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1	Demonstrating the contribution of dielectric permittivity to the in-phase EMI response
2	of soils: example of an archaeological site in Bahrain.

4 Christophe Benech¹, Pierre Lombard¹, Fayçal Rejiba², Alain Tabbagh²

¹ UMR 5133 Archéorient, Maison de l'Orient et de la Méditerranée – Université Lyon 2

6 ² Sorbonne Universités, UPMC Paris6, UMR7619, Métis, F-75252 Paris

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10 Abstract

Electromagnetic Induction, EMI, instruments (also called loop-loop, dipole-dipole or 11 Slingram) are now commonly used for archaeological prospection. They are truly light 12 instruments, which are able to measure both the apparent electrical conductivity and the 13 apparent magnetic susceptibility of the ground. During a field test on Bahrain Island, where 14 15 the soil has a high clay content and a high salt content, surprisingly high values of in-phase 16 response were obtained at all inter-coil spacings, using the CMD 'mini-explorer' (GF instrument Ltd, Brno) at 30 kHz, in both HCP and VCP configurations and the HCP and VCP 17 susceptibility variations were in total opposition. This apparent discrepancy is explained by 18 19 considering the in-phase responses to be dominated by the relative dielectric permittivity. Using the raw, in-phase, VCP and HCP data, it is possible to determine and map the apparent 20 permittivity and apparent magnetic susceptibility. For this case of slated soils with high clay 21 22 content the relative permittivity is strong, but in agreement with both experimental data at lower frequencies and theoretical models reported in the literature. 23

25 Key-words: Electromagnetic induction measurements, low induction number, relative

26 permittivity mapping of soil, magnetic susceptibility mapping of soil

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29 Introduction

The island of Bahrain, located in the Arabian/Persian Gulf on the tropic of Cancer, has 30 been occupied by humans for a long time. It is well known for its important necropolises 31 dating from the Dilmun civilization (Bronze Age) until the Hellenistic period. The burial 32 mounds are so numerous that until the 20th century, Bahrain was often referred to as 33 "Necropolis Island" with no permanent settlement. Archaeologists finally proved that a 34 brilliant and original civilization had prospered on this island, during the Dilmun period in 35 particular. This civilization played an important role as the crossroads for commercial traffic 36 37 in the Gulf (Bibby 1972, Crawford 1998, Lombard 1999), facilitating the trade of metals between Oman and Mesopotamia in particular. 38

Within the framework of the French archaeological mission, a set of geophysical tests 39 has been carried out at different sites on the island since 2011, in order to evaluate the most 40 relevant methods for various types of archaeological and environmental exploration. The site 41 of primary interest is that of Qal'at al-Bahrain, located on the island's north coast. This site is 42 a 17 ha 'tell', which was almost continuously occupied from the second half of the third 43 millennium BC until the 17th century AD. Although part of the site is now dominated by a 44 Portuguese fort built in the 16th century, excavations carried out since 1954 by a Danish team 45 from the Aarhus University led by Peter Vilhelm Glob have revealed a major settlement from 46 the Dilmun period, including a 'settlers' palace from Kassite Babylonia (15th c. B.C.), with 47 cuneiform archives (Glob 1968). The continuous stratigraphy is also a fundamental reference 48

for the history of the island, of which Qal'at al-Bahrain was a major settlement, and probably 49 the capital during the Dilmun period. 50

The soil is very clayey, and has developed over a marl weathered substratum, the 51 prevailing arid climate and proximity of the sea promoting the accumulation of salt. Due to its 52 high clay and salt contents, the ground's electrical resistivity is often lower than 10 Ω m, 53 which precludes the use of ground penetrating radars (GPR). Although very high responses to 54 conductivity-meters can also be expected (Frohlich and Lancaster 1986), there is no reason to 55 expect particularly strong magnetic properties. However, over most of the surveyed areas 56 surprisingly high results were obtained for the in-phase component of signals recorded by the 57 EMI instrument. 58

