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1 **Mapping of quadrature magnetic susceptibility/magnetic viscosity of soils by using**  
2 **multi-frequency EMI**

3

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5

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8

9 **Abstract**

10 Measuring magnetic viscosity significantly improves the information brought by the  
11 magnetic susceptibility about the history of soils. In the field its mapping can be achieved by  
12 TDEM measurement. Here we study the applicability of multi-frequency FDEM viscosity  
13 measurement in the low frequency range using a commercial EMI instrument. The  
14 dependence of the in-phase and quadrature out-of-phase components of the ratio of secondary  
15 magnetic field to primary magnetic field, electrical conductivity, magnetic susceptibility and  
16 magnetic viscosity is first described. The procedure allowing the determination of the three  
17 apparent properties is then proposed. It delivers first the conductivity using the differences  
18 between the quadrature responses at two different frequencies. Then, after removing the  
19 conductivity effects both in the in-phase and quadrature components, it provides the values of  
20 the magnetic susceptibility and viscosity. This procedure is tested on 1D and 3D synthetic  
21 cases to assess any arising uncertainty. The application of the method is attested in two  
22 archaeological case histories in Thessaly in conductive and magnetic soil contexts. The  
23 apparent magnetic viscosity maps are significantly different from magnetic susceptibility and  
24 conductivity maps thus bringing new information into the game.

25

26 **Keywords**

27 Low induction number, EMI, soil magnetic viscosity, soil magnetic susceptibility, soil  
28 electrical conductivity, multi-frequency.

29

30 **Introduction**

31 Frequency domain electromagnetic induction (EMI) instrument with Slingram  
32 geometry (dipole-dipole) is of common use in archaeological prospection (Scollar *et al.*,  
33 1990) and soil studies (Corwin and Lesch, 2005). It allows mapping simultaneously electrical  
34 conductivity and magnetic susceptibility of soils. These light mobile instruments present also  
35 the advantage to be easily towed on the field (De Smedt *et al.*, 2013).

36 For the low frequency domain, the choice to neglect displacement currents limits the  
37 used frequencies to 100 kHz and the geometric scale of the instruments, i.e. the metric inter-  
38 coil separation, determines the investigated volume. Consequently these EMI instruments  
39 respect the low induction number (LIN) approximation and thus: (1) the conductivity  
40 response is in quadrature out-of-phase from the transmitter moment that allows the  
41 measurement of the in-phase magnetic susceptibility, (2) the depth of investigation is only  
42 governed by the instrument's geometry. Only geometrical soundings can be achieved;  
43 therefore there is no advantage in using different frequencies.

44 Until now, with EMI frequency domain instruments, only the in-phase magnetic  
45 susceptibility is measured, while quadrature susceptibility/magnetic viscosity has been  
46 measured and mapped using TDEM instruments (Thiesson *et al.* 2007). However, some  
47 observations of this property with single frequency instruments have been also achieved (Mc  
48 Neill 2013).

49 To improve the interpretation of FDEM measurements one faces a series of  
50 difficulties; on one hand the magnetic susceptibility is a complex quantity which generates a

51 quadrature response that algebraically adds to the conductivity response and, on the other  
52 hand, the LIN approximation and low frequency approximation have their own limits. When  
53 either the conductivity or the frequency increases, a significant in-phase response appears that  
54 algebraically adds to the in-phase susceptibility response. Over clayed soils, the dielectric  
55 permittivity can also be sufficiently high to generate measurable responses in the higher  
56 portion of the low frequency range.

57         The use of several frequencies has been considered to overcome these limitations.  
58 Limiting the purpose of the present paper to magnetic properties, it is first preferable to stay in  
59 the lower part of the frequency range around or below 10 kHz. In this range, due to the  
60 absence of frequency dependence of the quadrature component of soil magnetic susceptibility  
61 (Mullins and Tite 1973), it is possible to separate its response from the one generated by the  
62 conductivity, which increases with frequency. This solution has already been proposed  
63 (Tabbagh, 1986a) and a two-frequency prototype instrumentation has been tested (Benech,  
64 2000).

65         Since 1996, a multi-frequency commercial instrument, the GEM-2, has become  
66 available. Its manufacturers claimed that it allows frequency soundings (Won et al., 1996).  
67 This statement raised a contestation (Mc Neill, 1996) recalling the LIN approximation  
68 implications. The argument was closed by the admission (Huang and Won, 2003) that  
69 frequency soundings can only be relevant for higher induction number conditions when the  
70 ground conductivity is sufficiently high (sea water bathymetry). Nevertheless, it remains  
71 interesting to check the results that can be obtained in practice with such multifrequency  
72 instrument for both electrical conductivity and complex magnetic susceptibility. In particular,  
73 the TDEM measurements, used to map of the quadrature susceptibility/magnetic viscosity,  
74 indicated spatial variations that can be significantly different from those of the magnetic

75 susceptibility and can be more clearly linked with nitrogen or carbon content of a soil  
76 (Thiesson *et al.*, 2012).

77 In the present paper, after a short recall about the soil electromagnetic properties and  
78 the theoretical responses they generate, we will consider synthetic and experimental results  
79 obtained in different sites and discuss about the reliability of quadrature susceptibility  
80 mapping.

81

## 82 **Measured soil properties**

83 In the frequency range where the displacement currents proved to be neglected (below  
84 100 kHz), the electrical resistivity,  $\rho$ , is well defined and extends from 1 to 2  $\Omega\cdot\text{m}$  in the  
85 intertidal zone to 10000  $\Omega\cdot\text{m}$  in permafrost or in crystalline dry soils. This very wide dynamic  
86 range is the greatest observed for usual geophysical properties, but values out of the [10, 1000  
87  $\Omega\cdot\text{m}$ ] interval remain occasional in soils studies. In accordance with the hypothesis where the  
88 polarization effects are negligible, in the particular range the conductivity is assumed  
89 independent of the frequency.

90 On the contrary, the magnetic susceptibility is complex and varies with frequency  
91 (Mullins, 1977); it must thus be written:  $\kappa(\omega) = \kappa_{ph}(\omega) - i\kappa_{qu}(\omega)$  where  $\omega$  is the angular  
92 frequency,  $\kappa_{ph}$  is the in-phase component and  $\kappa_{qu}$  the quadrature component. However, all the  
93 experiments, except those from iron working sites, undertaken over laboratory samples  
94 respect the dispersed single-domain grain theory (Néel, 1949) which states that the quadrature  
95 component is constant and linked to the frequency variation of the in-phase part by::

$$96 \quad \frac{2}{\pi} \kappa_{qu} = - \frac{\partial \kappa_{ph}(\omega)}{\partial \ln(\omega)} \quad (1)$$

97 (Mullins and Tite 1973, Dabas *et al.* 1992, Dabas and Skinner 1993). This decrease of the in-  
98 phase susceptibility and the value of the quadrature susceptibility correspond to the same  
99 parameter called magnetic viscosity. The viscosity is also measured in the field using TDEM  
100 instruments (Colani and Aitken 1966, Thiesson *et al.* 2007) and all the field results, (see for  
101 example Pétronille *et al.* 2010), correspond to a slope of the logarithmic decrease close to -1  
102 for the  $\frac{\partial B(t)}{\partial t}$  signal measured in the receiver coil in accordance with the above formula. The  
103 in-phase soil susceptibility range of values is also quite large, from  $1000 \cdot 10^{-5}$  SI in volcanic  
104 areas to  $10 \cdot 10^{-5}$  SI, but values close to  $1000 \cdot 10^{-5}$ SI are rare. Due to the presence of small  
105 mono-domain/superparamagnetic grains the quadrature susceptibility is significant and more  
106 often of the order of 6% of the in-phase susceptibility.

107         Consequently we will interpret the soil responses to a low frequency field excitation  
108 by considering a constant conductivity and a susceptibility following equation (1). The  
109 calculation of the response of a homogeneous ground, or of layered one, has been established  
110 by the work of Wait (1959), and is based on Hankel's transforms that can be rapidly  
111 calculated using convolution products (Guptasarma and Singh, 1997). Complete expressions  
112 and a description of the different subsequent approximations can be found in (Thiesson *et al.*  
113 2014). They allow expressing the measurement in terms of apparent conductivity and  
114 apparent susceptibility, based on a simplified conversion since the variations are monotonous  
115 although not simply linear.

116         To simplify the expressions in the following parts of the text, one will use the term  
117 magnetic susceptibility for the in-phase part only and use the term magnetic viscosity for the  
118 quadrature out-of-phase part.

119

## 120 GEM-2 instrument specificity

121 In this study we process data acquired with the GEM-2 instrument (Figure 1). This  
122 multi-frequency instrument is not a simple coplanar coil configuration Slingram device, but  
123 instead it has in fact two receivers coils, one serving as bucking coil for the other (Won *et al.*  
124 1996). They have the same surface and are mounted in opposite directions in such way that  
125 the primary field is exactly compensated: the “bucking” coil at a 1.035m distance from the  
126 transmitter coil having four times less turns than the “receiver” located at 1.66m distance. The  
127 measured quantity is thus:  $\frac{(H_{sR} - H_{sB} / 4)}{H_p}$ , where  $H_p$  is being the primary field at the  
128 ‘receiver’ location,  $H_{sR}$  the secondary field at the ‘receiver’ location and  $H_{sB}$  the secondary  
129 field at the ‘bucking’ location. Thus, one must first reconsider the relationships between this  
130 measured quantity and the ground properties.

