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Multiconfiguration electromagnetic induction survey for paleochannel internal structure imaging: a case study in the alluvial plain of the river Seine, France.

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Abstract

The La Bassée floodplain area is a large groundwater reservoir controlling most of the water exchanged between local aquifers and hydrographic networks within the Seine River Basin (France). Preferential flows depend essentially on sediment fills, whose characteristics are strongly influenced by paleomeander heterogeneities. A detailed knowledge of the internal heterogeneities of such paleomeanders can thus lead to a comprehensive understanding of its long-term hydrogeological processes. A geophysical survey based on the use of electromagnetic induction was performed on a representative paleomeander, situated close to the city of Nogent-sur-Seine in France. In the present study we assess the advantages of combining several spatial offsets, together with both vertical and horizontal dipole orientations (6 apparent conductivities), thereby mapping not only the spatial distribution of the paleomeander derived from LIDAR data, but also its vertical extent and internal variability.

1 – Introduction

Dipolar source electromagnetic induction (EMI) techniques are frequently used for critical zone mapping, which can be applied to the delineation of shallow heterogeneities, thereby improving conceptual models used to explain the processes affecting a wide range of sedimentary environments. This mapping technique is very effective for environments in which the spatial structure has strongly contrasted electromagnetic (EM) properties, especially that of electrical conductivity. The clay infilling of paleochannels, and the deposition of alternate layers of fine (conductive) and coarse (resistant) material in alluvial plain systems, are examples of natural geophysical processes having contrasted EM properties.

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EMI measurements have previously been applied to the imaging of fine-grained paleomeander infilling, produced by meander neck cutoff or river avulsion, which can form permeability barriers with complex geometries (e.g. Miall, 1988; Jordan and Prior, 1992). In addition to providing detailed local information on alluvial plain heterogeneities, which can be applied to the study of aquifer-river exchanges, the estimation of the geometry of the Seine river can provide valuable insight into its paleo-hydrology, as well as physical transformations resulting from climatic fluctuations during the Late Quaternary.

EMI devices are increasingly used for a large number of near-surface geophysical applications, as a consequence of their ability to produce 2D images of the apparent electrical conductivity, σ, over a large surface. A very large body of scientific literature has been dedicated to the study and use of near-surface electromagnetic geophysics, especially in the frequency domain, as described by Everett (2012).

By design, an EMI system energizes a transmitter coil with a monochromatic oscillating current, and the oscillating magnetic field produced by this current induces an oscillating voltage response in the receiver coil. The voltage response measured in the absence of any conductive structure is used as a standard reference. However, the magnetic field oscillations are distorted by the presence of nearby conductive structures, such that the voltage signal induced in the receiver coil experiences a shift in amplitude and phase with respect to that observed in the standard reference. This shift can be conveniently represented by a complex number, comprising quadrature and in-phase (respectively, real and imaginary) components, which can be inverted and then interpreted in terms of an apparent conductivity and an apparent depth of investigation (DOI).

Although EMI systems were initially used as mapping tools, and were designed to measure the lateral variability of σ associated with a single apparent DOI, the measurements they provide are now generally interpreted to provide information as a function of depth, albeit down to relatively shallow depths only. This interpretation relies on the fact that, for a given soil model, one specific apparent DOI is defined by three device setup parameters: (1) the offset between the transmitter and receiver magnetic dipole, (2) the orientation of the dipole pair, and (3) the frequency of the transmitter current oscillations. An EMI survey during which at least one of these parameters is varied can thus be used to resolve depth-related variations of conductivity. The real (as opposed to the apparent) DOI is determined from the computed distribution of the ground's electrical properties. This distribution can be retrieved by solving an inverse problem, which is derived from a large number of applications (e.g. Tabbagh, 1986; Spies, 1989; Nabighian, 1988; Schamper et al., 2012).

The physical model used in the inversion procedure must be suitably adapted to the electromagnetic properties of the surveyed ground. In the case of a medium characterized by typical conductive properties, at a low induction number the quadrature response is interpreted in terms of the apparent ground resistivity, which to a first order approximation varies linearly with the quadrature response (McNeill, 1980). In a resistive or highly conductive environment, such as that presented in the present study, the McNeill equation is no longer valid, and EMI recordings, in particular their in-phase component, must be interpreted within the specific measurement context, taking all of the physical properties of the local environment into account (e.g. Simon et al., 2015, Benech et al., 2016).

The present study focuses on the alluvial plain of La Bassée, a zone located in the southern part of the Seine basin, 2 km to the west of Nogent-sur-Seine (France). The aim of this study is to delineate the geometry of a paleochannel (i.e. its thickness and width), using a state-of-the-art 1D inversion routine applied to EMI apparent conductivity measurements. The inverted data consists in a set of EMI measurements implemented with (1) three different offsets, for two dipole configurations: horizontal (HCP) and vertical (VCP).