The aim of the present study is thus to develop an explanation for the in-phase EMI 59 results recorded at this site. We focus on a limited 40 x 40 m^2 surface area, surveyed at the 60 61 Qal'at al Bahrain Dilmun settlement site, where magnetic and low EMI induction number prospections were carried out, using the CMD 'mini-explorer' (Gf Instrument Ltd, Brno) in 62 both HCP (horizontal coplanar) and VCP (vertical coplanar) configurations. 63

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Constraints deduced from the magnetic survey

The surface area under consideration is part of the area surveyed in 2011, using the 66 G858 (Geometrics Ltd) total field cesium magnetometer with two sensors, the upper sensor 67 being positioned at a height of 1.03 m and the lower sensor at 0.4 m, this configuration allows 68 measurement either in vertical gradient of the magnetic field intensity mode or simply of this 69 70 intensity at each height. The inter-profile distance was 1 m and the finally restored mesh was $0.5 \times 0.5 \text{ m}^2$. Most of the archaeological remains revealed by the magnetic map appear to 71 72 belong to the late occupation of the site, probably to the medieval period (Fig. 1). In the NE corner of the map, the gradient clearly shows what can be interpreted as the continuation of 73

the Dilmun fortification. Along the southern side of the fortification, and parallel to this, one
can see a rectangular, 20 x 35 m building. A 5 m wide path is also visible, between this
building and the fortification. Although it is difficult to provide a more accurate description of
the internal organization of the building, its location and orientation suggest that it may also
belong to the Dilmun period.

On this site, the inclination of the Earth's magnetic field is 40° and its modulus is approximately 43800 nT. With the exception of a small number of iron objects disseminated over the path crossing the site, the vertical gradient lies in the range between -2 and +5 nT/m. Magnetic prospecting is one of 'potential' methods, the average magnitude of the field bears no relationship to the magnetic properties of the soil and depends on the location of the survey at the earth surface; lateral variations only can reveal characteristics of the underground structure and be used for comparison with other prospection methods.

If the gradient (or the field intensity at one level) variations are converted into vertical magnetization variations of a magnetized layer (Desvignes *et al.* 1999), centered at a depth of 0.25 m and a thickness of 0.5 m, an interquartile distance of 211 10^{-5} SI is obtained for the equivalent susceptibility. This value is quite high, but also includes the viscous magnetization which, for 4000 years (Mullins 1974, Pétronille *et al.* 2010), was equivalent in magnitude to the induced magnetization. The order of magnitude of the susceptibility's interquartile distance can thus be estimated at around 100 10^{-5} SI.

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94 CMD 'mini-Explorer' results

The CMD is a multi-receiver EMI (Electro-Magnetic Induction) slingram instrument. It comprises one transmitter coil and three receiver coils, located at 0.32, 0.71 and 1.18 m from the transmitter. All the coils are coplanar, allowing the instrument to be used in either the HCP or the VCP configuration. The instrument's operating frequency is 30 kHz, and in the 99 field it can be used in a continuous recording mode by a mobile operator. At the different sites 100 in Bahrain, this mode was used with a 0.1s recording interval, with the coil centers having a 101 clearance above the ground of h=0.12 m. In the following descriptions, we consider the 102 results obtained for both VCP and HCP configurations, using the 0.71 m and 1.18 m inter-coil 103 separations only.

104 The manufacturer chose to express the Hs/Hp in-phase measurements in ppt (part per 105 thousand) with two decimals digits and with a change of sign. For the quadrature out-of-phase 106 component, the Hs/Hp ratio is multiplied by $-\frac{4}{\mu_0 \omega L^2}$ (where *L* is the inter-coil distance, ω the

angular frequency, and μ_0 the magnetic permeability in vacuum) such that in the case of 107 media having a moderate conductivity, the displayed value corresponds to the apparent 108 conductivity when h=0. To respect the standard definition of any apparent property (the 109 110 physical property of a homogeneous ground giving the same response with the same instrument configuration in the same measuring conditions), prospector must retranslate this 111 value into the quadrature of the field ratio, and then apply the general formulas (Thiesson et 112 al. 2014) which take into account the non-linearity of the conductivity response, as well as the 113 clearance above the surface, when computing the apparent conductivity at each point. The 114 four apparent conductivity maps obtained for the HCP and VCP configurations and the 115 0.71 m and 1.18 m inter-coil distances are shown in Fig. 2. These are coherent, since the 116 slight increase in resistivity between the VCP and HCP configurations, and between the 117 118 measurements obtained at separations of 0.71 m and 1.18 m, can be explained simply by a 119 decrease in conductivity as a function of depth. The variations in resistivity are clearly different to those of the magnetic properties revealed by the magnetic map. 120

