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1 **A 3D electrical resistivity tomography survey to characterise the structure of a**
2 **albeluvic tonguing horizon composed of distinct elementary pedological**
3 **volumes**

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23

1 Abstract

2

3 Water and gas transfer in porous media like soils are determined by their porous
4 network, described by their structure. In soil, the horizon is usually considered to be
5 elementary and homogeneous functioning system in the description of gas and water
6 functioning. However, in some cases, a horizon is heterogeneous, and its structure is
7 defined by the 3D arrangement of Elementary Pedological Volumes (EPVs). The
8 horizon needs to be described in three dimensions to improve the characterisation of
9 the structure and, consequently, the prediction of its hydraulic functioning. The aim of
10 this study was to determine the feasibility of describing the 3D structure of a
11 heterogeneous albeluvic tonguing soil horizon composed of a juxtaposition of silty
12 white and clayey ochre EPVs, using 3D electrical resistivity tomography (ERT).
13 Electrical measurements were compared with geostatistical analyses from soil
14 photographs. We demonstrated that the resistivity of the white EPVs was greater
15 than that of the ochre EPVs. In addition, the general soil structure and organisation of
16 the soil horizon could be derived from the electrical resistivity data. We proposed a
17 method to discretise the soil electrical resistivity into a binary system that
18 corresponded to white and ochre volumes. Finally, a 3D representation of the soil
19 structure was created that could be used to improve soil hydraulic models.

20

21 **Keywords:** soil electrical resistivity, heterogeneous structure, Elementary
22 Pedological Volumes, electrical resistivity tomography, degraded horizon,
23 hydraulic modelling, geostatistical filtering, kriging component

24

1. Introduction

Soil naturally filters water as it is transported to groundwater reservoirs. Thus, soil structure influences water storage and transfer and gas diffusivity, which have major environmental and agronomic consequences. Therefore, it is important to know the soil structure to predict soil hydraulic functions.

Typically, soil horizons are considered to be elementary and homogeneous systems for the pedological description of soils (Jamagne and King, 2003; Bockheim et al., 2005). Furthermore, soil horizons are used for modelling water transfer properties and consist in the basic information of soil databases, such as the UNSODA¹ (Nemes et al., 2001) or HYPRES² (Wösten et al., 1999) databases, which are populated with soil data at the horizon scale. Nevertheless, in some cases, the horizon is heterogeneous and its structure, at the so-called n scale, is defined by the arrangement of pedological volumes at the (n-1) scale. Heterogeneous horizons are very common and include ploughed horizons (Richard et al., 2001), stony horizons (Cousin et al., 2003), or horizons with vertical leaching tongues (Diab et al., 1988; Frison et al., 2009).

To improve the characterisation of the soil structure and, consequently, its hydraulic function, the soil horizon needs to be described in three dimensions (3D). Several methods already exist to characterise heterogeneous soil horizons. These methods are based on (i) the visual description of the soil profile in a ploughed horizon (Roger-Estrade et al., 2004), (ii) the characterisation of water infiltration or (iii) soil property measurements, such as bulk density, porosity, and penetrability. However, these methods do not describe the horizon structure in 3D. Serial sections, X-ray tomography (XRT) and electrical resistivity tomography (ERT) are three techniques that can be used to obtain a 3D description of soil structure. The serial sections method is conducted by taking photographs of successive thin two-dimensional (2D) slices of an impregnated (e.g., with dye tracer – Trojan and Linden, 1998; Forrer et al., 2000) or non-impregnated (Pereira and FitzPatrick, 1998) volume of soil. These images are superimposed to reproduce the 3D soil volume (e.g. Cousin et al., 1996). This method can be applied to obtain a resolution from a few hundred micrometres (Cousin et al., 1996) to approximately one centimetre in the

¹ UNsaturated SOil hydraulic DAtabase

² HYdraulic PProperties of European Soils

1 field (Vogel et al., 2002). Since the work reported by Petrovic et al. (1982), XRT had
2 enabled researchers to characterise soil structure on large undisturbed samples of a
3 few cubic decimetres. Similar to the serial sections method, the XRT method is often
4 used to obtain topological information and porous network descriptions of the studied
5 sample. Unfortunately, the serial sections and XRT methods require destructive
6 sampling, which does not allow monitoring of the soil structure evolution with time.
7 Therefore, the use of non-destructive techniques should be encouraged. Among the
8 non-destructive techniques, ERT is of primary interest for obtaining a 3D
9 representation of the subsurface (Dahlin, 2001). ERT has been used to describe
10 changes in bulk density (e.g. Abu-Hassanein et al., 1996; Besson et al., 2004), stony
11 inclusions (e.g. Rey et al., 2006), and soil morphological structures (Séger et al.,
12 2009).

13 The aim of this work was to determine the 3D structure of a heterogeneous
14 albeluvic tonguinghorizon for an area of approximately one square metre using 3D
15 ERT. At this site, the heterogeneity is a juxtaposition of ochre clay and white silt
16 pedological volumes of a few cubic centimetres, called 'Elementary Pedological
17 Volumes' (EPVs) as described in Frison et al., 2009. These types of horizons are
18 very common in soils, but their three-dimensional heterogeneity is usually difficult to
19 describe and to be considered in soil hydric functioning models. However, the
20 hydraulic properties of the two types of EPV in this soil horizon are strongly different
21 and lead to complex hydric functioning (Frison et al., 2009). Data were analysed and
22 compared with soil photographs to assess the potential of electrical resistivity
23 measurements for describing the clay and silt volume arrangements.

