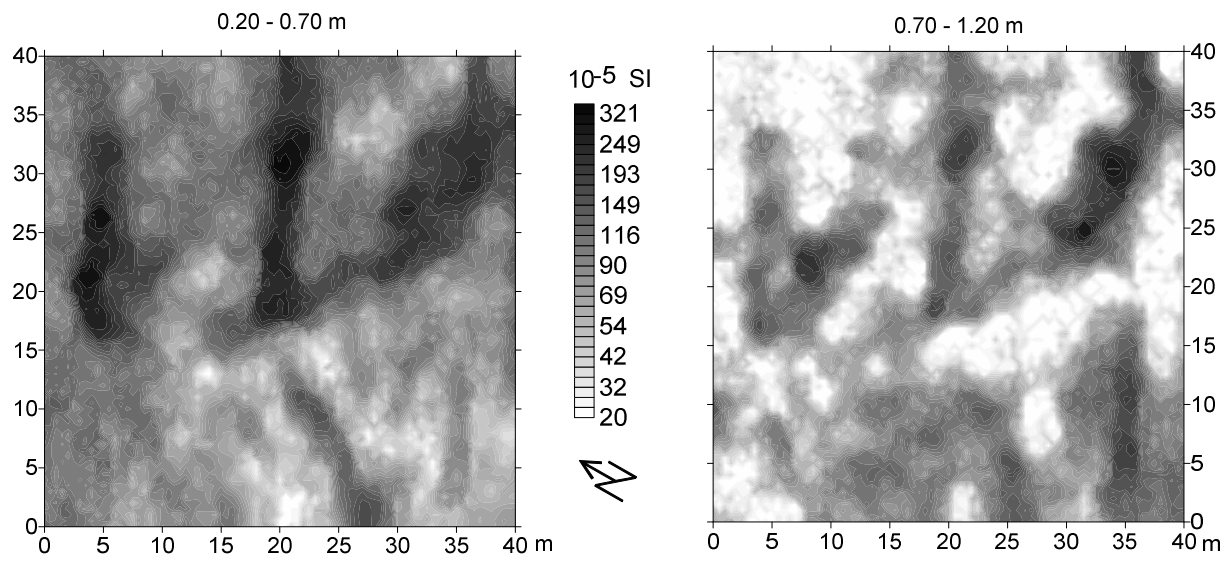


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609 Fig.

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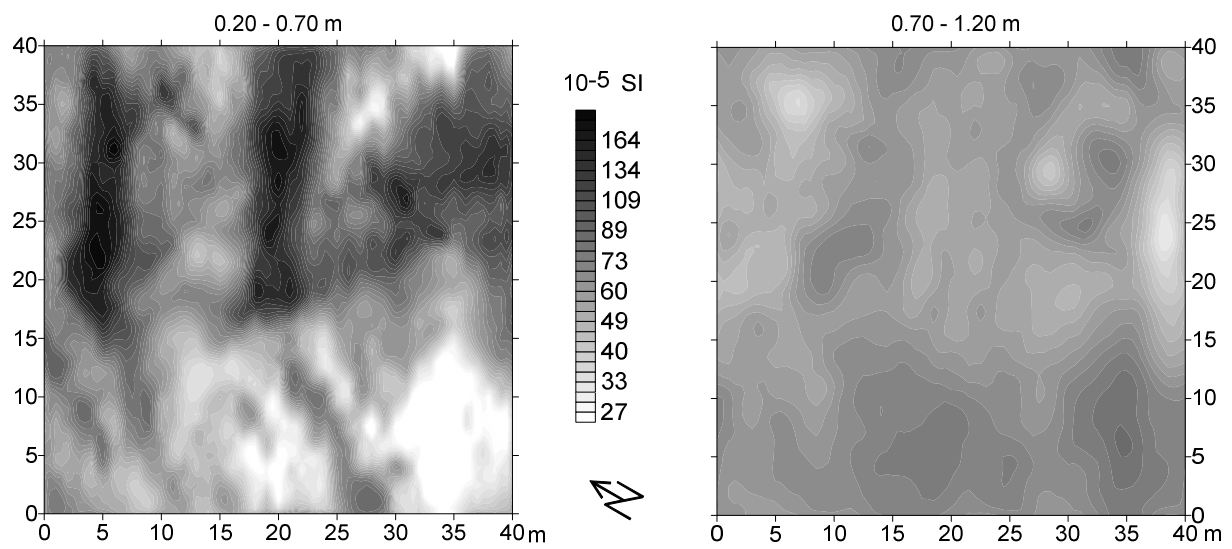
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612 Fig. 9a