131 Figure 2 presents the responses for both conductivity and in-phase susceptibility (the  
132 quadrature susceptibility being 6% of the in-phase) at 5 kHz and 40 kHz for the characteristics  
133 of the GEM-2 instrument when held at 0.3m height above the ground surface. It can be  
134 observed that while the quadrature response is simply correlated (quasi proportional) with the  
135 ground conductivity, the in-phase sensitivity to susceptibility changes is hampered by the in-  
136 phase conductivity response which seems totally dominating the response for lower  
137 susceptibilities at 40 kHz.

138 Another important aspect is the dependence on the height above the ground, as the  
139 HCP configuration is known to exhibit changes from positive to negative values in the in-  
140 phase response when the altitude increases (Tabbagh, 1986a). Figure 3 shows that while the  
141 quadrature response monotonically decreases with the altitude H, the in-phase one exhibits a  
142 sharp maximum around H=0.3 m. This response is shifted towards negative values when the

143 conductivity increases but it retains the same shape. This effect of the HCP configuration  
144 considerably affects the shape and the sign of the anomaly for the apparent magnetic  
145 susceptibility as its vertical distribution varies due to the pedogenesis process and sedimentary  
146 disturbance.

147 As can be observed in Figure 4 the response generated by the quadrature susceptibility  
148 is linear but of quite limited magnitude compared to the electrical conductivity response. This  
149 effect explains the invisibility of the magnetic viscosity on the raw data which more often  
150 appear only related to the electrical conductivity.

151

## 152 **Methodology**

153 The aim of any type of geophysical prospection is to identify the physical properties  
154 and the geometrical shapes of the different media present in the underground. This is achieved  
155 through a full inversion process but before implementing this heavy process, and to be able to  
156 start it with a relevant guess of a priori parameter values, it is necessary to have a first  
157 assessment of the information by transforming the raw data to apparent property variations.  
158 The general definition of an apparent property is the one of a homogeneous ground that would  
159 deliver the same measurement with the same instrument. Establishing apparent electrical  
160 conductivity, susceptibility and viscosity maps is the purpose of the present work but as  
161 several properties intervene the task is more difficult than when only one property can be  
162 considered, as is the case in D.C. resistivity prospecting where the transformation corresponds  
163 to a simple multiplication by a coefficient. Thus, it is necessary to describe the successive  
164 steps of the transformation of the raw data in apparent properties because different procedures  
165 would lead to (slightly but certainly) different results.



166 Measurement first implies a calibration step, e.g. transformation of instrumental digits  
167 into experimental (Hs/Hp) ratio in ppm, established on a methodology described by Thiesson  
168 *et al.* 2014). For the quadrature channel it is based on a comparison between an electrical  
169 sounding and measurements at (at least) two heights above the ground surface. In this case,  
170 we assume that the higher measurement is almost not affected by the magnetic properties but  
171 only by electrical conductivity. Thus, one obtains the calibration coefficient between the  
172 digits measured by the instrument and the theoretical response for the quadrature part of the  
173 EM signal. In the second calibration step the experimental in-phase response acquired with an  
174 aluminum sphere is compared with the theoretical one (Thiesson *et al.* 2014). For our  
175 instrument, in-phase coefficient is -0.70 digit/ppm and the quadrature coefficient -1.0  
176 digit/ppm. We repeat this calibration at each different field of survey, to ensure the stability of  
177 the instrument.

178 To extract apparent complex magnetic susceptibility it's required to beforehand  
179 calculate the electrical conductivity. Multi-frequency measurements allow removing the effect  
180 of the magnetic viscosity on the quadrature part of the signal. Considering the difference  
181 between two different frequencies this difference is then transformed in apparent electrical  
182 conductivity by correspondence with a reference curve calculated using the complete  
183 formulas (Thiesson *et al.* 2014).

184 In the second step of the procedure, the conductivity value is used to calculate the in-  
185 phase and quadrature parts of the signal generated by the electrical conductivity at each  
186 frequency. By subtracting these parts from the experimental data one can remove the  
187 conductivity parts on both in-phase and quadrature channels and retain the parts generated by  
188 the susceptibility and the viscosity. Magnetic viscosity strictly affects quadrature out-of-phase  
189 part of the EM signal while the magnetic susceptibility only affects the in-phase part of the  
190 signal. These imaginary and real parts of the secondary to primary field ratio, in ppm, are then

191 expressed in the apparent properties by comparing the values with master curves (magnetic  
192 susceptibility as a function of in-phase part of the EM signal in ppm, and magnetic viscosity  
193 as a function of quadrature out-of-phase part of the EM signal in ppm). The master curves  
194 were beforehand calculated using the full analytical solution.

195

## 196 **Synthetic data**

197 The advantages of synthetic data processing is to evidence the difficulties that can  
198 exist in the process before any perturbations generated during field work, the introduction of  
199 external noise and possible instrument default or failure(s). Synthetic data will be analyzed  
200 through a 1D case and a simple 3D geometry case.

### 201 *1D synthetic data*

202 As the raw data transformation applied to homogeneous ground responses restitutes  
203 the exact values of the three properties one considers here a two layers model. The first layer  
204 ( $\rho=100 \Omega.m$ ,  $\kappa_{phf1}=100.10^{-5}$  SI,  $\kappa_{phf2}=95.6.10^{-5}$  SI,  $\kappa_{qu}=6.10^{-5}$  SI) has an increasing thickness,  
205 starting to 0.1 meter up to 3 meter, the second one is a more conductive and less magnetic  
206 ( $\rho=50 \Omega.m$ ,  $\kappa_{phf1}=10.10^{-5}$  SI,  $\kappa_{phf2}=9.56.10^{-5}$  SI,  $\kappa_{qu}=0.6.10^{-5}$  SI). The susceptibility variation  
207 with frequency respects equation (1) for the frequencies of 5010 and 13370 Hz used by GEM-  
208 2. We simulated the response for the GEM-2 in a HCP configuration, at 0.3 m elevation. The  
209 variation of the apparent susceptibility is shown in Figure 5a and that of the apparent viscosity  
210 in Figure 5b. We observe a slight influence of the frequency that increases with the thickness  
211 of the first layer; it is low but clearly observable for the viscosity due to the small values of it.  
212 This corresponds to the apparent conductivity change, even if not totally corrected in the two  
213 layer case by the applied procedure: the slope of the quadrature response against viscosity is  
214 slightly dependent on the conductivity. The apparent magnetic viscosity delivered by the used

215 procedure is thus in (small) dependence on the electrical conductivity as shown in Figure 6 for  
216 both 5010 and 13370 frequencies. In this Figure the absence of conductivity dependence  
217 would correspond to horizontal straight lines for each magnetic viscosity value, and globally  
218 one can observe that its dependence is low. However, one must notice that the discrepancy (1)  
219 increases with frequency, (2) is, as expected, high for smaller viscosity values, but (3)  
220 increases also for high resistivity. In this last case the uncertainty is generated by the  
221 uncertainty in the evaluation of the resistivity itself.

222 Finally this example underlines that the determination of an apparent magnetic  
223 viscosity value using the proposed procedure is still valuable for medium and high magnetic  
224 viscosity (still as a possible value for common soil). As the discrepancy is frequency  
225 dependent, the determination of the magnetic viscosity with the lowest frequencies is much  
226 more preferable.

### 227 *3D synthetic data*

228 3D synthetic data were simulated by the moment method (Tabbagh, 1985). We put a  
229 resistive and magnetic block ( $\rho=500 \Omega\text{m}$ ,  $\kappa_{\text{phf1}}=150.10^{-5} \text{ SI}$ ,  $\kappa_{\text{phf2}}=143.10^{-5} \text{ SI}$ ,  $\kappa_{\text{qu}}=10.10^{-5} \text{ SI}$ )  
230 in a two layers medium. The first layer, of 0.2 m thickness, is more resistive and magnetic  
231 ( $\rho=100 \Omega\text{m}$ ,  $\kappa_{\text{phf1}}=50.10^{-5} \text{ SI}$ ,  $\kappa_{\text{phf2}}=49.10^{-5} \text{ SI}$ ,  $\kappa_{\text{qu}}=3.10^{-5} \text{ SI}$ ) than the second one ( $\rho=50 \Omega\text{m}$ ,  
232  $\kappa_{\text{phf1}}=10.10^{-5} \text{ SI}$ ,  $\kappa_{\text{phf2}}=9.10^{-5} \text{ SI}$ ,  $\kappa_{\text{qu}}=1.10^{-5} \text{ SI}$ ) as we have usually noticed on well-drained  
233 soil. In accordance with the Neel's theory the in-phase magnetic susceptibility still decreases  
234 with the frequency, depending on the value of the magnetic viscosity. The target is a block of  
235  $2 \times 2 \times 2 \text{ m}^3$  centered at a depth of 1.2 m, i.e. entirely in the second layer. The top of this  
236 target is close to the ground surface. This simulation uses the same acquisition parameters as  
237 in-field acquisition: a 1m measurement step, an altitude of 0.3 meter in the HCP configuration  
238 and with the same instrumental settings. We again used the two first frequencies of the

239 instrument, 5010 Hz and 13370 Hz. The synthetic data are then processed with the previously  
240 introduced procedure. We obtain 5 maps (Fig. 7): electrical conductivity on the one hand,  
241 magnetic susceptibility and magnetic viscosity at both frequencies on the other hand.

