

# The case for considering polarization in the interpretation of electrical and electromagnetic measurements in the 3 kHz to 3 MHz frequency range

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1	The case for considering polarization in the interpretation of electrical and
2	electromagnetic measurements in the 3 kHz to 3 MHz frequency range.
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#### 10 Abstract

11 Usually, in-situ electrical polarisation measurements (in geophysical prospection referred to as Induced Polarization (IP), or Spectral Induced Polarization (SIP)) have been 12 carried out at frequencies below 1 kHz. These techniques have been used mainly for mining 13 exploration, followed by a larger panel of environmental applications. However, in this ultra 14 15 and extremely low frequency domain, the duration of each individual measurement is long: 16 typically several tens of minutes for a single full SIP spectrum down to the mHz range. This 17 restriction makes it unrealistic to implement high-density measurement mapping campaigns 18 over large areas, which would otherwise be possible at higher frequencies. In the intermediate 19 frequency range [3 kHz - 3 MHz], laboratory studies of soil and rock samples have shown 20 that they can be strongly polarized notably in the presence of clays, and this property has been confirmed by several *in-situ* mapping experiments using electromagnetic induction (EMI) in 21 22 the time and frequency domains (FDEM and TDEM), as well as by the electrostatic method 23 (often named Capacitive Coupled Resistivity or CCR). The present paper recalls these results

in an effort to promote polarisation measurements at intermediate frequencies, and toemphasize the importance of measuring this phenomenon.

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27 Key words: electrical polarisation, permittivity, [3 kHz – 3 MHz] frequency range

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#### 29 **1.-Introduction**

30 For more than a century, electrical resistivity/conductivity has played a crucial role in near-surface geophysics (Jakosky 1940), for both large surface mapping and localised 31 tomographic/sounding studies based on the measurement of this property. Reference books 32 33 dealing with the electrical and electromagnetic methods themselves (Keller & Frischknecht 1966, Nabighian ed. 1988 and 1991) and describing different fields of application have 34 contributed to the development of their physical and theoretical foundations and provided 35 36 numerous practical examples (Scollar et al. 1990, Rubin & Hubbard 2005, Sharma 2008, 37 Dentith & Mudge 2015). Since the seminal work of Archie (1942), considerable research has been devoted to the analysis of several specific parameters - porosity, clay content, water 38 saturation, water mineralization, etc... - affecting the electrical resistivity (e.g. Glover 2015). 39 Various applications, ranging from mining exploration to precision farming can benefit from 40 airborne and ground surveys of this property, over large surface areas. Extensive review 41 papers can be found in the literature, as for example by Pellerin (2002) or Doolittle & Brevik 42 (2014) in the case of near-surface applications. However, as the use of induction 43 electromagnetic methods is commonly limited to electrical resistivity alone, they do not 44 provide a full description of the electrical response of near surface rocks and soils. The 45 determination of their polarisation properties can also be considered, as one cannot a priori 46 47 exclude unknown but possibly valuable information.

Polarisation phenomena were observed very early, in both surface and logging 48 measurements, and Schlumberger (1920) coined the term 'polarisation provoquée' 49 ("provoked polarisation" in English) which was later (with a possible confusion with the 50 51 electromagnetic induction) changed in English to 'induced polarisation' (IP). During the 50's the IP method was applied in time domain measurements (Bleil 1953), and encountered 52 considerable success in ground prospection campaigns applied to mining, as it was able to 53 54 reveal disseminated mineralization (mainly semiconductor sulphides, e.g. Pelton et al. (1978)). However, even in the absence of minerals, researchers became aware of the role 55 played by clay in IP, including mixtures of clay and coarser particles (Vaquier et al. 1957, 56 Okay et al. 2014). Over the last thirty years, significant developments were achieved on the 57 role of the clay and of the fluid characteristics on the IP signal in the context of groundwater 58 and environmental studies (e.g. Luo and Zhang 1998, Kemna et al. 2012, Binley et al. 2015). 59 60 Various laboratory studies and field exploration campaigns have been reported, and theoretical models have been proposed. The latter, in particular, established links between 61 62 electrical polarisation and hydraulic properties (Börner et al. 1996, Revil & Florsch 2010, Fiandaca et al. 2019). Field measurements were performed mostly in the time domain, by 63 measuring the voltage decay after cut-off, over a period ranging from one second to several 64 65 minutes. However, frequency domain measurements made it possible to gain a better understanding of the frequency dependence of IP (the spectral IP, SIP). Regular workshops 66 allowed the IP community to report on-going research, to publish in special issues, of which 67 68 the most recent were edited by Camerlynck, Chauris, Maineult and Schmutz (2015 and 2016), Fiandaca, Flores Orozco and Hördt (2017) and by Ntarlagiannis, Wu and Ustra (2019). 69

IP requires significantly long measurement periods: most frequency domain laboratory
 studies are carried out over the [1 mHz -1 kHz] frequency range, field measurements last for
 several minutes per point if such low frequencies are included. This requirement limits

complete field studies of IP to fixed point measurements, compatible with 1D soundings. 73 Current electrical resistivity tomography (ERT) acquisition devices used for IP limit the 74 practical frequency range above 1 Hz and below 100 Hz, , but as the number of periods 75 76 necessary for a good staking controls in the field the progression speed of towed instruments, such frequencies do not match with rapid motion. In order to overcome this limitation, shorter 77 measurement times and higher frequency ranges are needed. Adding higher frequencies to 78 classical IP field investigations will also give access to potential new information 79 (identification of relaxation phenomena with shorter time constant for example) and to a 80 better characterisation of known IP phenomena. 81