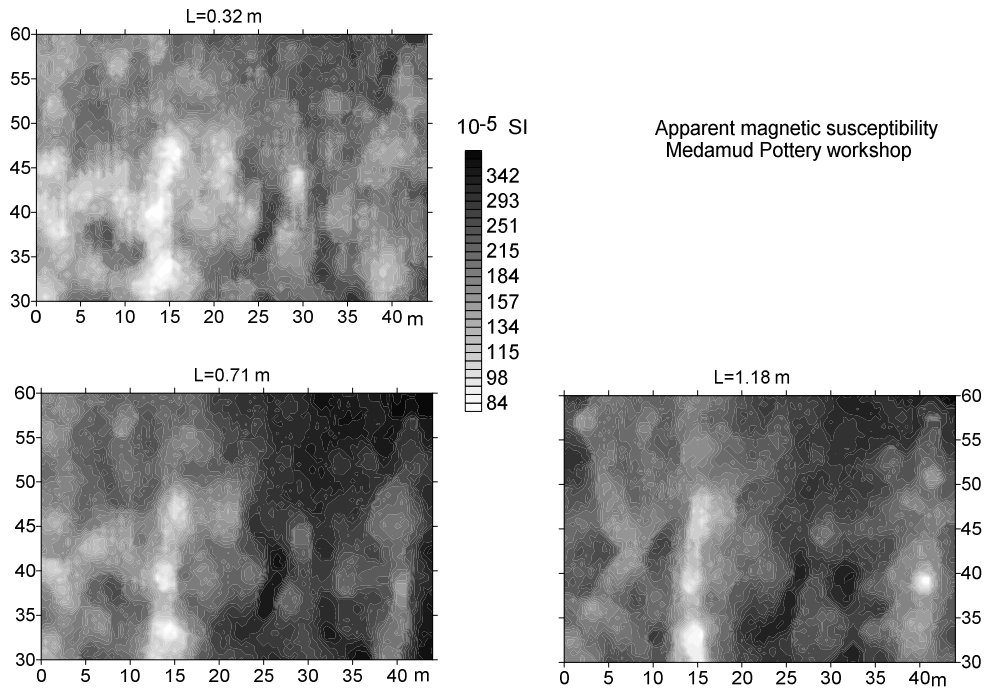
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615 Fig. 9b

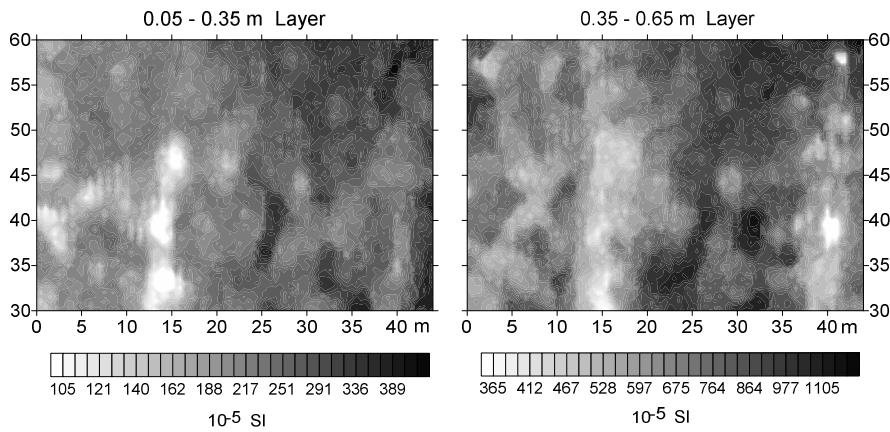
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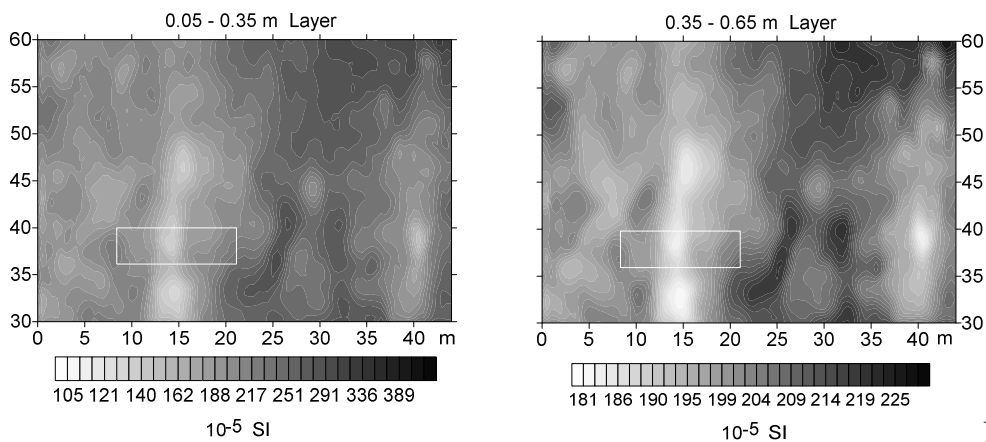
618 Fig. 10