242 As expected from previous theoretical studies (Tabbagh 1986b) for HCP  
243 configuration, the apparent electrical conductivity shows a complex shaped anomaly, which  
244 even for such a simple shaped target has three extrema. The shape of the apparent magnetic  
245 susceptibility contours is simpler than the electrical one. It shows a high value just above the  
246 center of the target and weak negative values around the block, but the shape of the anomaly  
247 and the shape of the target present differences. This point needs to be taken into account in the  
248 further interpretation steps. Considering the frequencies, both maps are exactly similar. For  
249 both frequencies the modes of apparent in-phase (susceptibility) and quadrature (viscosity)  
250 values are governed by the instrument geometry and without link with the anomalous  
251 causative body. We thus consider the variation of the data expressed by the difference  
252 between the maximum and minimum values of the anomaly on each map. At 5010 Hz  
253 frequency the differences are  $204 \cdot 10^{-5}$  SI in-phase and  $15.3 \cdot 10^{-5}$  SI in quadrature. This  
254 corresponds to a ratio of 7.5% between the two components. At 13370 Hz frequency the  
255 corresponding values are  $184.9 \cdot 10^{-5}$  SI,  $15.5 \cdot 10^{-5}$  SI and 8.4%. The amplitude of the in-phase  
256 susceptibility slightly decreases with frequency while the quadrature (viscosity) practically  
257 remains constant (considering the error resulting from the non-strictly addition of magnetic  
258 viscosity and electrical conductivity) in agreement with the susceptibility values introduced in  
259 the modelling. The viscosity/susceptibility ratio is slightly higher than the ratio of the body  
260 properties (6.7%) but this can also be explained by the influence of the higher ratio chosen for  
261 the second layer (11.1%).

262

## 263 **Field tests**

264 We employed the GEM-2 in two archaeological sites to map the complex magnetic  
265 susceptibility and the electrical conductivity. These two sites are located on the Thessaly plain  
266 in central Greece. The first one, Karatzantakli, in the mountain area, is covered by a high clay  
267 content soil which suggests a high conductivity. The second one, Almiriotiki, in plain, close  
268 to paleo-channel and floodplain deposits has also high clay content but with strong  
269 heterogeneities affecting the electrical conductivity. These human settlements are likely to  
270 change magnetic properties of soils and generate anomalies related to the archaeological  
271 features and handcraft activities area. It also looks well-suited to our studies. In-phase parts of  
272 the signal are affected by the electrical conductivity. As showed on the methodological part,  
273 the use of different frequencies allows removing its first order in-phase and quadrature  
274 effects. We are thus able to map the magnetic viscosity distribution over the area cover by the  
275 EM data and observe its significance.

276 Five different frequencies from 5010 Hz until 40050Hz (5010 Hz, 13370 Hz, 22530  
277 Hz 31290Hz and 40050 Hz) were used. Measurements were continuously acquired almost  
278 every meter along profiles 1m apart. The instrument was carried at an altitude of 0.3 m above  
279 the ground surface. Despite manufacturer advice, we preferred to carry the instrument at this  
280 height regarding the curve of sensitivity for the magnetic properties on the in-phase part of the  
281 instrument. Only the two lower frequencies are considered here for magnetic properties  
282 mapping.

### 283 ***Karatzantakli***

284 Karatzantakli is a Neolithic tell (“magoula”), consisting of an accumulation of  
285 anthropogenic material, which means high soil heterogeneity. On this site geomorphological  
286 variations are induced by different cover material in the different parts of the site. Some

287 features like kilns or fireplaces could increase considerably the magnetic susceptibility or the  
288 magnetic viscosity at some points. Measurements were recorded in a manual mode.  
289 Measurements were automatically acquired along the profile with a regular distribution of the  
290 measurements along each one.

291 The raw data, in Figure 8, show high contrast on the quadrature part of the signal and  
292 on the in-phase part of the EM signal. For the in-phase part of the signal, ranges of values are  
293 similar at both frequency but with a marked offset. On the quadrature out-of-phase part of the  
294 signal, the range of values for the higher frequency is approximately two times higher than for  
295 the lower frequency and both show a high conductivity who do affect the in-phase part of the  
296 EM signal (Fig. 8).

297 The five maps resulting from the raw data processing are presented in Figure 9.  
298 Apparent electrical conductivity shows some differences between the left and right parts of  
299 the area.. The important depth of investigation for this instrument in HCP geometry doesn't  
300 allow any shallow characterization of the soils and it is more representative of a too thick  
301 layer of soil. Apparent magnetic susceptibility shows more anomalies on the whole area.  
302 Values of susceptibility are extremely high. For 5010 Hz the median of values is  $227.10^{-5}$  SI  
303 and the interquartile is  $73.10^{-5}$ . These values of magnetic susceptibility correspond with very  
304 high values of magnetic viscosity due to the inter dependence of magnetic susceptibility and  
305 magnetic viscosity. The inter-quartile difference changes from  $73.10^{-5}$  SI to  $71.10^{-5}$  between  
306 the two frequencies. Decreasing of interquartile seems very small regarding the high value of  
307 magnetic susceptibility but could be also an effect of the distribution of the magnetic  
308 susceptibility. Some anomalies are common on both magnetic susceptibility and magnetic  
309 viscosity but generally speaking the maps look quite different. This means that the ratio of  
310 magnetic viscosity on magnetic susceptibility is varying from on part to another one which  
311 implies different compositions regarding the size of the magnetic grains. These differences

312 confirm the interest to be attentive to this soil property regarding the EM signal. The range of  
313 values of the ratio between magnetic viscosity interquartile value and magnetic susceptibility  
314 interquartile value is close to 26%. This high value could probably be explained by an  
315 insufficiently good relative gain calibration between the in-phase and quadrature channels.

### 316 *Almiriotiki*

317 The second field test is the Neolithic tell of Almiriotiki. Measurements were acquired  
318 with a GPS RTK (Javad Triumph) which allows covering a very large area in one day (around  
319 2 ha/day). Accuracy of the positioning is better than decimetric due to the differential  
320 correction of the GPS point. This site presents a settlement covering the top part of the tell  
321 (magoules) and a bottom part around the central elevation.

322 We present the raw data for the in-phase part and the quadrature parts of the EM signal  
323 in Figure 10. For the in-phase part we observe an offset between the two frequencies but the  
324 same dynamic range of values. Only small differences can be attributed to the electrical  
325 conductivity, especially in the north part of the map. The quadrature part of the signal shows  
326 two similar maps for the both frequencies, with contrasted ranges of values. This frequency  
327 evolution is the consequence of the dependence on the frequency of the electrical conductivity  
328 measurements. Both frequency and dynamic range of values are approximately multiplied by  
329 a factor of two. At first glance the part of magnetic properties is invisible on both quadrature  
330 and in-phase response maps.

331 The processing allows us to obtain the five different maps presented in Figure 11. In  
332 appearance, electrical conductivity is very close to the raw data due to the strong effect of the  
333 electrical conductivity on the quadrature part of the signal. The values of the conductivity  
334 show a global high conductivity. On the north part, the conductivity increases, probably due  
335 to the soil modification induced by flooding deposits. It explains the effect of the conductivity

336 on the in-phase part of the raw data for the same location. The tell is more resistive due to the  
337 mix of anthropogenic material and natural clay soils. For the susceptibility, interpretation is  
338 less obvious which is not surprising regarding the HCP configuration.

339 Both magnetic viscosity maps are very similar. In this case data are noisier than in  
340 previous example. Nevertheless value of magnetic susceptibility between 100 and  $300 \cdot 10^{-5}$   
341 S.I. is still very high. Regarding the link between the magnetic susceptibility and the magnetic  
342 viscosity we can again expected high value of magnetic viscosity. Ratio of magnetic  
343 susceptibility and magnetic viscosity (inter-quartiles) is still higher than expected and close to  
344 22%. Again, this effect could be derived from a poor calibration but again the viscosity maps,  
345 very coherent between the two frequencies, show underground patterns significantly different  
346 from those shown by susceptibility maps. This again demonstrates the high interest of  
347 viscosity measurements.

348

## 349 **Discussion**

350 The experiments here presented were acquired using the GEM-2 instrument in HCP  
351 configuration. This configuration and the existence of two receivers do not facilitated the  
352 interpretation but this manufacturer's design implies a better stability when moving the  
353 instrument on the field. In near future, it is necessary to implement the use of VCP geometry  
354 by improving the stability of the instrument and correcting for the slight modification of the  
355 axis orientation during a continuous acquisition. Regarding the greater simplicity of VCP  
356 sensitivity curves, these improvements will allow a better description of the magnetic  
357 viscosity underground variations. However, in its present configuration the GEM-2 is already  
358 usable to perform a significant and qualitatively reliable magnetic viscosity mapping at the  
359 same time as conductivity and magnetic susceptibility mappings.