Following a description of the study area, we present the technique used to calibrate the EMI measurements, which relies on reference ERI (Electrical Resistivity Imaging) measurements and an auger sounding profile. The EMI inversion is then constrained to limit the solution space to images that are consistent with the observations provided by the ERI and auger soundings. To this end, a local three-layer model is derived with fixed conductivities, and is then introduced into the inversion routine for each position of the surveyed area. The thicknesses of the soil and conductive filling, corresponding to the presumed paleochannel, are determined through the use of an inversion algorithm.

2- Description of the study area

The study site is located within a portion of the Seine river alluvial plain (locally named “La Bassée”), approximately one hundred kilometers upstream of Paris (France), between the confluence of the Seine and Aube rivers to the North-East, and the confluence of the Seine and Yonne rivers to the South-West (Figure 1). This 60 kilometer-long, 4 kilometer-wide alluvial plain constitutes a heterogeneous sedimentary environment, resulting from the development of the Seine River during the Middle and Late Quaternary. It is important to fully characterize a river’s alluvial plain geometry, in order to understand the fluvial system’s response to climatic fluctuations. More practical issues related to water resource management require an accurate understanding of the exchanges that took place between the regional aquifer and the superficial hydrosystem (Flipo et al. 2014).

Cartographic studies of this area have been carried out in the past, using geomorphological and sedimentological techniques (Mégnien, 1965; Caillol et al., 1977; Mordant, 1992; Berger et al., 1995; Deleplancque, 2016), thus allowing the broad-scale distribution and chronology of the location of the main Middle and Late Quaternary alluvial sheets to be estimated.

In addition, the French Geological Survey (BRGM) has compiled a database of more than 500 soundings, which are uniformly distributed over the Bassée alluvial plain, and most of which reached the cretaceous chalky substrate. A detailed analysis and interpretation of this database has allowed the substratum morphology to be reconstructed, the alluvial infilling thickness to be evaluated, and a preliminary quantitative analysis of the sedimentary facies distribution to be determined (Deleplancque, 2016). The maximum thickness of the alluvial infilling is thus known to lie between 6 and 8 m.

Geophysical investigations of gravel pits (after removal of the conductive topsoil) were carried out using ground-penetrating radar (Deleplancque, 2016), and have contributed to the characterization of the sedimentary contrast of the sand bar architecture, between the Weichselian and Holocene deposits. The Weichselian deposits are typical of braided fluvial systems, with fluvial bars of moderate extent (< 50 m) truncated by large erosional surfaces. The thickness of the preserved braid-bars rarely exceeds 1.5 m. The Holocene architecture is associated mainly with single-channel meandering fluvial systems, characterized by thick point-bar deposits (> 4 m) with a lateral extent of several hundred meters, sometimes interrupted by clayey paleochannel infillings. Traces of small sinuous channels, probably using the paths of former Weichseilian braided channels, are also identified at the edge of the alluvial plain.

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Aerial photography and a LIDAR topographic survey (Figure 2) have been used to characterize the paleochannel plan-view morphologies (style, width, meander wavelength), of the most recent (Holocene) meandering alluvial sheets in this area (Deleplancque, 2016). These measurements were complemented by auger soundings and ^{14}C dating of organic debris or bulk sediment (peat), in order to determine a time-frame for the development of the Seine meanders, to allow this changes to be compared with other regional studies (e.g. Antoine et al. 2003; Pastre et al., 2003). The paleochannel investigated in this study is located 2 km to the South-West of Nogent-sur-Seine, and is characterized by larger dimensions than the present-day Seine river. Its width is estimated to lie between 150 and 200 m, with a meander wavelength between 2 and 3 km. According to the alluvial sheet analysis and the dating of organic material in the mud-plug of the abandoned meander, it is very likely that this paleochannel was active between the Late Glacial and Preboreal periods.

The main objective of the present study is to refine the lateral extent, and to determine the depth of this paleochannel. The use of geophysical exploration for this investigation is of significant importance, since it should pave the way towards paleo-hydrological reconstruction of the Seine river (estimation of its cross-sectional geometry and paleo-discharge).

3 - Methodology

3.1 Measurement setup

The survey coordinates were determined through the use of a LIDAR map, combined with the analysis of a series of auger soundings made along a reference transect almost 400 m in length (Figure 2, Figure 3). The lateral extent of the meander was delineated using an electromagnetic induction system (CMD explorer) produced by GF instruments s.r.o., with non-regular gridding and non-perfect overlapping inside the same area.

The identification of Holocene clay infilling along this reference profile was confirmed by measuring several electrical resistivity profiles (ERI), along the reference transect. For this, a Wenner-Schlumberger array was selected, with 48 electrodes positioned at a 1 m spacing for the first 340 m, and a 0.5 m spacing thereafter.