619



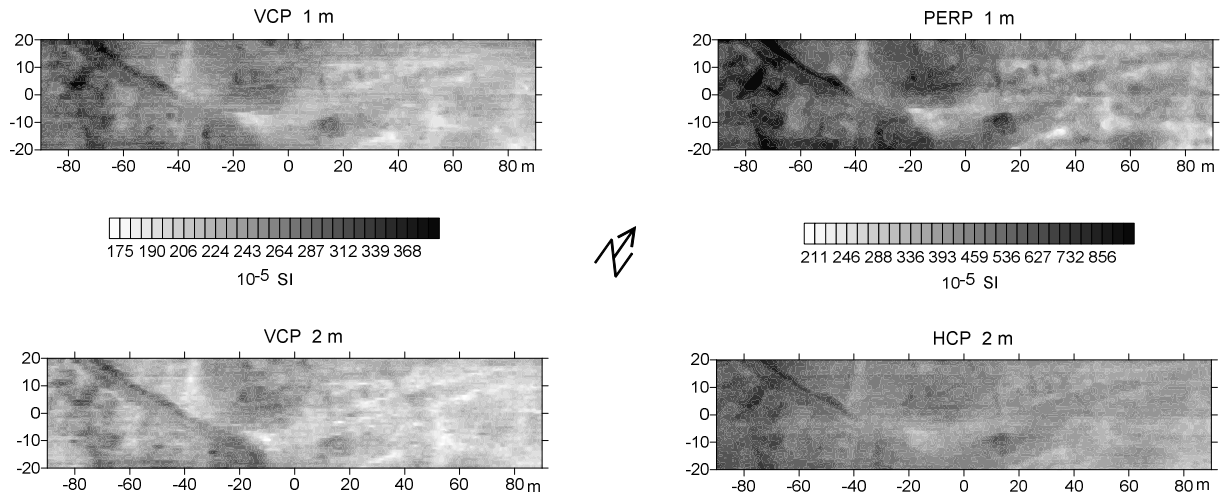
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621 Fig. 11a