360 Due to the different physical properties taken into account, the transformation of the  
361 raw data in apparent properties is not straightforward but it is efficient. If the quantitative  
362 interpretation must use the raw data, the mapping of apparent properties proves to be feasible  
363 and informative. As the way to express the apparent properties is clearly established and the  
364 uncertainty assessed, it is possible to take into account the potential error on the estimation.  
365 The adopted definition of the apparent properties is thus satisfactory; especially because the  
366 error effect of this assumption is lower than the spatial variability of soil properties.  
367 Nevertheless, this error adds to the possible different gains between the in-phase and  
368 quadrature measurement channels, and prevents any precise quantitative determination of the  
369 ratio between the magnetic susceptibility and the magnetic viscosity, which can open the way  
370 to study the in-field variations of the grain size distributions. In all published magnetic  
371 viscosity measurements in the field (Thiesson *et al.* 2007, Pétronille *et al.* 2010), the maps of  
372 this ratio were informative and from the archaeological point of view supported assumptions  
373 about the functions of the detected features (metallurgy, pottery, domestic waste). In paleo-  
374 soil studies too, when this ratio is recalculated from the frequency dependence of the in-phase  
375 magnetic susceptibility, this ratio is more discriminant for layer identification than the  
376 susceptibility itself (Thiesson 2007)

377

## 378 **Conclusion**

379 The first series of tests and experiments aiming at mapping the magnetic viscosity,  
380 together with the electrical conductivity and the magnetic susceptibility, using a commercial  
381 multi-frequency FDEM instrument have been demonstrated. In spite that the instrument  
382 characteristics and its coil configuration are far from optimal for soil studies, the results are  
383 convincing and the experiments confirm its effectiveness in mapping this parameter: the

384 viscosity maps are not simple traces of the in-phase component of the magnetic susceptibility.  
385 Further comparisons with TDEM measurements are planned to elucidate the relative  
386 advantages of both ways of measurement. For FDEM, going ahead in the study of the  
387 magnetic grain sizes distribution necessitates to adopt a more convenient coil configuration  
388 and to progress in the relative gain calibration between in-phase and out-of-phase channels.

389 In the two examples examined, only the two lower frequencies were taken into  
390 account. For these frequencies the proportionality of the quadrature response with the  
391 conductivity is almost exact and only in high conductivity areas the effect on the in-phase part  
392 of the signal can be observed. When increasing the frequency, another parameter may affect  
393 the responses, namely the dielectric permittivity (Huang and Fraser, 2001). A significant  
394 amount of work must yet to be undertaken to assess all the possibilities offered by low  
395 frequency EMI instruments in soil study contexts.

396

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399 Approaches for the study of Early Agricultural villages of Neolithic”) project which is  
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403

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464

#### 465 **Figure captions**

466 Figure 1: In-field data acquisition in HCP geometry for the GEM-2 (Geophex Ltd.) on a  
467 Neolithic magoules (credit: Meropi Manataki). Instrument is hold at a height of 0.3 m in a  
468 hand operating acquisition mode.

469 Figure 2: Opposites of the responses, expressed by  $H_s/H_p$  ratio, (a) versus conductivity for  $\kappa_{ph}$   
470  $= 50 \cdot 10^{-5}$  S.I., and (b) versus in-phase susceptibility for  $\sigma=50$   $\Omega \cdot m$  (the quadrature  
471 susceptibility being 6% of the in-phase), at 5 kHz and 40 kHz for the GEM-2 instrument when  
472 held at 0.3m height above ground surface.

473 Figure 3: In-phase (a) and quadrature response (b) as functions of the height above ground  
474 surface, GEM-2, for  $\kappa_{ph}=50 \cdot 10^{-5}$  S.I., and  $f=5010$  Hz.

475 Figure 4: Quadrature response as functions of the quadrature out-of-phase part of the  
476 magnetic susceptibility for both 100 and 500  $\Omega.m$  and  $f=5010\text{Hz}$

477 Figure5 : (a) Apparent magnetic susceptibility and (b) apparent magnetic viscosity variations  
478 with increasing the thickness of the first layer for 5010 Hz and 13370 Hz frequencies.

479 Figure 6: Value of the apparent magnetic viscosity obtained with the proposed procedure as a  
480 function of electrical conductivity and magnetic viscosity a)  $f=5010$  Hz and b)  $f=13370$  Hz.

481 Figure 7: Result of the processing of synthetic data, a) simulated model, b) apparent electrical  
482 conductivity, c) apparent magnetic susceptibility for 5010 Hz, d) apparent magnetic  
483 susceptibility for 13370 Hz, e) apparent magnetic viscosity for 5010 Hz, f) apparent magnetic  
484 viscosity for 13370 Hz.

485 Figure 8: Raw data for the site of Karatzantakli (Grece): a) In-phase measurement in ppm for  
486 5010 Hz, b) In-phase measurement for 13370 Hz, c) Quadrature out-of-phase measurement  
487 for 5010 Hz, d) Quadrature out-of-phase measurement for 13370 Hz.

488 Figure 9: Processed data for the site of Karatzantakli (Greece): a) apparent electrical  
489 conductivity, b) apparent magnetic susceptibility for 5010 Hz, c) apparent magnetic  
490 susceptibility for 13370 Hz, d) apparent magnetic viscosity for 5010 Hz, e) apparent magnetic  
491 viscosity for 13370 Hz.

492 Figure 10: Raw data for the site of Almiriotiki (Greece): a) In-phase measurement in ppm for  
493 5010 Hz, b) In-phase measurement for 13370 Hz, c) Quadrature out-of-phase measurement  
494 for 5010 Hz, d) Quadrature out-of-phase measurement for 13370 Hz.

495 Figure 11: Processed data for the Neolithic site of Almiriotiki (Greece): a) apparent electrical  
496 conductivity, b) apparent magnetic susceptibility for 5010 Hz, c) apparent magnetic

497 susceptibility for 13370 Hz, d) apparent magnetic viscosity for 5010 Hz, e) apparent magnetic  
498 viscosity for 13370 Hz.

499

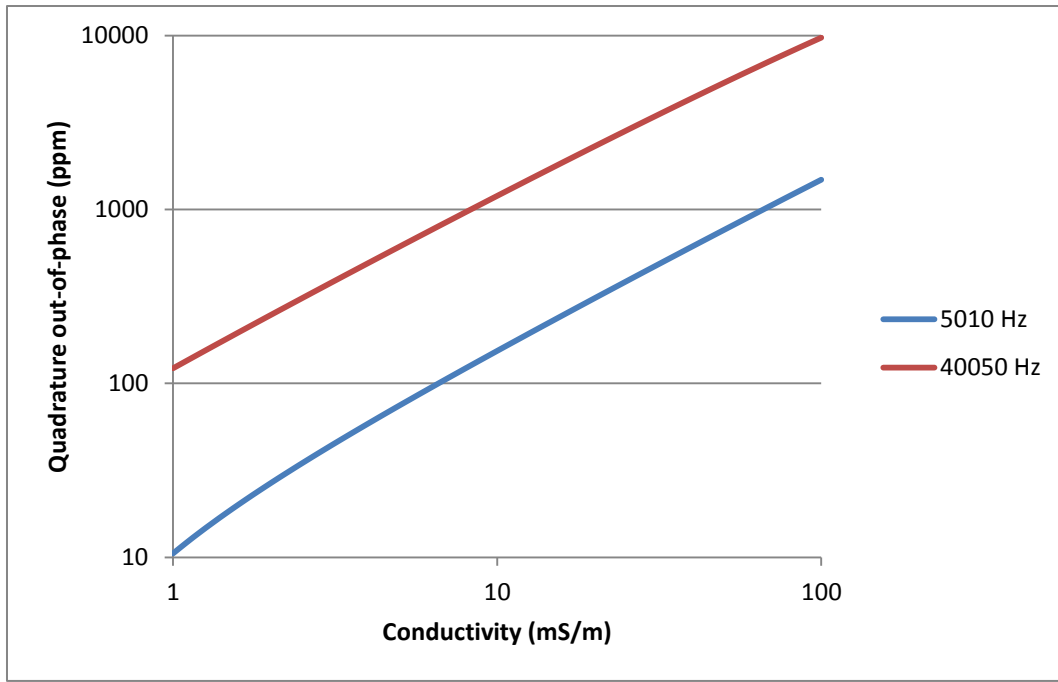


Fig. 1

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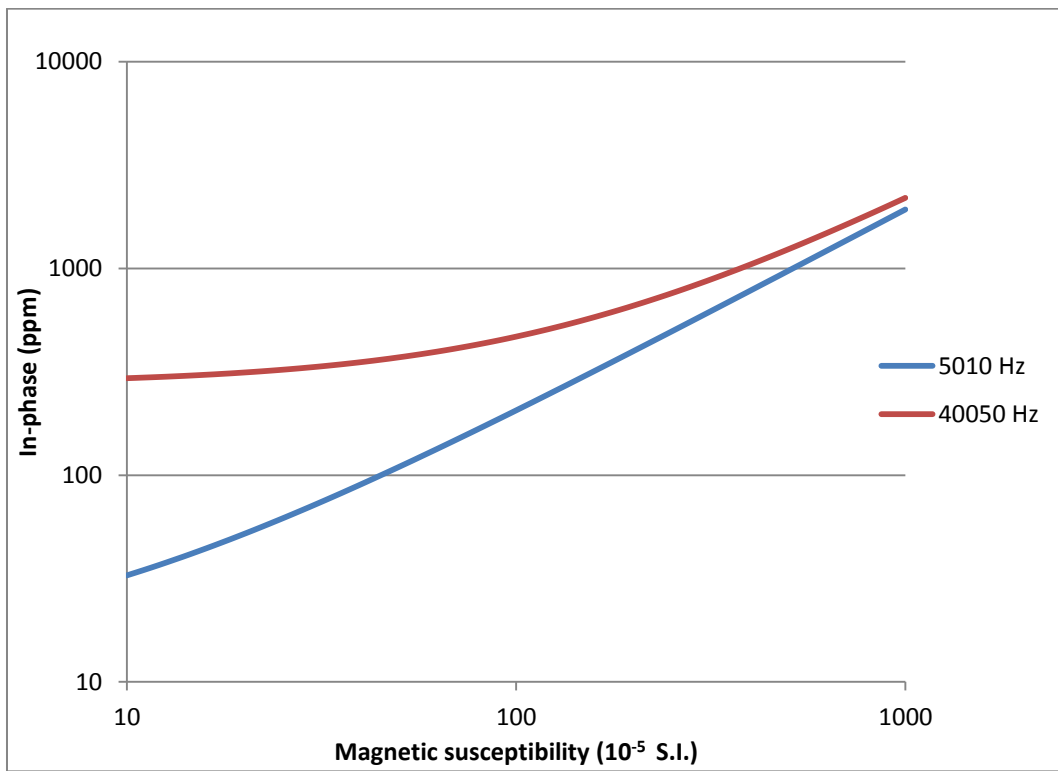
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Fig. 2a