ElectroMagnetic Induction (EMI) surveys were carried out using a CMD explorer (GF instruments), with vertical (Horizontal CoPlanar - HCP) and horizontal (Vertical CoPlanar - VCP) magnetic dipole configurations. The CMD explorer operates at 10 kHz, and allows simultaneous measurements to be made with three pairs of Tx-Rx coils, using a single orientation (T-mode). Three different offsets were used between the centers of the Tx and the Rx coils, namely: 1.48 m, 2.82 m and 4.49 m, each corresponding to a distinct DOI. As the VCP and HCP surveys were made separately, slightly different sampling intervals were used. In addition, GPS reception difficulties led to several gaps in the VCP and HCP surveys. It was thus important to carefully evaluate these shortcomings, before attempting to merge the HCP and VCP measurements during the inversion. As the CMD allows the user to export raw out-of-phase data (including the factory calibration only), no pre-processing is needed to obtain the value of the ratio between the secondary and primary magnetic field amplitude.

3.2 Auger sounding results

A total of 13 hand auger soundings down to a maximum depth of 2.4 m (Figure 4), were made along the reference profile. Some of these soundings did not reach the base of the paleomeander mud-plug (clay / gravel transition), suggesting that the maximum depth of the paleomeander is greater than 2.4 m. The auger soundings revealed the presence of two main units. The uppermost unit is comprised of topsoil, which overlies a layer of loam containing a significant proportion of gravel and sand in the eastern part of the reference profile portion of the paleochannel. A clayey layer, the bottom of which was not reached in the deepest portion of the paleochannel, is situated below this unit. In some soundings, the clayey facies contains layers of peat (PTA, 04, 05, 08, and 09, in Figure 4).

3.3 ERI results

The ERI cross-section (Figure 5) is produced using a dataset of more than 5000 measurements. In order to estimate the true resistivity distribution, the resulting apparent resistivity sections were processed by means of inverse numerical modeling, using the Res2dinv software (Loke et al., 2003) with its default damping parameters, and the robust (L1-norm) method. Following a total of 7 iterations, the resulting ERI profiles had an rms error of 0.48% and 0.93%, for the case of the 1 m and 0.5 m electrode spacings, respectively.

The resistivity cross-section reveals two main units: an uppermost conductive unit with a resistivity below 20 Ωm, corresponding to a clayey matrix, and a second, more resistive unit with a resistivity greater than 60 Ωm, associated with a medium/coarse-grained silty horizon. The auger soundings are always achieved by a refusal, which is most likely due to the fact that they had reached the resistive second unit. When compared to the analysis achieved using auger soundings, the electrical properties of the topsoil/loam formation appear to be merged with the clayey formation, with the exception of the western portion of the cross-section, which has significant sand and gravel content. This outcome could also be due to the finer spatial resolution of the ERI measurements (electrode spacing of 0.5 m).

3.4 EMI calibration from ERI

Apparent electrical conductivities measured using EMI are particularly sensitive to the orientation of the device, the height above the ground at which the EMI system is installed during the survey, and the 3D variability of the conductivity. In addition, for the interpretation of the measurements, the ground is assumed to be horizontally layered at any given location, even for the smallest dipole offset. Although the orientation (vertical or horizontal) and height of the dipole are initialized at the beginning of each survey, the noise associated with the measurements is related to the near surface variability and in a certain way to variations in orientation and height of the EMI device during acquisitions.

In order to improve absolute (not relative) evaluation of EMI data, in situ calibration of EMI data is important. Ideally, calibration must be performed for several heights and over a perfectly known half space which electromagnetic properties spanned over a representative range of conductivity values. For the CMD instrument, calibration factors are provided by the manufacturer for 0 (laid on ground) and 1 m heights. However those factors are valid for a given conductivity range and are dependent on the prospection height (which is never exactly 1 m). This height effect, as mentioned above, has a relative stronger influence on the shortest offsets; consequently, to improve the absolute estimation of the apparent conductivity, it is important to have a reference zone where the ground is very well constrained. A series of hand-made auger soundings were used to obtain reliable direct observations down to a depth of 2 m. It shows that the interface between the silty clay and the gravel corresponds to the conductive filling; this was observed at some of the auger sounding locations, namely soundings numbered: 01, 02, 03, 10, 11, 12, and 13, which barely attained a depth of 2 m. In order to obtain deeper information, an ERI prospection has been carried out; the inversed ERI section provides reference and absolute values of the local resistivities and can be used in the calibration process as described in Lavoué et al. (2010). It is worth noting that other in situ ways of calibration could be performed, particularly, using the theoretical response of a metallic and non-magnetic sphere (Thiesson et al., 2014).

During the field data acquisition we faced several difficulties that prevent us to do a CMD profile exactly on the reference profile. Actually, the EMI data used for the calibration have been taken from the mapped data closest to the reference profile. This has led to several positioning and alignment errors : 1) the EMI data do not exactly cross the reference profile, 2) the EMI data are irregularly spaced along the ERI profile, and 3) the orientation of the CMD device was not exactly the same, for each measurement retained for the calibration.