In the context of highly conductive soil, part of the in-phase response is generated by its conductivity. In order to correct for this effect, one has computed, at each point of the survey, the in-phase response corresponding to the apparent conductivity determined from the

quadrature response. After subtracting this part, the remaining in-phase signal is usually 124 considered to have been generated by the soil's magnetic susceptibility (Scollar et al. 1990, 125 Farquharson et al. 2003, Bonsall et al. 2013, De Smedt et al. 2014). The response to soil's 126 susceptibility is linear and the corresponding coefficients are provided in the second column 127 of Table 1 (at frequency f=30 kHz, and height h=0.12 m). The slopes given in this table can 128 be seen to depend on the distance between the coils, and to be positive for the VCP, and 129 negative for the HCP configurations, this opposite variation has been verified by observing 130 the in-phase variation with *h* over low conductivity grounds. 131

The four maps of the in-phase ratios corrected from the conductivity responses are 132 presented in Fig. 3 with the corresponding magnetic susceptibility scales; it should be noted 133 that in the case of in-phase responses resulting from mechanical deformations (mainly thermal 134 drift) of the instrument's structure, the uncertainty remains close to the exact value of zero, 135 136 even when regular checks are carried out by raising the instrument (Thiesson et al. 2014). A totally unexpected outcome, contrary to all of the results previously acquired with this 137 138 instrument and other EMI sensors, is revealed in this figure: the variations in magnetic 139 susceptibility in the VCP and HCP configurations are in total opposition, i.e. the VCP minima correspond to HCP maxima, and vice versa. 140

141 Two complementary remarks can be made:

142 1) The global variability, expressed by the standard deviation in magnetic 143 susceptibility is greater at a coil separation of 1.18 m than at 0.71 m (47 10^{-5} SI in HCP at 1.18 m, 40 10^{-5} SI in HCP at 0.71 m, 70 10^{-5} SI in VCP at 1.18 m and 20 10^{-5} SI in VCP at 1.15 0.71 m), and this effect is more pronounced in VCP than in HCP.

146 2) These results are strongly correlated with the resistivity map.

147 How can this outcome be explained?

149 The role of the dielectric permittivity

Following a series of verifications, we came to the conclusion that the in-phase responses obtained with the CMD at Bahrain were influenced by the instrument's response to dielectric permittivity, rather than its response to magnetic susceptibility.

In general, with EM measurements, the electrical properties intervene in the Maxwell-153 Ampère equation via (in the frequency domain) a complex expression ($\sigma + i\omega\varepsilon$), in which the 154 conductivity, σ , corresponds to the macroscopic electric charge motion, whereas the 155 156 permittivity, ε , corresponds to the macroscopic electric polarization, i.e. the non-coincidence between the barycenter of positive electric charges and the barycenter of negative electric 157 charges. Although at low frequencies one can write $\sigma >> \varepsilon \omega$ (which does not mean that the 158 influence of ε is negligible when compared to that of the magnetic susceptibility), when the 159 conductivity is low the polarization is usually taken into account even in the low frequency 160 161 range (Huang and Fraser 2001, Hodges 2004).

To assess the physical meaning of the polarization response in EMI instruments on can consider the analogous of the induction number where $(\sigma+i\omega\varepsilon)$ replaces σ . It can be then deduced that the response, there approximately proportional to $i\mu_0\omega(\sigma+i\omega\varepsilon)L^2$, will increase as L^2 and the permittivity response will be in phase and proportional to ω^2 . The in-phase response will thus be 9 times more sensitive to the permittivity at 30 kHz than at 10 kHz, and 2.8 times more sensitive at an inter-coil spacing of 1.18m than at 0.71m.