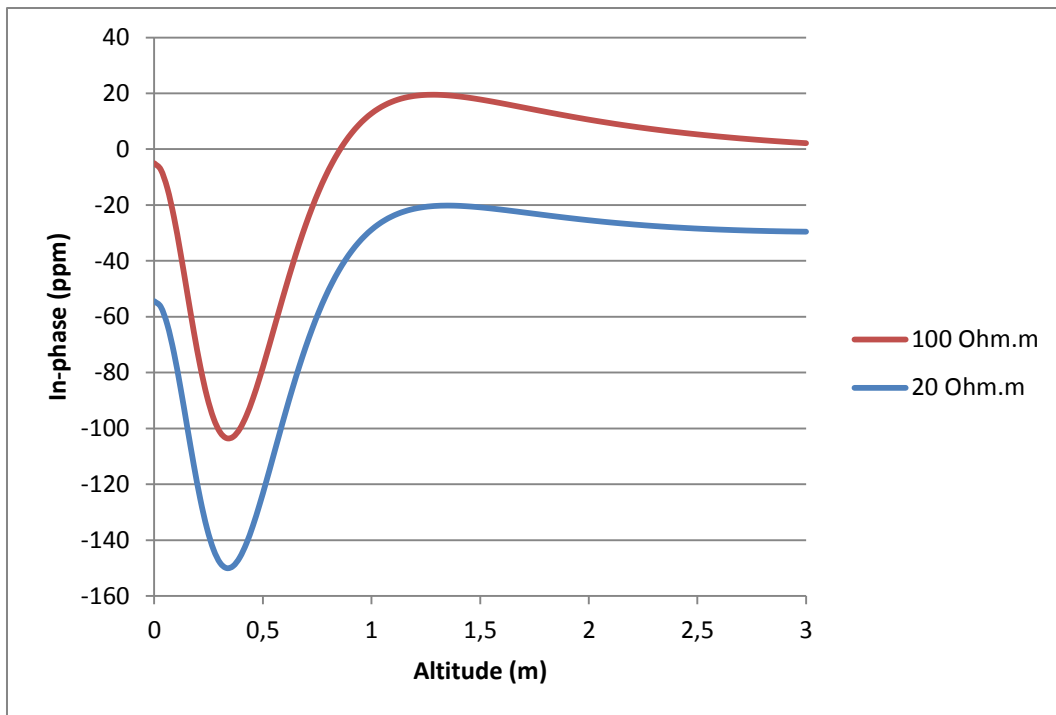
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Fig. 2b

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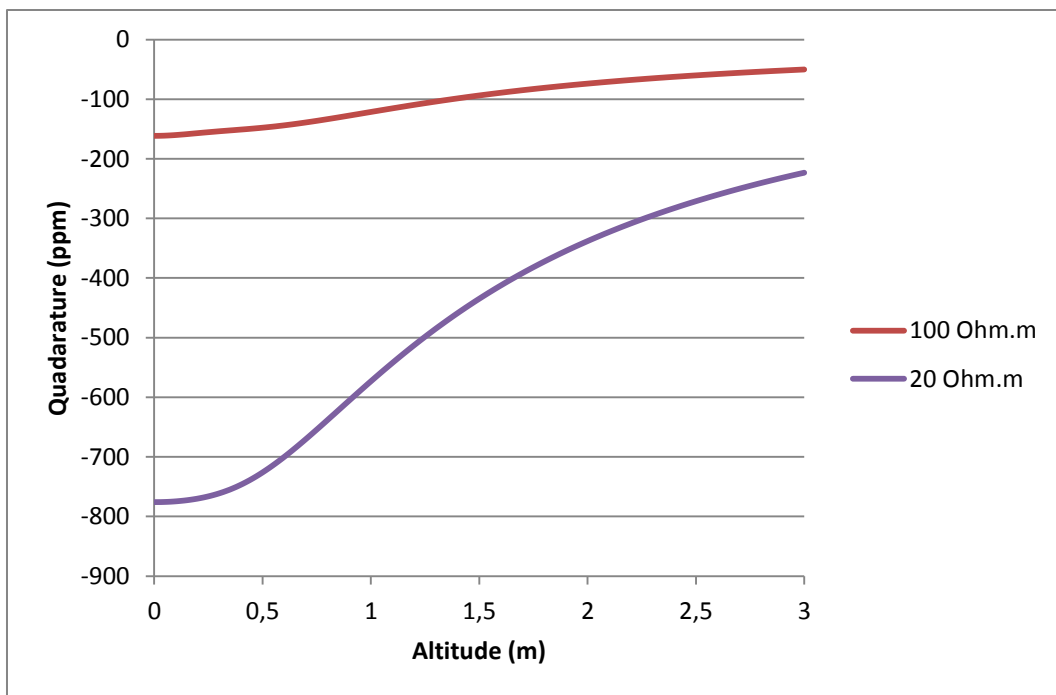




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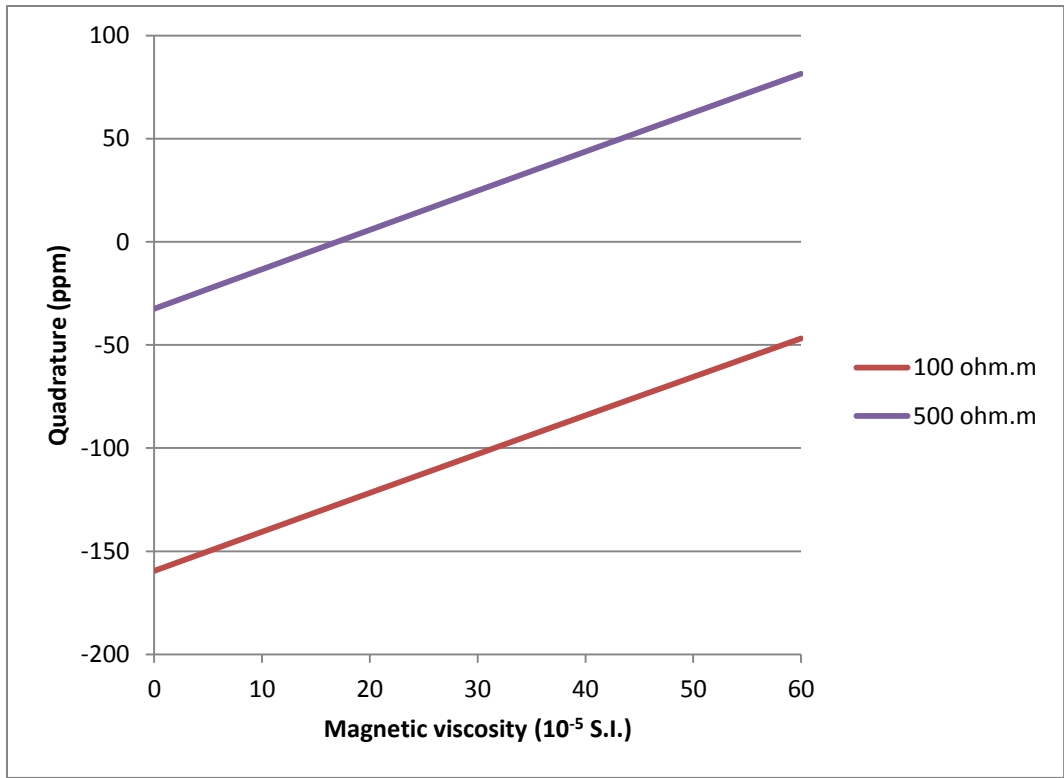
Fig. 3a