622

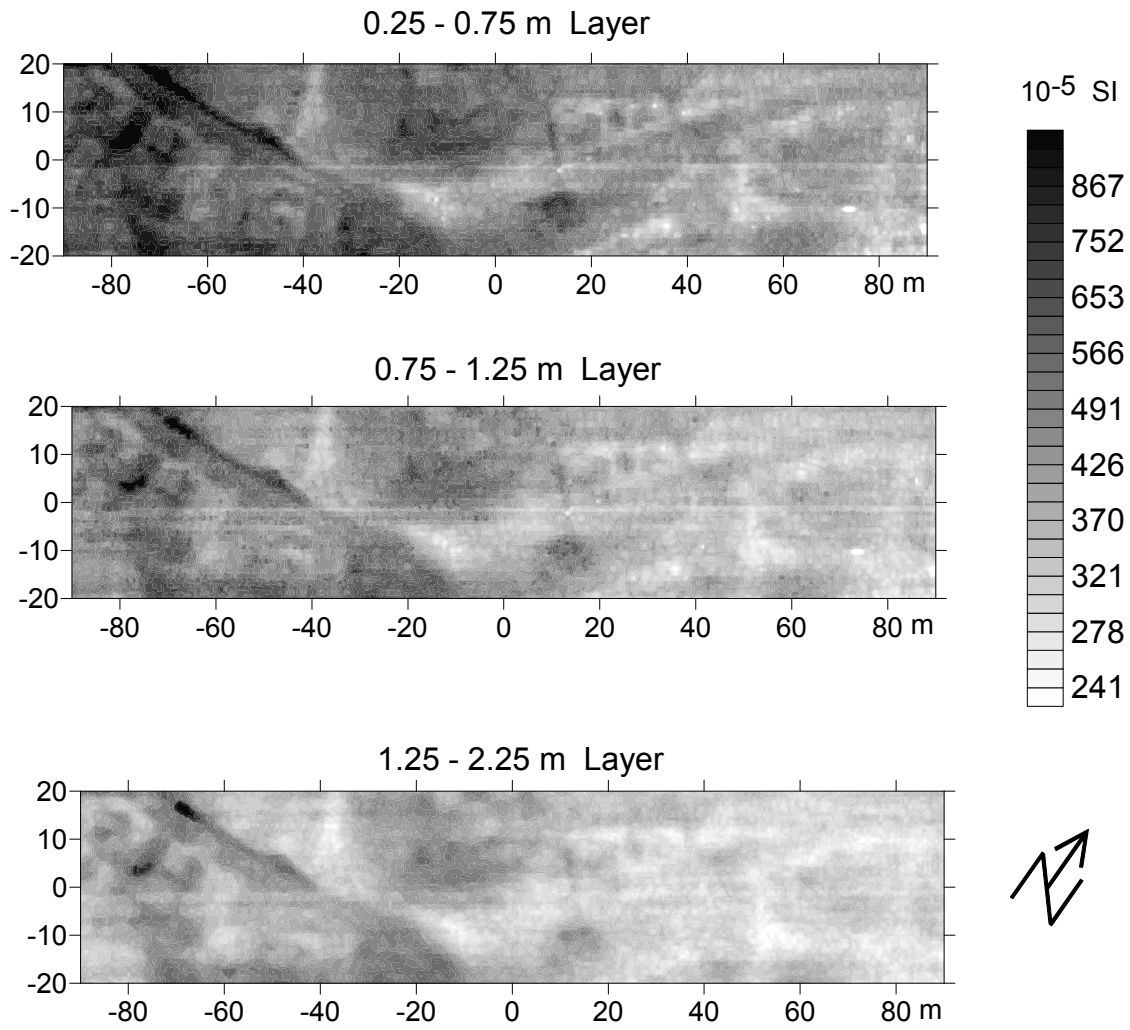
Fig. 11b



623

624 Fig. 12

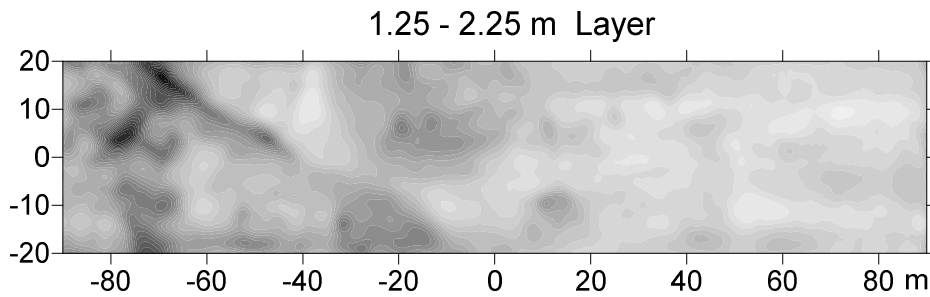
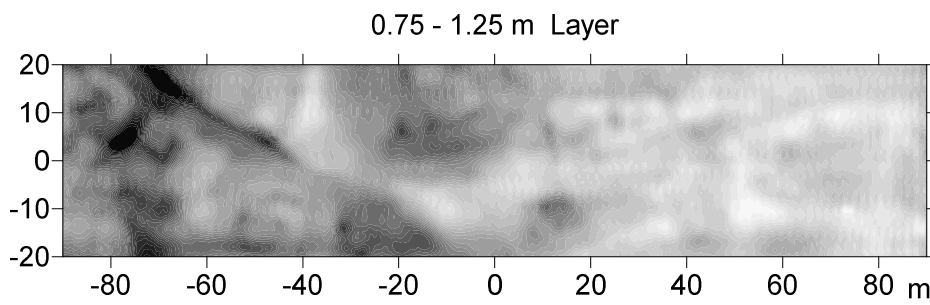
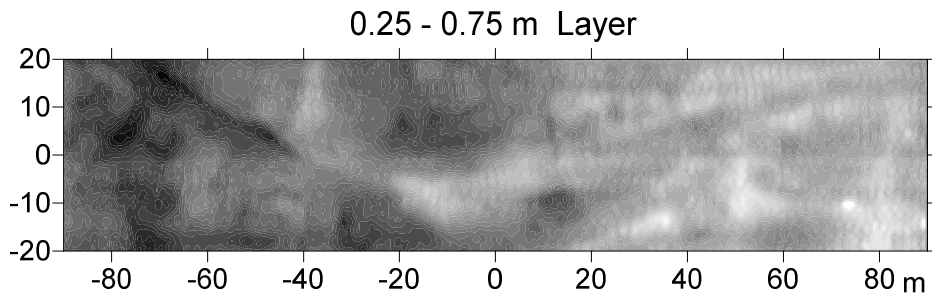
625



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627 Fig. 13

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630 Fig. 14