Using the complete EM calculation (Thiesson *et al.* 2014), Fig. 4 shows the plots of the in-phase response as a function of magnetic susceptibility and dielectric permittivity, for VCP, HCP, and different values of coil spacing. These results were computed using the characteristics of the CMD when operated above a homogeneous ground (conductivity = 0.1 Sm⁻¹ in all cases, magnetic susceptibility κ_{ph} =50 10⁻⁵ SI in the case of variable permittivity, and relative permittivity ε_r =1000 in the case of variable susceptibility). All the responses are

linear, and the magnetic susceptibility and relative permittivity responses are strictly additive. 174 The slopes of the permittivity responses increase when the spacing is increased from 0.71m to 175 1.18m. The major result of this analysis is that, whereas all the slopes have the same sign in 176 VCP, the slopes of the permittivity and susceptibility responses are of opposite sign in HCP. 177 Thus, if the in-phase response is (incorrectly) considered to be generated by the susceptibility, 178 whereas it is in fact dominated by the permittivity, this can lead to a change in sign of the 179 computed HCP susceptibility. This gives a perfect explanation for the apparent contradiction 180 observed at the Bahrain Island site, and provides evidence of the dominant influence of the 181 soil's permittivity when compared to that of its susceptibility. 182

The slope of both properties (α for the slope of the susceptibility, and β for the slope of 183 the permittivity) are provided in Table 1. It can be seen that, although the instrument's 184 sensitivity to a change of 1 in relative permittivity is much weaker than its sensitivity to a 185 change of 1 10⁻⁵ SI in susceptibility, its permittivity response can become greater than its 186 susceptibility response when the permittivity reaches high values, i.e. 1000 or more. Are such 187 high values likely to occur in soils in this frequency range? Yes, due to the Maxwell-Wagner 188 polarization, membrane polarization and Stern layer polarization effects when the soil 189 contains a sufficiently high proportion of clay platelets and ions (Börner et al. 1993, Cosenza 190 et al. 2008, Tabbagh et al. 2009, Kessouri 2012, Kemna et al. 2012, Revil 2013, Okay et al. 191 2014, Weller et al. 2015). This is clearly the case in Bahrain. The in-phase measurements 192 must therefore be interpreted as the algebraic sum of the susceptibility and permittivity 193 responses, with the latter having a significantly greater magnitude. 194

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Determination of both susceptibility and permittivity

Is it possible to separate the responses of these two properties? Several approaches canbe considered: (i) the use of several different frequencies, since, to a first approximation, the

permittivity response is proportional to the square of the frequency, whereas that of the 199 susceptibility is comparatively independent on frequency, (ii) the use of both HCP and VCP 200 measurements, acquired at each survey point, and (iii) the comparison of responses measured 201 at different inter-coil spacings. The first solution cannot be applied with the CMD instrument, 202 since it operates at one fixed frequency, and the third solution is confronted with the very 203 complex problem of untangling the respective variations in susceptibility and permittivity as a 204 function of depth. In practice, this can be solved only through the use of a full inversion 205 206 process. However, the second approach can be applied in the present context.

As the in-phase response dependences on these parameters are linear, a solution is required for the following system of two equations:

209
$$Ph(Hs/Hp)_{VCP} = Zero_{VCP} + \alpha_{VCP}Kph + \beta_{VCP}\varepsilon_r$$

210
$$Ph(Hs/Hp)_{HCP} = Zero_{HCP} + \alpha_{HCP}Kph + \beta_{HCP}\varepsilon_{HCP}$$

As already noted above, as a consequence of the slight mechanical instability of the instrument's structure, it is difficult to accurately fix the in-phase zero offset. We thus assume that the zero is the same for both coil configurations, and has a value that minimizes the average cross-product between the HCP and VCP in-phase measurements. It is important to note that the uncertainty in this zero value does not affect the magnitude of the variations in the apparent property strengths.

The resulting susceptibility and permittivity maps are presented in Fig. 5. The computed standard deviation of the permittivity is 4850 at L=0.71 m, and 4450 at L=1.18 m. The maps can be seen to be very similar, and well correlated with the resistivity maps (Fig. 2). The computed standard deviation of the susceptibility is 25 10⁻⁵ SI at L=0.71 m and 63 10⁻⁵ SI at L=1.18 m. The variations in susceptibility can be seen to be considerably weaker in the case of the shorter coil spacing. As the instrument response is dominated by variations in the ground's permittivity, it is not surprising that the two susceptibility maps (at L=0.71 and 1.18 m) appear to be less coherent.