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509

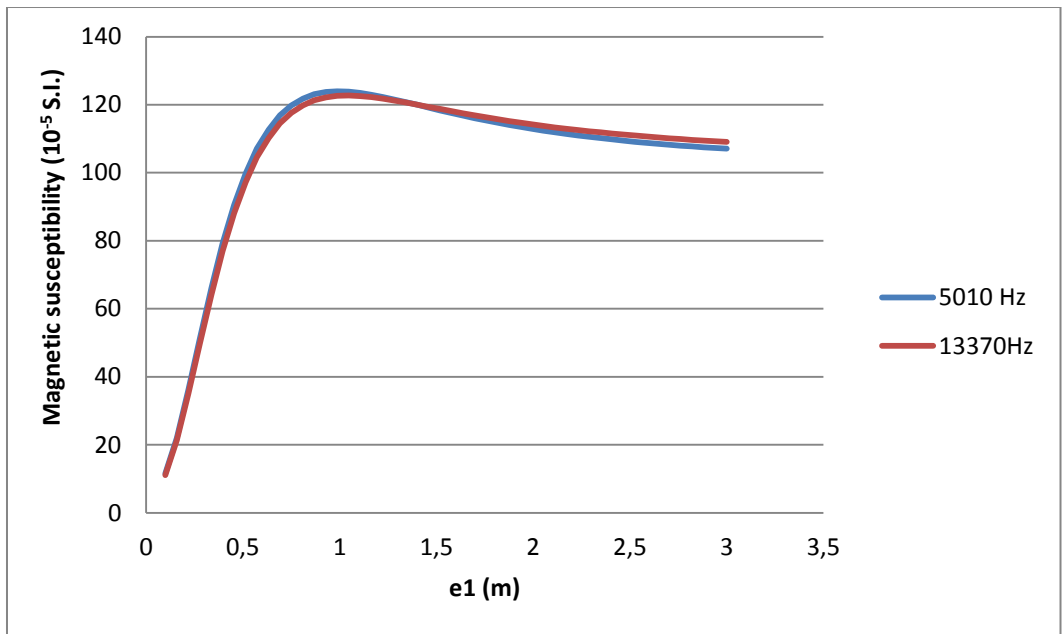
Fig. 3b



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Fig. 4

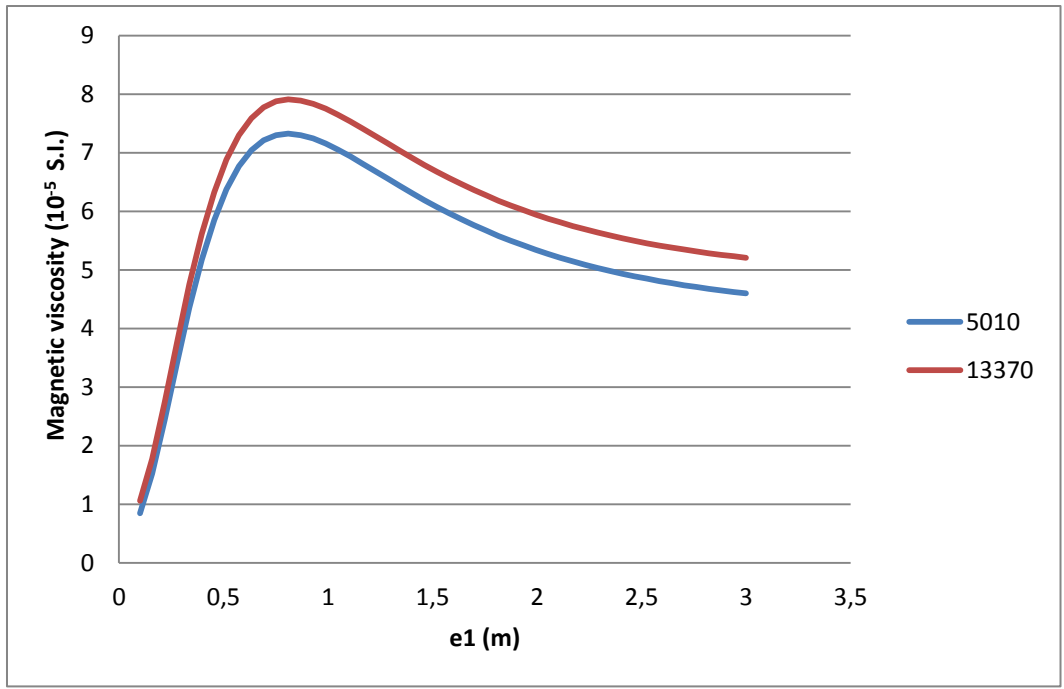
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Fig. 5a

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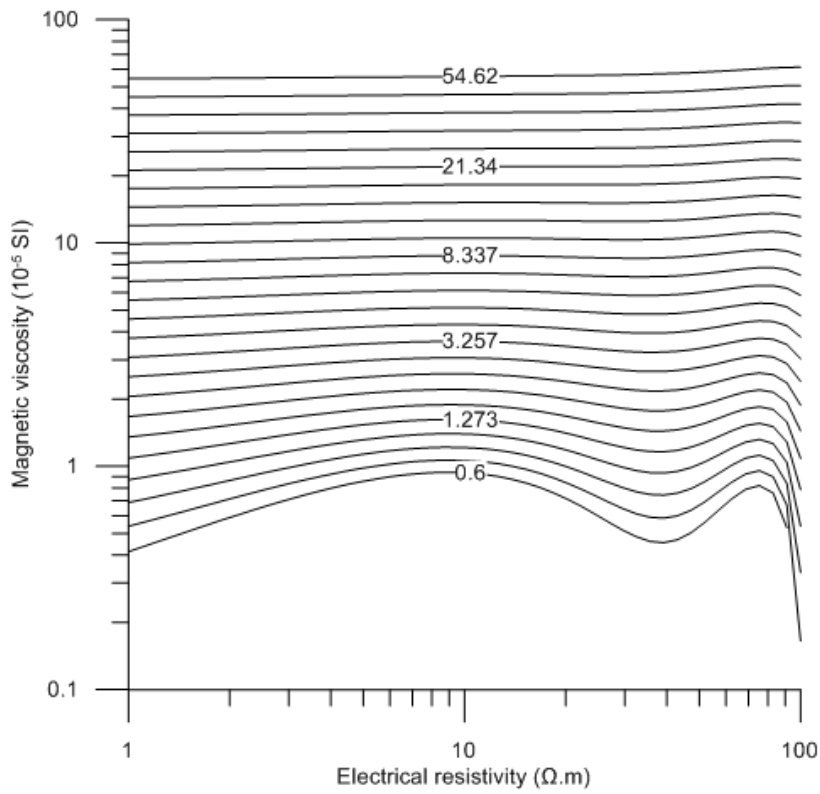
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Fig. 5b

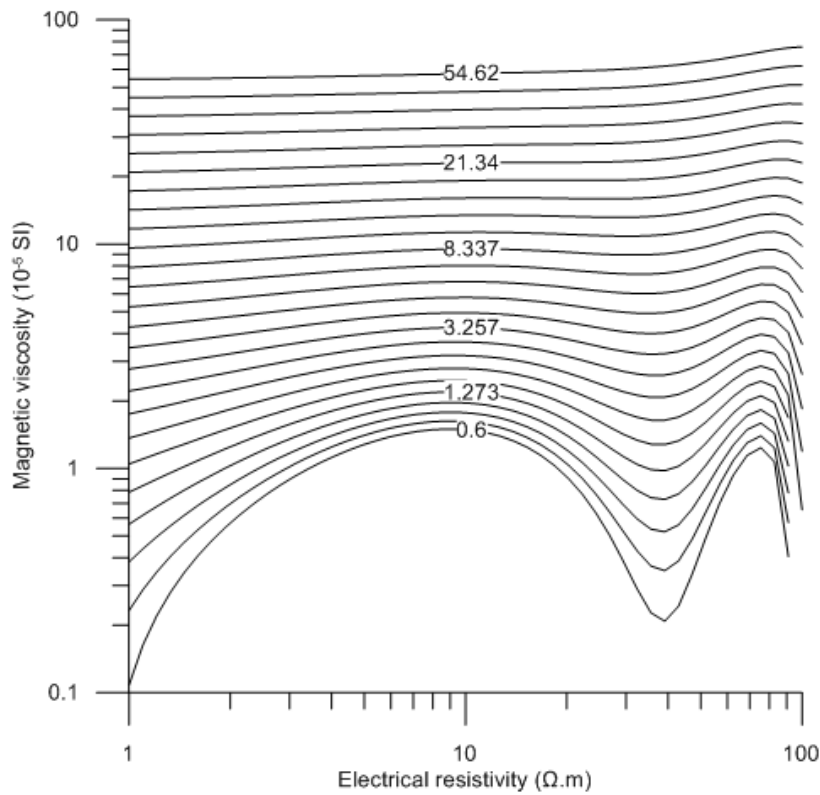
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a. Value of the apparent magnetic viscosity obtained with the proposed procedure as function of electrical conductivity and magnetic viscosity  $f=5010$  Hz