There also exists specific in-situ difficulties associated with galvanic IP 82 measurements: ground dependent EM coupling between cables or electrode polarisation 83 84 (Bhattacharyya and Morrison 1963, Pelton et al. 1978, Kelter et al. 2018). In the [3 kHz - 3 Hz] frequency range these specific difficulties can be overcome by using other measurement 85 86 principles: magnetic sensors (coils) (Simon et al. 2019) and capacitive poles (Grard and Tabbagh 1991). If one uses metallic electrodes (or liquid electrodes) inserted in the ground 87 one has both a capacitance and a resistance thus a phase shift and significant risk of phase 88 89 rotation if one of the two characteristics changes, while if one only uses capacitances there is no phase shift and the only difficulty is linked with the relative magnitude of the capacitance 90 91 at the poles and at the feeding wire (but the leaks are proportional to the capacitances and a model can be performed), poles are only required to present significantly higher capacities 92 than feeding wires 93

The range of permittivity and conductivity values relevant to Ground Penetrating Radars (GPR) and Time Domain Reflectometry (TDR) applications, have been well documented at frequencies above 30 MHz, and electrical polarisation is usually interpreted in terms of the orientation of polar water molecules. However, little is known between SIP and

GPR frequency ranges. At frequencies in the [3 kHz - 3 MHz] interval, which includes VLF 98 (Very Low Frequency), LF (Low Frequency) and MF (Medium Frequency) measurements, a 99 small number of field observations and tests have been carried out, using three different 100 101 techniques: Time-Domain Electromagnetics (TDEM), Frequency-Domain Electromagnetic induction (FDEM), and the electrostatic method (Capacitive Coupled Resistivity, CCR). 102 103 However, with all these techniques the measured responses are usually dominated by the 104 electrical conductivity and the polarisation part is most often neglected. Nevertheless a larger 105 number of both laboratory and field experiments are needed to evaluate the validity of this choice. An accurate evaluation the influence of electrical polarisation would permit a better 106 107 understanding of its magnitude in various field contexts.

108 At the macroscopic scale, electrical polarisation corresponds to a situation in which the 109 barycentre of the positive charges does not coincide with the barycentre of the negative charges. At the microscopic pore/grain scales, different processes with different relaxation 110 111 geometric scales and time constants limit the free displacement of electric charges. Although their detailed classification (Kemna et al. 2012) could be questioned, one can cite: electrode 112 polarisation, membrane polarisation (Marshall and Madden 1959), electrochemical 113 polarisation, interfacial polarisation/diffuse layer polarisation (Revil 2013), and Maxwell-114 Wagner polarisation (Chen and Or 2006). Depending on the frequency and temperature 115 116 ranges involved, all of these processes can contribute to the magnitude of the polarisation and can add together so that it could be difficult to single one out and a regular decrease with 117 frequency can be often observed. It must also be underlined that anisotropy in the shape of the 118 polarized volume plays a major part in the magnitude of their moment (Tabbagh et al. 2009). 119

In a first step towards the assessment of polarisation in the [3 kHz - 3 MHz] frequency
range and in view of a better interpretation of EMI or CCR surveys, the present paper

provides an overview of published experimental results, at both field and laboratory scales,and in both time and frequency domains.

Part of these experimental results were collected during the course of laboratory SIP experiments, at frequencies of 10 kHz or higher. The considered published results serve as a basis to illustrate the global magnitude of polarisation and conductivity values without being able to identify the different polarisation processes. In an effort to focus this study on common rocks and soils, we do not consider measurements carried out on media containing electronic conductor/semiconductor minerals (oxides, sulphides, metallic particles or graphite).

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#### 132 **2.-How should the electrical polarisation be expressed?**

In the Maxwell-Ampère equation, the electrical polarisation is represented by thedisplacement currents. In the frequency domain this can be written:

(1),

135  $\operatorname{curl} H = (\sigma_0 + i\omega\varepsilon)E$ 

where *E* is the electric field, *H* is the magnetic field,  $\sigma_0$  is the direct current electrical conductivity,  $\omega$  is the angular frequency ( $\omega = 2 \pi f$ ),  $i = \sqrt{-1}$ , and  $\varepsilon$  is the dielectric permittivity. Although this last property describes the dielectric behaviour, in order to take the dielectric losses into account it must be considered complex quantity:  $\varepsilon = \varepsilon' - i\varepsilon''$ . Here, the imaginary term has the same phase as the motion of free carriers (direct current conductivity,  $\sigma_0$ ), from which it cannot be experimentally distinguished. The measured conductivity thus corresponds to:  $\sigma' = \sigma_0 + \omega \varepsilon''$ , which leads to the Maxwell-Ampère equation being written as:

143 
$$\operatorname{curl} H = (\sigma_0 + \omega \varepsilon'' + i\omega \varepsilon')E = (\sigma' + i\omega \varepsilon')E$$
 (2)

144 These properties can be also expressed in the form of a complex conductivity ( $\sigma'$ + 145  $i\sigma''$ ) or a complex resistivity ( $\rho' - i\rho''$ ), leading to the following correspondences:  $\sigma' = \sigma_0 +$ 146  $\omega \varepsilon''$  and  $\sigma'' = \omega \varepsilon'$ .