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226 Conclusions and perspectives

EMI measurements carried out using the CMD 'mini-Explorer' on Bahrain Island 227 must be interpreted within their specific context: a clayey soil close to the sea, in an arid 228 climate. When interpreting these data, it is important to remember that the soil's properties, 229 230 both magnetic and electrical, can affect the EM measurements. However, as the high permittivity of a salt-laden, clayey soil is also associated with a very high conductivity, the 231 prospector should be aware of the risk of the in-phase response being dominated by the soil's 232 permittivity, rather than by its magnetic susceptibility. This tendency becomes stronger when 233 234 higher frequencies or coil separations are used.

235 With EMI, as with other geophysical techniques, it is always possible to directly invert the raw data through the use of a complete inversion process, without prior transformation of 236 237 the data into apparent property maps. This step is however very important, because it can have a major influence on the entire interpretation process. In the case of EMI prospection, spatial 238 variations in permittivity correspond to variations in the soil's characteristics, such as clay 239 content, clay type, ionic force, pore size, whereas fluctuations in magnetic susceptibility are 240 indicative of variations in the oxido-reduction conditions occurring during pedogenesis, and 241 resulting from human occupation. 242

The combined use of EMI measurements, obtained with different instrumental configurations, was determinant in the interpretation of data recorded over the soil on Bahrain Island. This type of combined measurement, using different coil configurations, represents a highly interesting approach. In the future, this may allow one of the objectives of EM prospection to be achieved: the simultaneous measurement of electrical conductivity, 248 dielectric permittivity, magnetic susceptibility and magnetic viscosity, at different depths of249 investigation.

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318 **Figure captions**

- Figure 1: Qal'at al- Bahrain site, a) general view and locations of the Portuguese fort, of the
- Hellenistic fortress, of the magnetic vertical gradient map and contour of the 40 x 40 m^2 E.M.
- test area, b) detail map of the vertical gradient of the total field with proposed interpretation in
- 322 link with the Dilmun period.
- 323 Figure 2: Apparent resistivity measured with the CMD EMI Instrument at 30 kHz, in HCP
- and VCP configurations, and with 0.71 m and 1.18 m inter-coil spacings.
- 325 Figure 3: In-phase response maps after removal of the in-phase part of the conductivity
- response (CMD, 30 kHz, HCP and VCP, 0.71 m and 1.18 m) and corresponding magnetic
- 327 susceptibility scales.
- 328 Figure 4: In-phase responses versus relative permittivity and magnetic susceptibility
- 329 (calculated using *f*=30 kHz, *h*=0.12 m, σ =0.1 Sm⁻¹, ε_r =1000 for the susceptibility curves, and
- 330 $\kappa_{ph}=50 \ 10^{-5}$ SI for the permittivity curves).
- Figure 5: Apparent magnetic susceptibility and relative permittivity maps derived from HCPand VCP in-phase data.
- 333

334 Table captions

- Table 1: Coefficients of the dependences of the in-phase responses on magnetic susceptibilityand relative dielectric permittivity.
- 337
- 338



341 Fig. 1a



342

343 Fig. 1b

Qalat - al - Bahrain Apparent résistivity





Qalat - al - Bahrain In-phase respones after removal of the conductivity responses





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349 Fig. 3









Qalat - al - Bahrain

Apparent Susceptibility 0.71 m

40m

40 m

360 Table 1

CMD	$\partial Ph(Hs/Hp)$	$\partial Ph(Hs/Hp)$
h=0.12 m, f=30 kHz	$\alpha = \frac{1}{\partial \kappa_{ph}}$	$\beta = \frac{1}{\partial \varepsilon_r}$
	in ppm/E-05 SI	in ppm
L=1.18 m HCP	-4.15	0.128
L=1.18 m VCP	4.70	0.109
L=0.71 m HCP	-2.94	0.046
L=0.71 m VCP	4.25	0.035