In order to compute the apparent conductivity of a layered ground, based on measurements made using a horizontal or vertical magnetic dipole configuration, we used the well-known electromagnetic analytical solution for cylindrical model symmetry, given by (Wannamaker et al., 1984; Ward and Hohmann, 1988; Xiong, 1989). However, in the case of thin layers or high frequency content, convergence problems can be encountered in the numerical integration of the corresponding oscillating Bessel functions. At frequencies below 100 kHz, as in the case of the present study, the numerical filters developed by Guptarsarma and Singh (1997) were found to provide an efficient solution to this problem. The inversion scheme developed in Schamper et al. (2012) was used to invert the EMI measurements. For each offset and dipole orientation, a linear relationship (shifting and scaling) is determined between each measured apparent conductivity and the apparent conductivity estimated from the resistivity models (derived from the ERI panel, Figure 6). Once the calibration done, the new EMI inversion matches the ERI used for the calibration which illustrates the validity of the procedure. Actually, despite the linear relationship assessed between the EMI and ERI resistivities, several non-linear operations are applied: (1) ERI local 1D models along the profile are used to simulate EMI measurements, (2) EMI field data are then fitted (linearly) to those simulations using a non-linear optimization procedure to estimate calibration factors, (3) finally the calibrated/shifted data are inverted with a non-linear forward modeling. All those non-straightforward steps imply that a check is necessary to ensure that the calibration process has been correctly applied. Step (3) does not guarantee that estimated interfaces will match the ERT interfaces 1) if the fixed/chosen resistivities are not correct, or 2) if EMI does not integrate the ground in the same way as the ERI in case of strong anisotropy, which seems not to be the case here, since a good match is obtained.

The correlation coefficients are comprised between 0.5 and 0.7. Such values can be explained by several sources of errors in the estimation of the EMI apparent conductivities along the reference profile: 1) the differences in the location between the EMI measurements used for the calibration and the ERI profile, 2) the fact that the one dimensional model used for the EMI modeling is extracted from the inversed 2D resistivity section, 3) the difference of sensitivity between the ERI and EMI data. The regressions indicate the need of a stronger correction for the VCP configuration than for the HCP configuration. The scaling correction decreases as a function of offset, particularly for the HCP, which can be explained by the fact that small offsets are more sensitive to positioning and orientation errors, as well as natural near-surface variabilities.

3.5 Inversion parameters

Once the calibration process is completed, the corrected, apparent HCP and VCP conductivities are inverted, following their interpolation (by kriging) onto the same regular grid. The ERI results indicate a two-layer model (but do not highlight the topsoil), while the auger sounding show clearly a topsoil layer of few decimeters thickness above the conductive formation. Consequently, a three-layer model seems reasonably justified all over the site during the inversion process to represent the studied area: a resistive topsoil, a conductive clayey filling, and a resistive sand/gravel layer. The resistivity of each layer corresponds to the peak values of the bimodal histograms of the reference 1-meter-spaced ERI profile, as shown in Figure 7. The topsoil conductivity derived from the half-meter-spaced ERI profile in the eastern portion is found to be very similar to the conductivity of the resistive layer inferred from the 1m-spaced ERI profile; the first and third layer conductivities are thus considered to be equal. This leads to the following model for the mean conductivity of the three layers: σ_1 = 13 mS/m; σ_2 = 72 mS/m; σ_3 = 13 mS/m. It should be noted that the CMD explorer is operated at a single frequency (10 kHz). The sounding height was taken to be 1m for all the field measurements.

Figure 8 shows the inverted thicknesses of the first and second layers, and the data residual for the HCP (3 offsets), the VCP (3 offsets), and the combined HCP and VCP conductivities (6 apparent values). The standardized root-mean-squared residual for *N* independent measurements is given by:

$$\sqrt{\frac{\sum_{i=1}^{N}\left(\frac{d\quad(i)-d_{meas}(i)}{std(i)}\right)^2}{N}}$$

Where *N* is the number of data points, *d* is the forward response of the estimated model at the end of the inversion, d_{meas} contains the data, and *std* is the stand deviation of the data.

The standard deviation *std* was estimated from repeated measurements at several locations, as 1 mS/m (with a minimum error of 5%).

4- EMI inversion results and discussion

4-1 General trend

The layer thickness inversion was performed using three different datasets: (1) the HCP dataset, (2) the VCP dataset, and (3) the combined HCP and VCP dataset (Figure 8).

Whatever the dataset used for the inversion, the thickness computed for the topsoil formation (indicated by *"Thickness 1"* in Figure 8) is very small (blue), whereas that computed for the conductive infilling (indicated by *"Thickness 2"*) has a significantly higher value (red), and *vice versa*. Although it varies in thickness, the conductive layer formation spans most of the survey area, whereas the resistive topsoil formation varies mainly in two distinct locations: (1) the south-western limit of the surveyed area, where it reaches a depth of 2 m and (2) the mid-northern portion of the surveyed area, where its thickness never exceeds 0.6 m. In addition, very small scale topsoil formations are scattered over the surveyed area. Nevertheless, all of the observed topsoil formations appear to be correlated with a local increase in data residual. The thickness of the conductive infilling lying below the topsoil formation, ranges between 0 m, in the south-western portion of the studied zone, and its maximum value of almost 2 m at the center of the map.