In several publications authors usually refer to a formula derived from the Cole-Cole(1941) model to describe polarisation phenomena (e.g. Pelton et al. 1978):

149 
$$\rho(\omega) = \rho_0 \left[ 1 - m \left( 1 - \frac{1}{1 + (i\omega\tau)^c} \right) \right] \quad (3)$$

where  $\rho_0$  is the direct current resistivity, *m* is the chargeability and *c* expresses the enlargement of the relaxation constant ( $\tau$ ) distribution. Note that Eq. (3) is an empirical representation of the polarization mechanisms occurring in geological media, but other empirical models exist, among which multiple or generalized Cole-Cole (see Ghorbani et al. 2009), or constant phase angle model (see for instance Dias (2000) for an extended model collection).

In the following text, in an effort to homogenise and clarify the representation of polarisation and in agreement with other researcher approaches (Knight and Endres (2005), Revil (2013), Loewer et al. (2017)), we regroup all the different polarization mechanisms that can contribute and we express the electrical polarisation in terms of a real effective parameter, the relative permittivity  $\varepsilon_r$ , defined by  $\varepsilon' = \varepsilon_0 \varepsilon_r$  ( $\varepsilon_0$  being the permittivity in vacuum,  $\varepsilon_0 = 8.854$  x  $10^{-12}$  Fm<sup>-1</sup>). Consequently, when considering the published results expressed by the imaginary

162 part of the conductivity we introduce 
$$\varepsilon_r = \frac{\sigma''(\omega)}{\omega \varepsilon_0}$$
, and when they are expressed by equation

163 (3) we identify  $\rho(\omega)$  with  $\frac{1}{\sigma' + i\omega\varepsilon_0\varepsilon_r}$ . In the following text this relative effective

164 permittivity is for sake of simplicity denominated permittivity, we also use the term imaginary 165 part of the permittivity for  $\epsilon^{"}/\epsilon_0$ .

167

#### 7 **3. Looking first at simple experimental cases**

As introductive illustrations of both the magnitude and the frequency dependence of the permittivity we present in Figure 1a and b the experimental results obtained in laboratory for one soil sample and one rock sample in the [100 Hz - 10 MHz] range using a capacitive cell and a vector multi-meter (PSM 1735, NumetricQ, Ltd). The cell dimensions are, Figure 1c, 19 x 160 x 160 mm<sup>3</sup>.

173 The soil is a clay loam coming from the A horizon of the 'Jardin du Roy' in Paris. This material is indeed complex, where beside mineral grains exist a lot of biological active 174 and residual elements but the presence of a soil layer is usual in geophysical surveys. It has a 175 high porosity, n=0.481 (bulk density 1.34 g.cm<sup>-3</sup>). When dried, at 105°C for 24 hours, the real 176 part of the permittivity equals 3 over the whole frequency range in agreement with the Topp 177 et al. (1980) equation. In that soil sample the drying has eliminated all the polarisation 178 179 mechanisms except the atomic polarisation of solid grains. The presented measurements have been achieved at a high volumetric water content:  $\theta$ =0.446 (quasi saturation). One can 180 observe (Figure 1a) that the imaginary part is linearly decreasing with frequency, the slope 181 corresponding to a DC conductivity of 21.6 mS.m<sup>-1</sup> thus to 46  $\Omega$ .m (thin line). The real part 182 has very high values in low frequency as it starts from 9 x  $10^5$  at 100 Hz, and reaches 4 000 at 183 184 3 kHz. Its linear decrease fits with a Jonscher's exponent of -1.45 (Jonscher 1977). Such a regularity in the decrease corresponds to a large distribution of relaxation times. Higher 185 frequency values agrees relatively well with the Topp et al. formula: for  $\theta$ =0.446,  $\varepsilon_r$ =29. The 186 187 curves corresponding to the modelling expression,

188 
$$\varepsilon_r = (9 \ 10^5 \ (\omega/\omega_0)^{-1.45} + 29 - i \ 0.0216/(\omega\varepsilon_0))$$
 (4),

are drawn by a thin continuous lines in the Figure 1a,  $\omega_0$  being the angular frequency corresponding to 100 Hz.

191 The rock sample is a Lutetian limestone extracted from the Saint Pierre Aigle quarry 192 (Aisne, France). It contains calcite, 85% in weight, sand 10% and a few percent of 193 phyllosilicates (clay). The open porosity *n* equals 0.18. The results presented in Figure 1b are 194 measured when the sample is dry,  $\theta$ =0.017, and the conductivity is too low to be measurable. 195 In addition to the high frequency permittivity behaviour, one can observe a unique relaxation 196 process which fits the following expression (thin lines in Figure 1b),

197 
$$\varepsilon(\omega) = \frac{\Delta \varepsilon}{1 + (i\omega\tau)^{c}} + \varepsilon \mathbb{C}' - i\varepsilon \mathbb{C}'' \qquad (5),$$

where  $\Delta \varepsilon = 28$ , the real part of the high frequency permittivity  $\varepsilon_h' = 4.5$ , its imaginary part equals  $\varepsilon_h'' = 0.5$ , c = 0.65 and  $\tau = 1.75 \ \mu s$ .