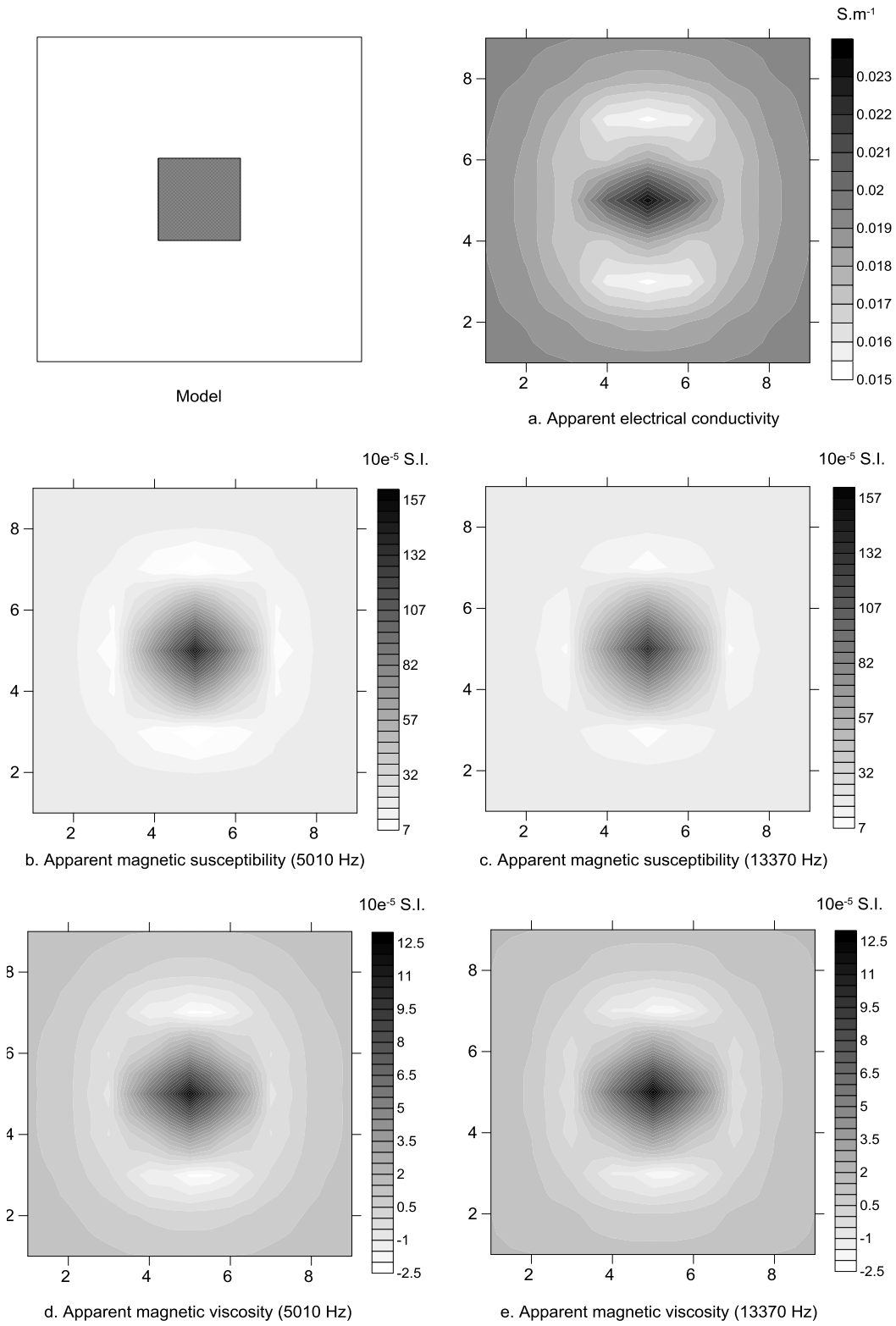
b. Value of the apparent magnetic viscosity obtained with the proposed procedure as function of electrical conductivity and magnetic viscosity at  $f=13370$  Hz

518

519 Fig. 6

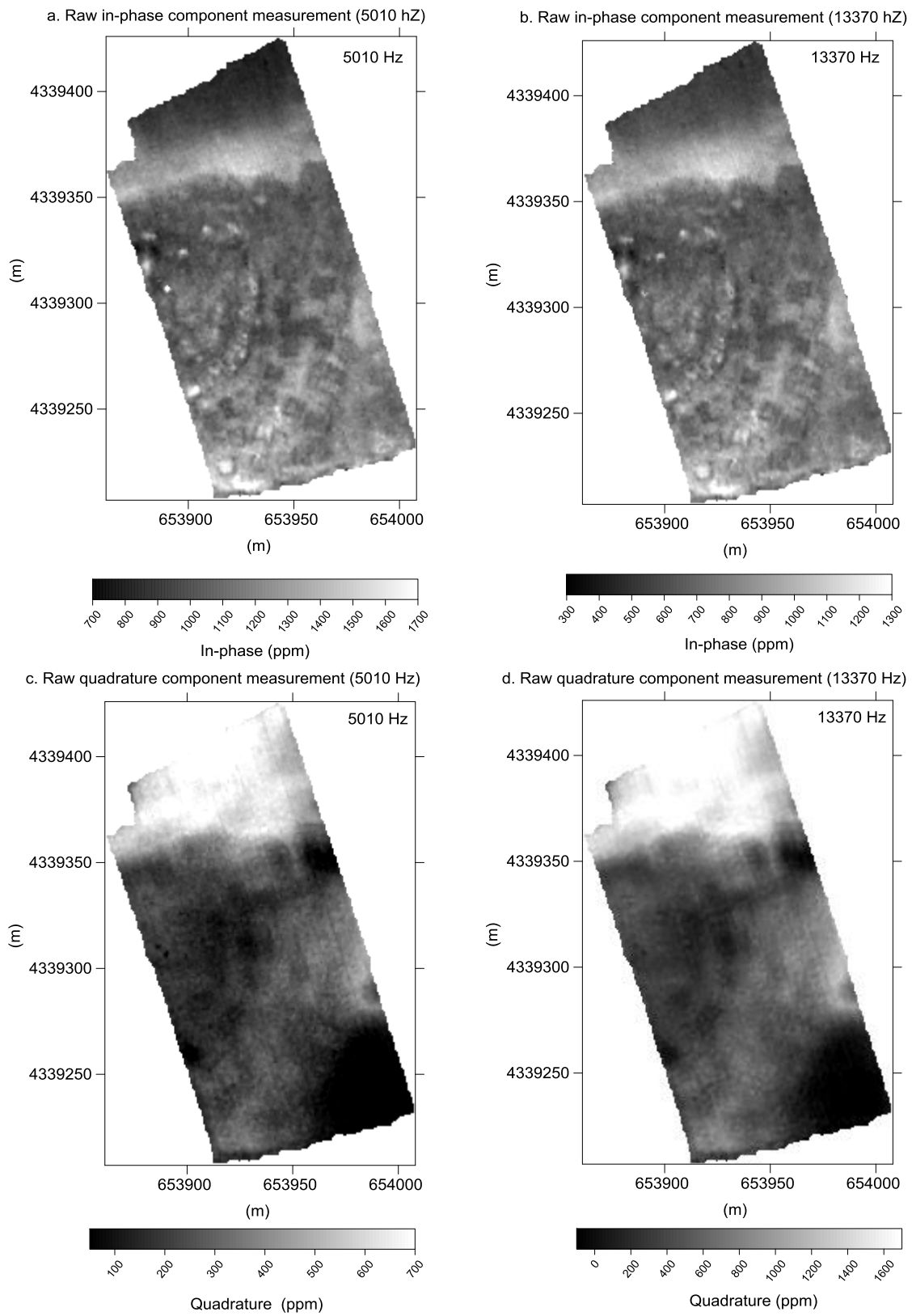
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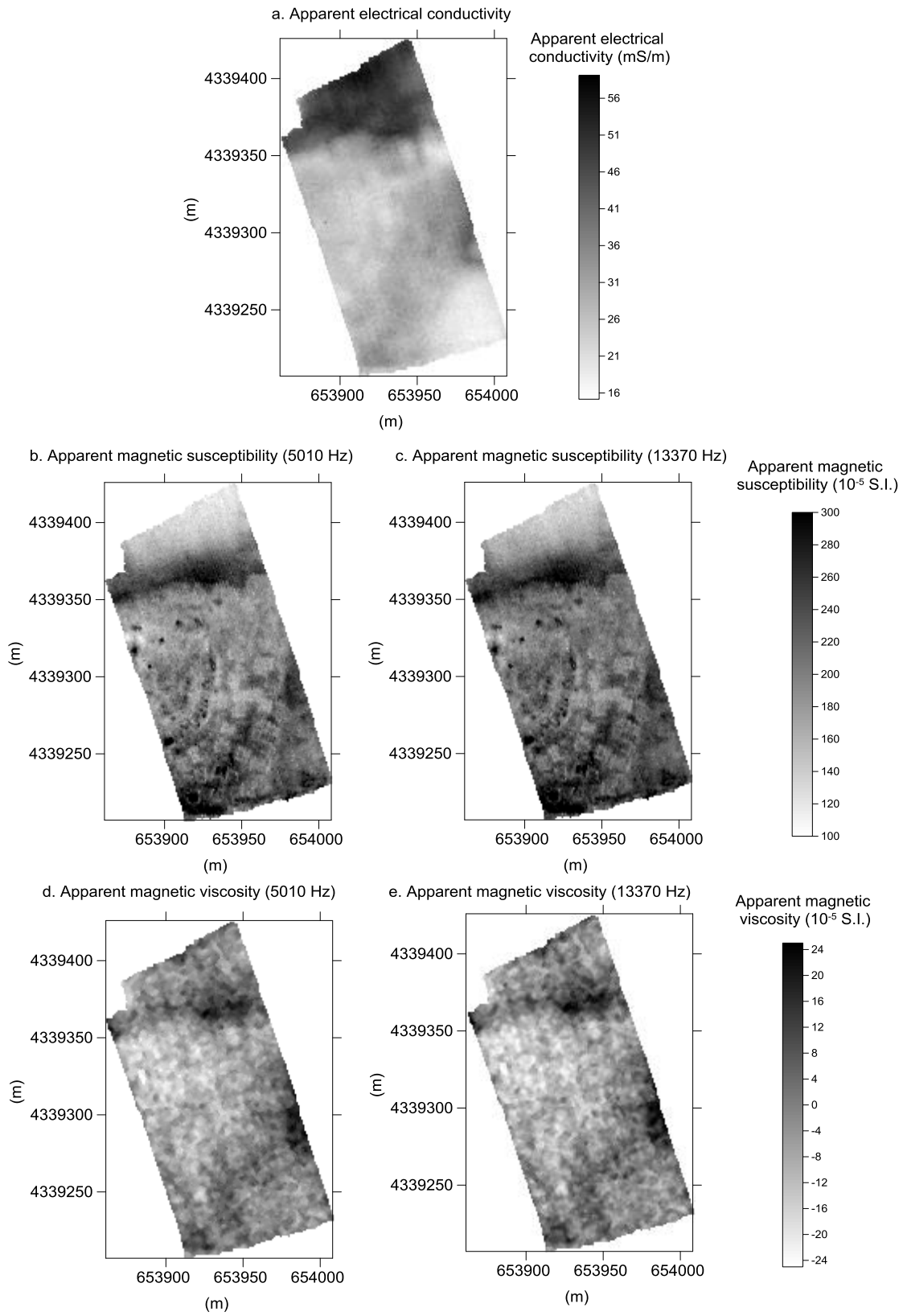
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523 Figure 7