The VCP mode increases the measured thickness of the shallowest portions of the topsoil layer, whereas the HCP mode tends to negate this layer over most of the surveyed area (central part), where it is not extremely thick. This tendency appears to be correlated with a slight increase in the thickness of the second conductive layer.

The inversion of all data, in the form of a single dataset, appears to lead to a mixture of the properties inherent to each of the constituent datasets. This outcome is particularly noticeable in the case of the topsoil formation, where certain structures retrieved by both

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datasets are emphasized with respect to structures that are present in only one or the other of these.

4-2 Internal variability

In addition to strong meander wavelength variations, each dipole orientation reveals different level of heterogeneities in the material present in the conductive fill, as well as the topsoil. Concerning the material close to the surface (< 2 m), this variability is clearly illustrated by the auger soundings, whereas the conductive unit identified by the ERI section is considerably more complex. In simple terms, the thickness of the conductive material tends to decrease, wherever the silty and sandy material reaches the surface.

It should be noted that the inversions observed for each dipole orientation are not systematically preserved in the inversion produced by combining the data from both dipole orientations. This result indicates that in the present context, each orientation is complementary, and contributes a specific set of information. This is particularly relevant in the northern portion of the studied area, where the thickness of the first resistive layer is more variable when it is measured with the horizontal dipole configuration (VCP), than with the HCP configuration.

The data residual has numerous peaks in the south-western portion of the study zone. In this zone, the resistive topsoil reaches a thickness of 1 m, leading to EMI measurements with a lower sensitivity (and thus lower signal to noise ratio - SNR). The combined HCP&VCP data inversion naturally leads to the occurrence of higher values of data residual, than in the case of the individual HCP or VCP inversions.

5- Conclusion

We presented the results of geophysical investigations of a paleochannel in the alluvial plain of La Bassée (Seine basin, France). The location of this paleochannel and its internal variability, suggested by a LIDAR campaign, have been accurately mapped using a multi-configuration (various offsets and orientations) electromagnetic induction device (CMD explorer from GF instruments).

In order to correct the sensitivity issues arising from EMI measurements, a calibration procedure was implemented, based on the use of a linear correction with ERI inversion results and auger soundings. The shifting and scaling of EMI HCP and VCP measurements was made for the three available offsets (1.48m, 2.82m and 4.49m), at a frequency of 10 kHz. Six apparent conductivities allowed the inversion of a reliable three-layer model, comprising a conductive filling with a conductivity equal to 72 mS/m below the topsoil, and a resistive substratum having a conductivity equal to 13 mS/m. The conductivities of the three-layer model were adjusted using the bimodal histogram distribution of the reference ERI profile.

In conclusion, the inverted thicknesses are characterized by a significant internal variability in the conductive filling and the topsoil, associated with the paleochannel geometry. The joint inversion of multi-offset HCP and VCP configurations leads to a very interesting result, in which the internal variability description is considerably enhanced. We believe that multiconfiguration EMI geophysical survey carried out at an intermediate scale, should provide a great complement to TDR (Time Domain Reflectometry) for a quantitative and physical calibration of remote sensing soil properties and moisture content.

Although the generalization of combined VCP and HCP prospection could significantly improve the accuracy of hydrogeological modeling, it would also lead to a substantial increase in survey costs. This option thus remains to be debated during the 7th phase (WP 1: Sedimentary, Morphological, Hydrogeological and Thermal properties of Hydro-ecological Corridors) of the PIREN Seine research program (2015-2019).

6- Data availability

In order to access the data, we kindly ask researchers to contact the corresponding author.

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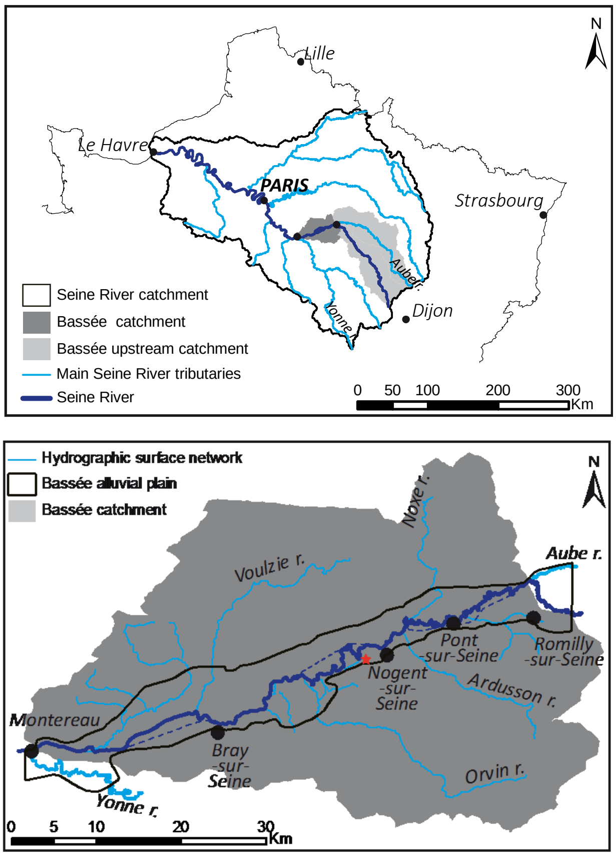
439 **Figures**