In this second sample, the behaviour of the permittivity is very different in amplitude and in frequency dependence from that of the moist soil, but even this dry rock sample has a real part of the permittivity staying above 30 between 100 Hz and 10 kHz, significantly higher than 4.5 at high frequencies.

204

#### 205 4.-Published effective permittivity values in laboratory

### 206 4.1 Experiments covering the [3 kHz – 3 MHz] frequency range

In order to understand in-field observations made at ground surface or by means of well logging, and to assess the different hypotheses that can be proposed to interpret the data, various laboratory studies have been carried out on both natural and synthetic samples. Unfortunately, there are more published results derived from laboratory studies than from field campaigns. Several studies have covered a wide frequency range, and the results of some are given in Table 1. It can be observed that clayey formations have permittivity values abovehundred or thousand between 10 and 100 kHz.

214 4.2 Values determined at 10 kHz by SIP experiments

SIP gave rise to a large number of laboratory studies, designed to assess the roles played by minerals, their grain size distribution, as well as their fluid nature and content. Several different models have also been tested in the context of these studies, some of which were carried out at frequencies of several tenths of a kilohertz, allowing the permittivity to be determined at 10 kHz (Table 2). Again values of permittivity above 1000 are reported for clayey formations.

221

#### 222 5.-Published in-Situ data

#### 223 5.1 Electrostatic measurements (CCR)

This method can be seen as a generalization of the DC resistivity, where the injection electrodes are replaced by an open capacitor and the voltage electrodes by another open capacitor (Grard and Tabbagh 1991, Tabbagh et al. 1993, Kuras et al. 2006). To reduce the pole impedances, the transmitted frequency(ies) must in practice be larger than or equal to 10 kHz. By adopting 100 kHz as the upper frequency limit imposed by the induction effect (Benderitter et al. 1994, Tabbagh and Panissod 2000), an adequate depth of investigation is achieved for most engineering and environmental applications.

- Table 3 summarises the ranges of resistivity and permittivity obtained following the acquisition of profile or map data series.
- 233 5.2 Electromagnetic frequency domain measurements

Is it possible to measure IP using an inductive system, which would pave the way to 234 direct and large ground and airborne applications? This old question (Hohmann et al. 1970) 235 led to a series of studies that concluded negatively, although these were carried out using 236 237 simulations and experiments limited to 1.5 kHz for transmitter coil - receiver coil instrument configurations. More recently, some in situ experiments have been performed at higher 238 frequencies, using both helicopter-borne and ground-based devices (Table 4) and the coil-coil 239 configuration gave reliable results even at medium frequencies (Kessouri et al. 2016). For 240 FDEM measurements using uniform primary fields, radio-magnetotellurics (RMT) or wave-241 tilt measurements, the influence of the electrical polarisation has been considered in theory 242 (Grossley 1981) with permittivity values as high as 200 (Sinha et al 1977) but unfortunately 243 the published experiments are limited to very high resistive areas (permafrost and/or 244 crystalline basement) where the permittivity remains below 10 (Kalscheuer et al. 2008). 245

#### 246 5.3 TDEM measurements

In principle, TDEM measurements (Nabighian and Macnae 1988) correspond to an 247 extended frequency range, and, as the cut-off time can be as short as 4 µs (Thiesson et al. 248 2007, Auken et al. 2019), the frequency range considered in the present review corresponds to 249 the early time-domain samples but IP effects can also be observed at late times. The presence 250 251 of electrical polarisation is observed as an unexpected cancellation of monotonicity in the decrease of the step and impulse responses by reference to what would be expected with the 252 same transmitter/receiver configuration when only conductivity and magnetic viscosity are 253 considered. This phenomenon has been observed since the 70's (Lee 1975), and can only be 254 explained by electrical polarisation (Weidelt 1982). In some cases, the authors were able to 255 check these observations by direct current IP measurements and/or by Cole-Cole modelling. 256

The corresponding permittivity values, listed in Table 5 below, are estimated from the following equation:  $\varepsilon_r = \frac{1}{\omega \varepsilon_0} \operatorname{Im}(\frac{1}{\rho(\omega)})$ .

259

6- General appraisal: amplitude of the polarisation response and relation with
 conductivity

An overview of the permittivity and resistivity variations is synthetized in Figure 2. Although these results do not give an exhaustive list of the experimental studies reported in the literature, they are sufficient to establish what the electrical polarisation looks like in the [3 kHz - 3 MHz] frequency range.

- 266 (1) The magnitude of the electrical polarisation expressed in  $\varepsilon_r$  can exceed 267 10 000. It is certainly higher than that observed in the range of frequencies 268 used for GPR/TDR, as summarized by the Topp et al. (1980) cubic 269 formula;
- 270 (2) It can be seen that there is consistency between laboratory (Tables 1 and 2)
  271 and field measurements (Tables 3, 4 and 5).
- 272 (3) Below approximately 300  $\Omega$ .m (above 3.3 S.m<sup>-1</sup>), the permittivity looks 273 inversely correlated with resistivity. It exhibits a high variability at least as 274 strong as that of the resistivity. Figure 2 illustrates this anti-correlation. 275 However points are not grouped along a straight or curved line, but 276 scattered. Consequently a significant part of information existing in 277 permittivity is independent on that existing in resistivity.
- (4) As expected, the existence of several relaxation mechanisms with gradually
  increasing time constants corresponds to a decrease of the polarisation with
  frequency.