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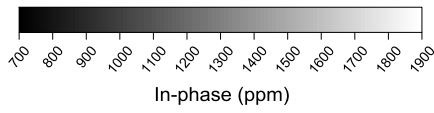
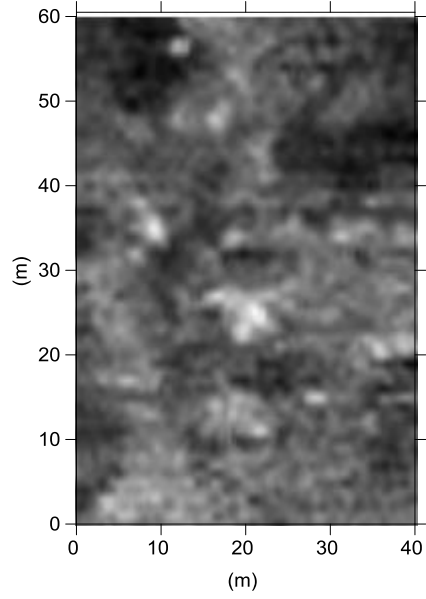
525 Fig. 8



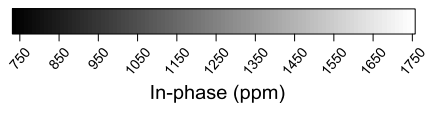
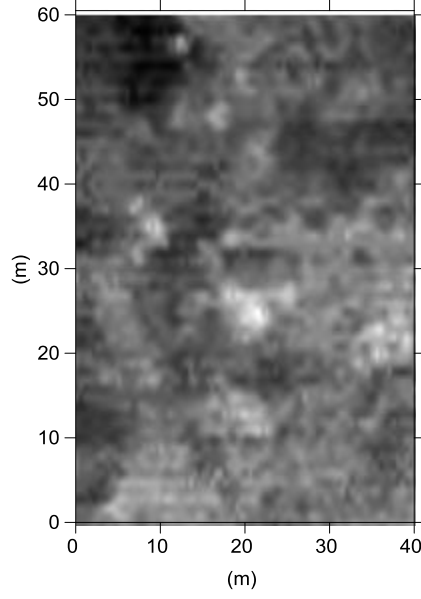
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527 Fig. 9

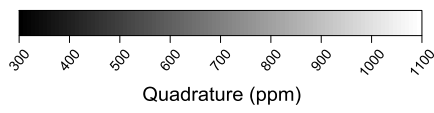
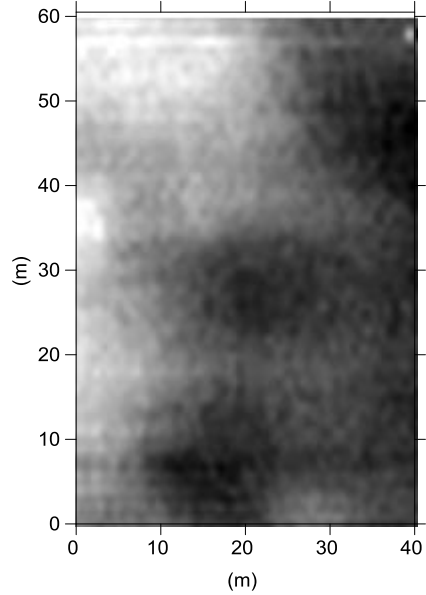
a. Raw in-phase component measurement (5010 hZ)



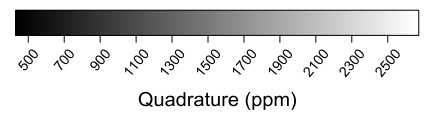
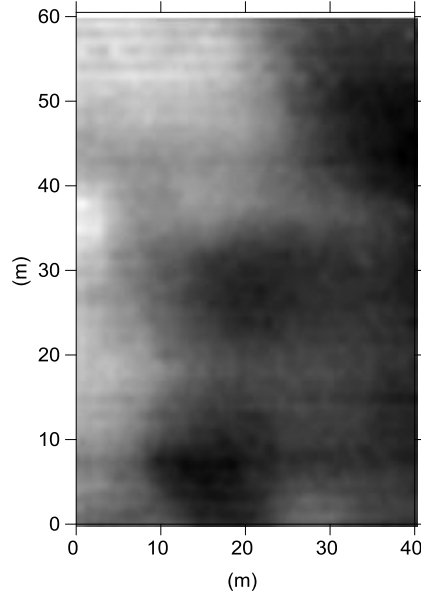
b. Raw in-phase component measurement (13370 hZ)



c. Raw quadrature component measurement (5010 hZ)



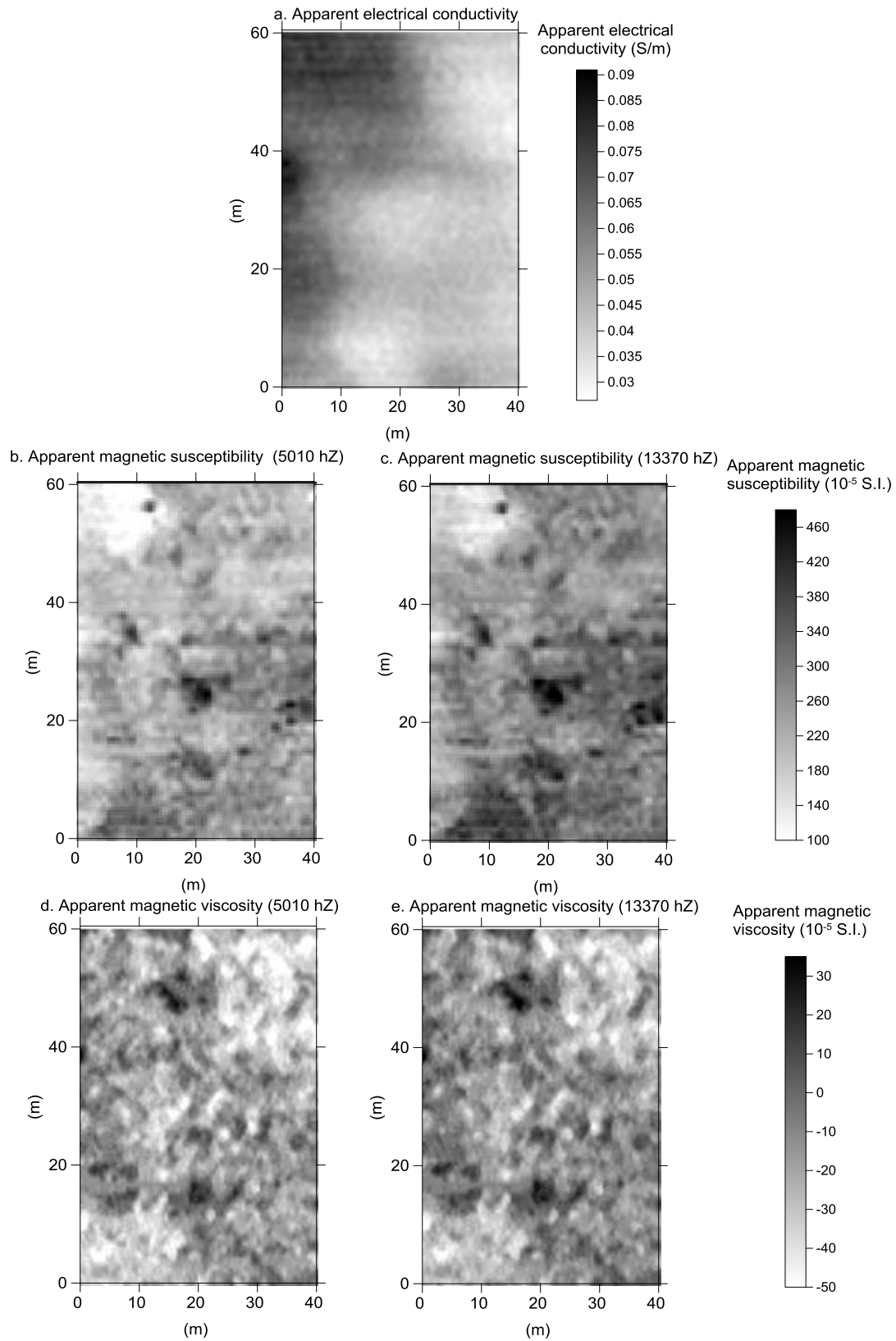
d. Raw quadrature component measurement (13370 hZ)



528

529 Fig. 10





530

531 Fig. 11

532