440

441 Figure 1: maps of the Seine catchment (top) and the Bassée alluvial plain.

442

443 Figure 2 : LIDAR map of the studied area, showing the contemporary location of the Seine
444 river, together with the narrow and wide paleochannel interpretations.

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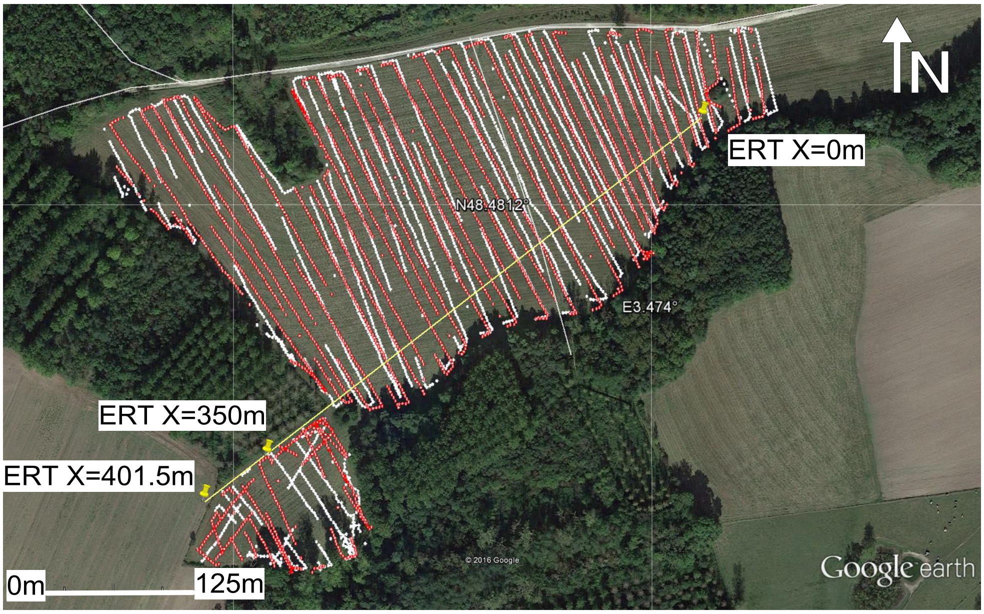

Figure 3: Map of the surveyed area, showing the loci of the VCP (red) and HCP (white) measurements. The reference (ERI) profile, recorded with a Wenner-Schlumberger configuration using 1 m electrode spacing between 0 and 350 m, and a 0.5 m electrode spacing between 350 m and 401.5 m, is indicated by the yellow line.

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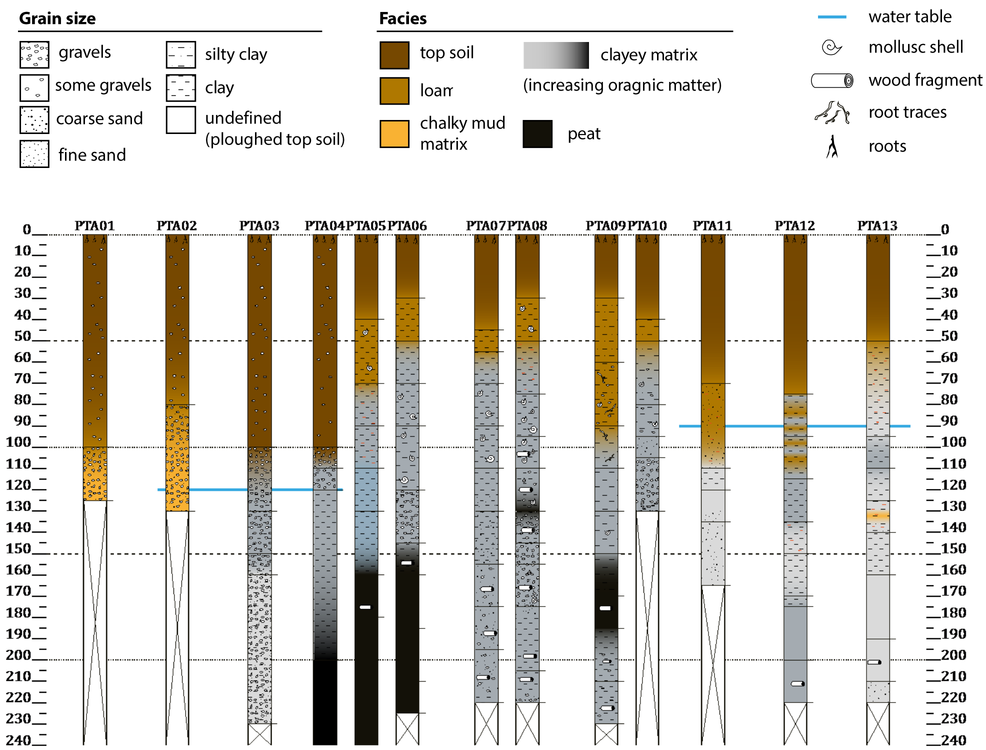

Figure 4: log of hand auger soundings performed along the reference profile. The position of each sounding along the ERI profile is shown in Figure 5.