281 (5) In all tabulated results, clay content and ionic strength contribute282 dominantly to polarisation.

283 Figure 3 plots the product  $\varepsilon_0 \varepsilon_r \omega$  as a function of  $\sigma$ , derived from laboratory samples. It can be seen that the samples can be divided into two distinct groups, depending on the 284 presence (higher conductivity) or absence (lower conductivity) of clay. In the first group, 285 most of the data points lay between the lines indicating a contribution of 0.1 and 0.01 of the 286 permittivity relatively to the conductivity. This shows that although conductivity dominates 287 288 the response, the permittivity responses should also be taken into account. In the second group, the permittivity responses clearly dominate the results. It is thus always necessary to 289 consider both responses. 290

Tables 1 to 5 reveal that, when the measured resistivity is high, its decrease as a function of frequency due to the presence of dielectric losses,  $\omega\epsilon$ ", is more easily observable. In cases where the dielectric losses contribution is significant, it would be useful to compare these frequency-dependent measurements with the direct current resistivity, in the field as well as in the laboratory.

#### 296 **7 Implications for field measurements**

It is clear that any processing of field data should consider the polarisation processes 297 independently from the usual conduction processes in the [3 kHz - 3 MHz] frequency range 298 where short measurement durations open the way to high density surveys. In this range the 299 300 different electrical methods can be split in in three groups: the coil – coil EMI methods, the EMI methods using distant sources, and the electrostatic method (CCR). In the first group, for 301 lower frequencies, measurement interpretation may be even more complicated by the 302 303 influence of the magnetic properties. Thus, two situations can be considered: in the first, the method is not sensitive to magnetic properties, which may intervene in the second situation. 304

306

#### 7.1 In absence of magnetic property influences

In the first situation, given that the Maxwell-Ampère equation states that the 307 conduction the displacement currents are 90 degree's out-of-phase from the conduction ones, 308 the measurement of both in-phase and out-of-phase components (by reference to the primary 309 source signal) is necessary and sufficient to determine the apparent resistivity and the 310 apparent permittivity. Recent electronics devices can easily perform the separation between 311 in-phase and out-of-phase components. The calculation of apparent properties can be done by 312 inversion (Kessouri et al. 2016), by lookup tables (Huang and Fraser 2002) or master curves. 313 314 Using an inversion procedure is of common use with the electrostatic method (Souffaché et al. 315 2010, Przyklenk et al. 2016) and with coil -coil FDEM instruments where the frequency is sufficiently high and/or the coil separation sufficiently large (Simon et al. 2019). However, in 316 317 Magnetotellurics (or Radio MT in the considered range) the influence of the permittivity modifies both the amplitude of the wave impedance and the phase lag between the electric 318 319 and magnetic fields. Consequently both amplitude and phase sounding curves are distorted 320 and a precise interpretation would be impossible in absence of a phase reference locked on the source of the primary field. 321

322

#### 7.2 In presence of magnetic property influences

For small FDEM or TDEM instruments setup, the magnetic properties may have a strong influence. For FDEM, to the best of our knowledge for ground measurements if the magnetic susceptibility do not exceed  $10^{-3}$  SI, the rule of thumb criterion (*f L*)> $10^{6}$  Hz.*m* is relevant (*L* being the separation between coils) for neglecting the magnetic susceptibility response. If not, several possibilities exist: 328 (1) in FDEM determine the magnetic susceptibility by moving the frequency at the 329 lower possible values (for example for a metric inter-coil spacing instrument use a frequency 330 around 10 kHz), where the rule of thumb criterion (f L)<3.10<sup>4</sup> Hz.m is relevant to neglect the 331 permittivity response, and in TDEM determine the magnetic viscosity by the late time 332 response.

333 (2) in FDEM set the height of the instrument in HCP (horizontal coplanar) coil 334 configuration in such way that the magnetic response is negligible as it is known that the 335 magnetic susceptibility response crosses 0 if the instrument altitude equals 0.38L (for example 336 if *L*=3.66 m the instrument can be held at a height of 1.4 m)

(3) in FDEM use both HCP and VCP (vertical coplanar) configurations because in the
HCP the permittivity in-phase response opposes the magnetic susceptibility while in the VCP
it adds (Benech et al. 2016). In all cases, instruments must be carefully calibrated (Thiesson et
al. 2014).

341 The same ideas of combining coil separation and clearance can be applied in TDEM342 (Finco 2019).

343

#### 344 8- Conclusion

We present the results of varied laboratory and field experiments conducted over different material for different objectives. A very brief review of our scope and objectives is in order here.

First, since the magnitude of the permittivity response can be significant (and in some case dominant), exploration geophysicists should not neglect  $\varepsilon \omega$  in favour of  $\sigma$ , when implementing EM inductive (both frequency and time domain) and electrostatic exploration methods. In other words, (i) even if present practices are limited to conductivity, taking into

account the permittivity will allow a better determination of the conductivity itself which is imperative when simultaneously interpreting different type of conductivity measurement techniques and (ii) there is no reason to *a priori* exclude information.

Second, the measurement and in-field mapping of permittivity may open opportunities for the exploration of a broad range of new types of geophysical information. In the considered frequency range, both conductivity and permittivity depend on the total amount of mobile ions, conductivity corresponding to free motion and permittivity to constrained motions limited by what may oppose to the ion displacements: pore size and throat configuration, disposition, shapes and types of clay platelets, etc...