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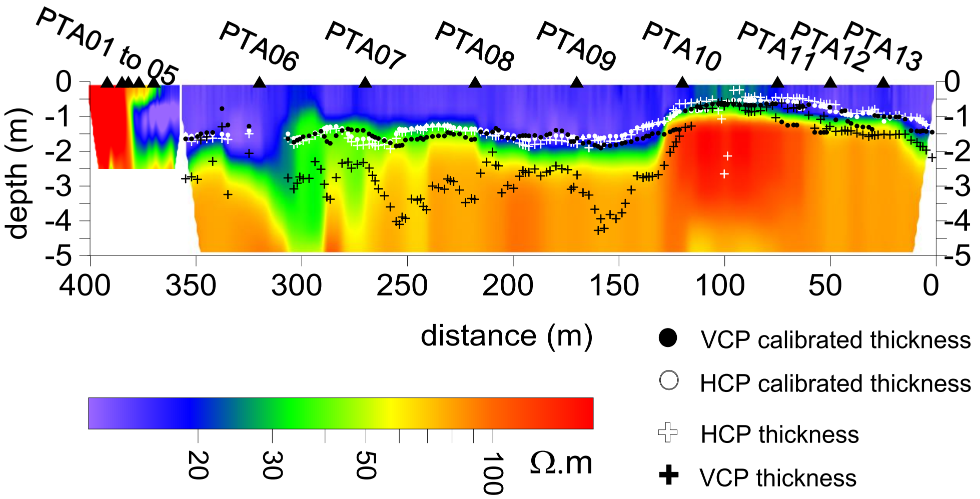

Figure 5: Results from the electrical resistivity tomography (ERI) inversion, computed along the reference profile. This map clearly reveals the two main (conductive and resistive) geological units. The markers correspond to the inverted loci of the interface between the conductive unit and the substratum, before and after linear calibration (Figure 6). This figure shows that calibration of the raw VCP measurements leads to significant corrections in inverted depth, when compared to the calibration of the HCP measurements.

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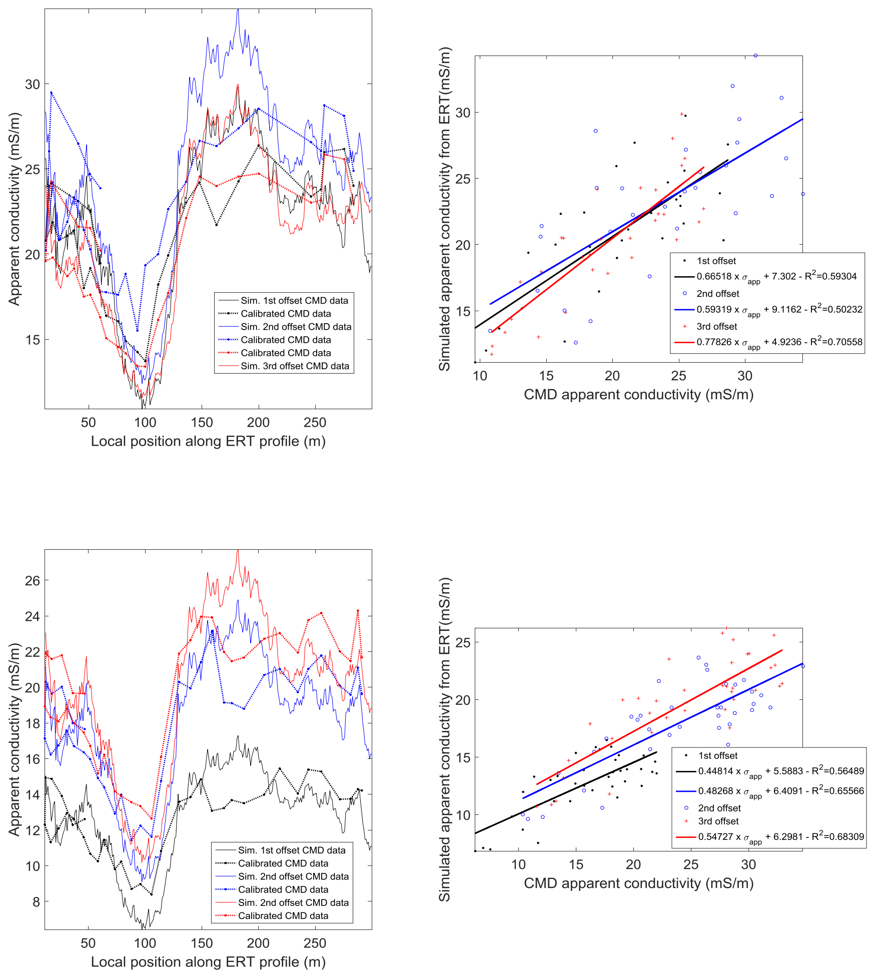