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#### 513 **Figure captions**

514 Figure 1: Example of frequency variation of the permittivity of (a) a clay loam soil (A

515 horizon) sample, (b) the Saint Pierre Aigle limestone: (bold continuous line for the real part,

516 bold dashed line for the imaginary part). The corresponding models (respectively expression

- 517 (4) and (5)) are in thin continuous lines, (c) capacitive cell and PSM vector multi-meter.
- Fig 2: Relationship between the relative permittivity and the conductivity (in  $\text{Sm}^{-1}$ )/resistivity
- 519 (in  $\Omega$ .m). For the different tables (left) and for the different frequencies (right).
- Fig 3: Laboratory results: comparison between  $\varepsilon_0 \varepsilon_r \omega$  (in S m<sup>-1</sup>) and  $\sigma$  (in Sm<sup>-1</sup>) values
- 521

#### 522 **Table captions**

523 Table 1: Permittivity values in laboratory experiments covering the [3 kHz – 3 MHz] range.

524 (Notations: *a* is the side of a square cell, *e* is the thickness of disk, cylindrical or square cells

- 525 and *d* is the diameter of cylindrical or disk cell).
- 526 Table 2: Permittivity values delivered at 10 kHz by laboratory SIP experiments. (Notations: e
- 527 is the thickness of disk or cylindrical cells and *d* is the diameter of cylindrical or disk cell).
- 528 Table 3: Permittivity values obtained by *in-situ* electrostatic measurements.
- 529 Table 4: Permittivity values obtained by *in situ* frequency domain measurements.
- 530 Table 5: Permittivity values obtained by *in situ* TDEM measurements.













Reference	Sample size and	Sample characteristics	Frequency	<b>Electrical</b>	<b>Relative</b>	
	Cylindrical		10 kHz	200 O m	300	
Scott et al. 1967.	capacitance cell		100 kHz	200 S2.m	300. 80	
J.G.R., 72, 5101-	d=2.54 cm	Mancos shale (3.8%	100 KHZ	200 \$2.111	80.	
5115.	e=2.54 cm 2 electrodes	volume water content)	1 MHz	200 Ω.m	26.	
Kenyon 1984 Journal of applied Physics, 55 ,3153-3159	Coaxial cell	Whitestone calcite saturated with 1.07Ω.m NaCl solution	1 MHz	18 Ω.m	800	
	Disk-shaped	CH66-79 Berea	100 kHz	11,000 Ω.m	35.	
Knight & Nur 1987,	capacitance cell	sandstone, Sw=0.36 deionized water	1 MHz	10,000 Ω.m	18.	
Geophysics 52(2), 644-654.	d=5.1  cm e=0.5 cm	St Peter's sandstone	100 kHz	50,000 Ω.m	10.	
	2 electrodes	S <sub>w</sub> =0.36 deionized water	1 MHz	50,000 Ω.m	9.	
		102 1 1	10 kHz	27 Ω.m	5,000.	
Compatible Compa	Disk-shaped	102 shary sand brine	100 kHz	24 Ω.m	450.	
Garrouch & Sarma	capacitance cell	saturated (8%)	2 MHz	23 Ω.m	45.	
50(6) 000 017	e=3 to 10 mm	144 and - alar huing	10 kHz		15,000.	
J9(0) 909-917.	2 and 4 electrodes	144 sandy clay brine,	100 kHz	Not given	500.	
		saturated (8%)	2 MHz		100.	
		Sandy alay loom	10 kHz	70 Ω.m	900.	
		Salluy Clay Ioalli,	100 kHz	70 Ω.m	800.	
	Square	Saturated 43 70	1 MHz	70 Ω.m	400.	
Tabbagh 1994,	capacitance cell	Volcenic cand	10 kHz		50.	
Archaeometry, 36,	a=190 mm	volcanic sand,	100 kHz	Not given	25.	
159-170.	e=19 mm	saturated 45.0 %	1 MHz		15.	
	2 electrodes	Porous limestone	10 kHz		40.	
		saturated 16 5%	100 kHz	Not given	35.	
		Suturated 10.570	1 MHz		25.	
Lesme & Frye 2001,	Disk-shaped	Berea sandstone	10 kHz	80 Ω.m	200.	
J.G.R., 106-B3,	capacitance cell	acitance cell (68% quartz),	100 kHz	80 Ω.m	60.	
4079-4090	2 electrodes	saturated (0.01M NaCl)	1 MHz	<u>80 Ω.m</u>	30.	
		Avra valley sandy silt	10 kHz	<u>22 Ω.m</u>	1,200.	
Sternberg &		with clay,	100 kHz	<u>20 Ω.m</u>	260.	
Levitskaya 2001.	Coaxial cell	water content10.6%	1 MHz	<u>19 Ω.m</u>	45.	
Radio Science $36(4)$ ,		Brookhaven sandy soil, water content 9.75 %	10 kHz	180 Ω.m	25.	
/09-/19.			100 kHz	180 Ω.m	10.	
			I MHZ	180 Ω.m	9.	
	Disk-shaped	Sandy soil,	100 kHz	45 Ω.m	150.	
Oh & al. 2007, Environ Geol	capacitance cell	water content 23%	1 MHz	45 Ω.m	20.	
51, 821-833	e=2  mm	Sandy soil with 10% bentonite,	100 kHz	6 Ω.m	480.	
	2 electrodes	water content 23%	1 MHz	6 Ω.m	60.	
Wagner et al. 2011	Coaxial cell d=7 and 16 mm	Silty clay loam	10 kHz	9 Ω.m	5,000	
IEEE Geoscience & Remote Sensing		Germany)	100 kHz	8.5 Ω.m	410	
49-7,		content 0.38	1 MHz	8 Ω.m	295	
		sandy lime	10 kHz	40,000 Ω.m	60.	
Abou El-Anwar &		sandy lime-	100 kHz	17,000 Ω.m	30.	
Gomaa, 2013,	Cylindrical,		1 MHz	6,000 Ω.m	18.	
Geophys. Prospect.,	2 electrodes	sandy dolomitic	10 kHz	80,000 Ω.m	50.	
61, 630-644.		bioclastic wackestone-	100 kHz	30,000 Ω.m	23.	
		mudstone	1 MHz	8,000 Ω.m	13.	

546 Table 1

Reference	Sample size and cell	Sample characteristics	Electrical resistivity	Relative permittivity
Pärnar at al. 1002	Culindrical	KT2 Clay	1.0 m	10 KHZ
Goophys Prosp 41	d=20mm	$\frac{K12 \text{ Clay}}{F14 \text{ shally conditions} (\pi -0.01 \text{ S/m})}$	$1 \Omega_{2.111}$	1,200.
83-98	e=30mm	E14 shary sandstone ( $\sigma_{\rm w}$ = 0.001 S/m)	125 O m	210
05 70.	4 electrodes	BEN bentonite with bring $(\sigma -1 S/m)$	$123 \Omega$	210.
	1 electrodes	<b>BEN bentomite with brine</b> $(\sigma_w - 1 \text{ S/m})$	10 O m	18,000
Breede et al. 2012	Cylindrical	Sand/Clay (5%) mixture	100 <u>22.111</u>	900
Near Surface	d=8 cm	saturated	100 22.111	500.
Geophysics, 10, 479-489	e=10 cm 4 electrodes	Sand/Clay (20 %) mixture saturated	50 Ω.m	1,800.
Okay et al. 2014, Geophysics, 79(6), E353-E375.	Cylindrical d=20 cm e=10 cm	Saturated, kaolinite with 20% sand $\sigma_w=0.02 \text{ S/m}$	25 Ω.m	540.
	4 electrodes in square array	Saturated smectite with 20% sand $\sigma_w \!\!=\!\! 0.02 \; S/m$	3.3 Ω.m	1,800.
Kremer et al. 2016, Geophys. J. Inter	Cylindrical	drical Saturated silica sand		234
207, 1303 – 1312.	d=30 cm Rectangular 4	Saturated silica sand $\sigma_w = 100 \text{ mS/m}$	Not given	1,440.
	electrode array over a section	Saturated carbonated sand $\sigma_w = 15 \text{ mS/m}$	Not given	180.
		Saturated carbonated sand $\sigma_w=100 \text{ mS/m}$	Not given	1,260.
Loewer et al; Geophysical Journal	Cylindrical cell	Soil A: moist silty clay water content 0.358	12,6 Ω.m	1,000
International 210, 1360-1373	length 70 mm d=20mm	Soil B laterite water content 0.303	100 Ω.m	630
	4 electrodes array	Soil C humus water content 0.368	63 Ω.m	200
		Obersulzbacher sanstone Formation factor 34 Archie exponent 2.19	100 Ω.m	400
Revil et al. 2017, Water Ressources	Disk shaped d=7. cm	Peat (AC_0580585123), $\sigma_w=0.031S/m$	4.26 Ω.m	21,600.
Research, 53, WR020655	e=2.5 cm 4 electrodes in	Clay (CW_0580586130), $\sigma_w=0.031S/m$	7.1 Ω.m	14,400.
	Wenner array	Sandy Clay (AR_1126238AA) $\sigma_w=0.031$ S/m	5.85 Ω.m	10,800.
Revil et al. 2018 Geophysics, 83(2), E55-E74	Cylindrical 4 electrodes	Low porosity sandstone (Eocene deltaic formation) $\sigma_w=0.11 \text{ S/m}$	42 Ω.m	25.

548 Table 2

Reference	Array configuration	Soil or rock context	Frequency	Electrical resistivity range	Relative permittivity
	_				range
Grard & Tabbagh 1991, J.G.R., 96-B3, 4117-4123.	1m x 1.17m rectangular array	Quaternary alluvial sand	128 kHz	500 – 2500 Ω.m	22. – 60.
Tabbagh et al. 1993, Geophysical Prospecting, 41, 579- 597.	1m x 1.17m rectangular array	Sandy soil above rhyolite	128 kHz	1500 – 7000 Ω.m	10. – 200.
Przyklenk et al. 2016	Wenner arrays	Ice over Triassic	10 kHz	17000 Ω.m	150
Geoph. J. Int., 206 1352-1365.	a=1m, 1.5m, 2m	limestone in a tunnel	30 kHz	9000 Ω.m	80
Souffaché et al. 2016, Archaeometry, 58-5, 705-721.	0.15m x 0.27m rectangular array	Lutetian calcareous stone in monuments	31.25 kHz	100 – 30000 Ω.m	5 - 10000