Figure 6: HCP (top) and VCP (bottom) calibration results obtained along the reference profile. Left: the simulated apparent CMD conductivities based on ERI inversion compared to the calibrated EMI measurements. Right: scatter plot of the measured *vs* simulated apparent conductivities. The solid lines indicate the corresponding linear regressions.

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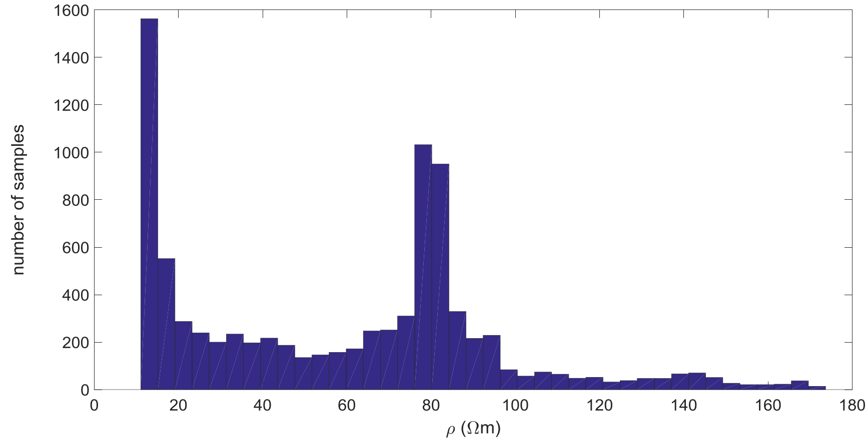

Figure 7: histogram of the electrical resistivity values determined for the tomographic cross section shown in Figure 5.

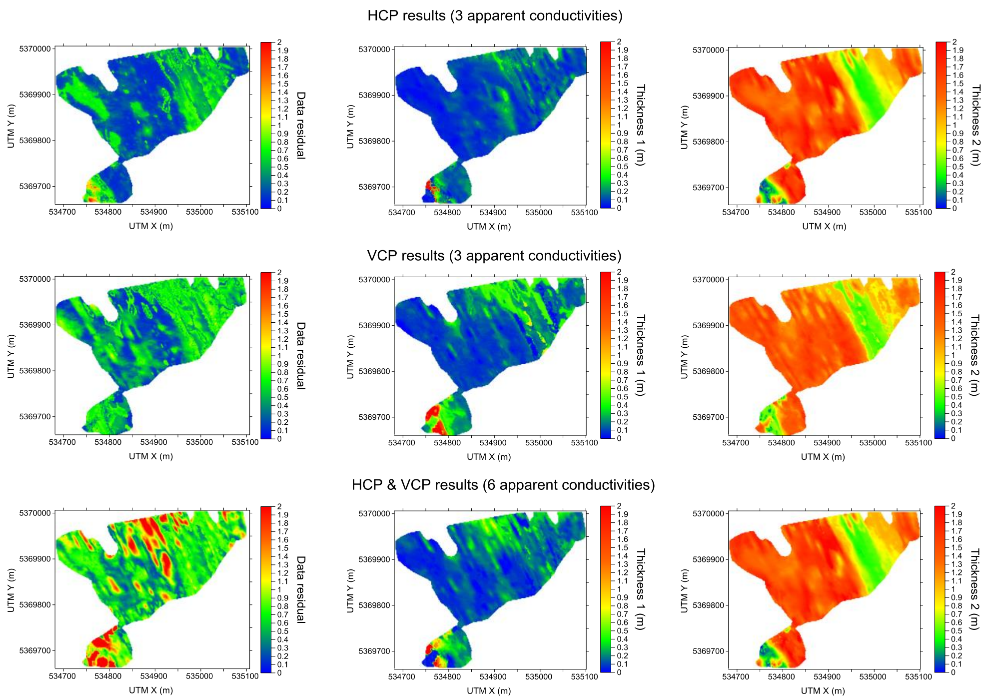

Figure 8: Results of the CMD inversion, including the data residual (left column), for a three-layer model (1: topsoil, 2: conductive filling, and 3: resistive substratum). The thicknesses 1 and 2 correspond to the topsoil and conductive filling, respectively. The prospection height is 1 m. The conductivities are set to σ_1 = 13 mS/m, σ_2 = 72 mS/m and σ_3 = 13 mS/m. A noise level of 1 mS/m on the apparent conductivities was assumed, with a minimum relative error of 5%.