551 Table 3

552

Reference	Instrument &	Soil or geological	Frequency	Electrical	Relative
	COll configuration	context		resistivity range	permittivity
		<b>a</b>	# < 1 TT	200 120 000 0	range
Huang & Fraser 2001,	Helicopter borne	Crystalline	56 kHz	300 - 120,000 Ω.m	10 - 80.
Geophysics, 66(1) 148-	Dighem HCP	basement in			
157	L=6.3 m	northern Canada			
Huang & Fraser 2002,	Helicopter borne	At the center of a	56 kHz	2,800 Ω.m	65
Geophysics, 67(3) 727-	Dighem HCP	shallow lake in			
738	L=6.3 m	Northern Canada			
Hodge, 2004, SEG	Helicopter born	Slave geological	56 kHz	2,200 – 24,000 Ω.m	3.9 - 17.2
74th (abstracts), 660-	Dighem HCP	province, northern			
663.	L=6.3 m	Canada			
Kalscheuer et al. 2008	Tensor RMT	Ävrö Island	14 – 226 kHz	Granite median	6
Geophysical J. int.,175,		(Sweden)		value50,000 Ω.m	
486-514		Granite			
Benech et al. 2016	CMD	Salted clayey soil	30 kHz	2 - 15 Ω.m	1,500 - 30,000
Near Surface	HCP and VCP	over a marl			
Geophysics 14(4) 337-	L=1.28m &	weathered			
344.	0.71m	substratum			
Simon et al. 2019 Near	GEM-2	Archaeological site	21.03 kHz	12 - 80 Ω.m	2,000 - 4,300
Surface Geophysics 17,	HCP	bordering the shore	43.35 kHz	12 - 80 Ω.m	1,500 - 4,000
27-41	L=1.66m	line, Loam	89.43 kHz	12 - 80 Ω.m	1,200 - 2,200
Simon et al. 2019 Near	GEM-2	Archaeological site	21.03 kHz	44 - 700 Ω.m	1,400 - 2,600
Surface Geophysics 17,	HCP	Loam	43.35 kHz	44 - 700 Ω.m	700 - 1300
27-41	L=1.66m		89.43 kHz	44 - 700 Ω.m	500 - 900
Kessouri et al. 2016	CE 120 prototype	Clay loam	1.56 MHz	20 - 60 Ω.m	35 - 110
Geophysics 81(1) E1-	PERP				
E16	L=1.2m				
Kessouri et al. 2016	CE 120 prototype	Sandy alluvial	1.56 MHz	650 – 10,000 Ω.m	8 - 18
Geophysics 81(1) E1-	PERP				
E16	L=1.2m				

553 Table 4

Reference	TDEM	Local Geology	Cole-Cole interpreted	٤ <sub>r</sub>	٤ <sub>r</sub>
	instrument		parameters	10 kHz	100 kHz
Walker & Kojikawasaki,	EM37	Permafrost, clay	1000 m first layer	83.	1.
1988, Geoexploration,	400m x 400m	and/or gas	$\rho_0 = 1000 \ \Omega.m, m = 0.5,$		
25, 245-254	central-loop	hydrates	$\tau = 0.00069$ s, c=1.		
Flis et al. 1989,	Early time	pelite/sandstone	layer 1 (15m thick): $\rho_0=22$	747.	48.
Geophysics, 54(4), 514-	SIROTEM 100m		$\Omega$ .m, m=0.13, $\tau$ =0.01s,		
523	x 100m coincident		c=0.25		
	loop		layer 2: $\rho_0 = 600 \Omega.m$ ,	9.	1.
			m=0.05, $\tau$ =0.01s, c=0.25		
Descloitres et al. 2000,	PROTEM 47	Caldera of Fogo	60 m first layer $\rho_0=10000$	153.	37.
J. App. Geo., 45 1-18;	100m x 100m	Volcano	$\Omega.m$ , m=0.85, $\tau$ =0.00002s,		
	Receivers at		c=0.8		
	several offsets				
Hallbauer-Zadorozhnaya	KARIER	Hydrocarbon	20 m first layer $\rho_0=15$	4,626.	47.
& Bessonov, 2002,	5m x 5m	contaminated	$\Omega$ .m, m=0.25, $\tau$ =0.00018s,		
EJEEG, 7, 239-264	coincident loop	quaternary sand	c=1.		
		above Albian			
		clay			
Antonov & Shein 2008,	100m x 100m	Clay quarry	Second layer between 4	755.	25.
Russian geology and	Coincident loop	overlain by	and 48m, $\rho_0=16 \Omega$ .m,		
geophysics, 49, 790-802		quaternary	m=0.073, τ=0.00076s,		
		alluvium	c=0.53		
Hallbauer-Zadorozhnaya	Zerotem	Marine clay	Fourth layer below 59 m	7,275.	73.
et al. 2016, J. App. Geo.,	50m x 50m central		$\rho_0=0.5 \ \Omega.m, m=0.25,$		
133, 16-24.	loop		$\tau = 0.0035$ s, c=1.		
Finco et al. 2018,	TEM-FAST	Sebkha Kelbia	2 m first layer $\rho_0=1.5 \Omega$ .m,	83,300.	926
Hydrological Processes,	25m x 25m	salted wetland	m=0.84, τ=0.01s, c=0.955		
32, 3954-3965	coincident loop				
5 Table 5					