24 25 **2. Materials and methods**

26 27 **2.1. Study site**

28 29 **2.1.1. Soil description**

30
31 The studied soil is located on the crest of the Yonne plateau, France, in a
32 cultivated field. This soil is an Albeluvisol (WRB, 1998) that was developed on
33 aeolian Quaternary loam that was deposited over an Eocene clay layer. This soil is
34 characterised by the three following horizons (Figure 1).

- 1 - From 0.00 to 0.35 m, a silty, brown to grey, ploughed A horizon with a granular
2 structure that becomes more massive below a depth of 0.3 m.
- 3 - From 0.35 to 0.60 m, a transitional albeluvic tonguing E&Bt horizon with a
4 polyhedral structure that is characterised by the juxtaposition of different sub-units
5 (Frison et al., 2009) from the upper and the lower horizons. These subunits include
6 white-grey (10YR8/2 to 10YR7/1) to pale-brown (10YR7/4) albeluvic tongues that are
7 called “white Elementary Pedological Volumes (EPVs)” and ochre (10YR5/6 with
8 10YR5/8) volumes that are called “ochre EPVs”. Black concretions and inclusions
9 were observed in the ochre EPVs. This E&Bt horizon, that exhibited the maximum
10 structural heterogeneity (Diab et al., 1988; Montagne et al., 2007, 2008; Frison et al.,
11 2009) was the object of this study.
- 12 - From 0.60 to 1.00 m, a Bt horizon that exhibits white albeluvic tongues (equivalent
13 to those of the E&Bt horizon) in the ochre matrix. The structure of this horizon is
14 more prismatic than that of the E&Bt horizon.

16 2.1.2. EPV description

18 Several EPVs (15 - 30 cm³) were collected from the E&Bt horizon in the field
19 by gently separating this soil by hand according to colour. These samples were
20 collected at two depths, from 0.35 to 0.45 and from 0.45 to 0.55 m. The samples
21 were stored at their field moisture contents at 4°C in hermetic boxes prior to
22 conducting any measurements. The water content was measured on a mass basis
23 for each EPV using approximately six replicates. The bulk density was determined
24 using the kerosene method (Blake and Hartge, 1986) on approximately ten
25 replicates. The clay content of each EPV was determined by blending ten EPVs and
26 using Robison’s pipette method following ultrasonic dispersion in water and the
27 addition of NaPO₃ and Na₂CO₃ (according to the French normalised protocol, X 31-
28 107).

29 The bulk density of the white EPVs was slightly lower than the bulk density of the
30 ochre EPVs (Table 1). The water content in the white EPVs was slightly higher than
31 that in the ochre EPVs. However, in both cases, the water content did not depend on
32 the position of the EPVs in the profile (Table 1). The clay content was higher in the
33 ochre EPVs and increased with depth (Table 1).

34

2.2. Field measurements

2.2.1. Protocol experiment and colour photographs

The measurements were realised at the depth 0.35 to 0.55 in the highly heterogeneous E&Bt horizon. A trench 0.5 m x 1.0 m, with a depth of 1 m was dug for the people to stay. Before the electrical measurements, the ploughed horizon was removed from the upper surface of the E&Bt horizon to obtain a regular and planar x-y surface of approximately one square metre. This x-y plane was called “A level” and was located at a depth of $z = 0.35$ m (Figure 1). Colour photographs were taken of the A level before conducting electrical measurements. A 0.06 m layer of the soil was removed to obtain a second x-y surface. This second x-y surface is referred to as “B level” and was at a depth of $z = 0.41$ m. A second sequence of electrical measurements and colour photographs was collected from the B level. The same procedure was repeated to obtain a third x-y surface at a depth of $z = 0.47$ m, which is referred to as the “C level”. All colour photographs were taken with a digital camera (Panasonic, DMC-FZ5, focal distance 2.8, speed 1/60 s, ISO-150) and with natural sunlight.

2.2.2. Electrical measurements

Electrical resistivity measurements were performed with a programmable multi-electrode system that was connected to a resistivity meter (Syscal R1 Plus, IRIS Instruments). Brass electrodes of 2 mm diameter were positioned on supports and inserted approximately 2 mm into the soil. To obtain high-quality electrical resistivity measurements, the resistance between the soil and electrode was measured to check if the contacts were reliable and steady. Indeed, it then ensure that the current intensity and resulting potential are high enough to be measured with a correct significativity. Electrodes were positioned far enough from the excavation (60 cm) to avoid border effects.

Three types of electrode configurations (Figure 2) were employed for the electrical resistivity measurements, including (i) a line of 32 electrodes spaced at 0.03 m apart (*Wen32*), (ii) a line of 16 electrodes spaced at 0.03 m apart (*Wen16*) and (iii) a regular square grid of 32 electrodes spaced at 0.09 m apart (*Sqr32*). The

1 Wenner- α array was used for the line configurations (*Wen32* and *Wen16*) because it
2 is known to be relatively sensitive to vertical changes and has the best signal-to-
3 noise ratio. In addition, this array type can be used in areas with high background
4 noise (Loke, 2001; Dahlin and Zhou, 2004; Samouëlian et al., 2005), which occurs in
5 the studied E&Bt horizon. The square array (*Sqr32*) is important for investigating
6 anisotropic soil resistivity measurements (Samouëlian et al., 2004) and is considered
7 relevant for recognising 3D objects (Senos Matias, 2002).

8 For the A level, seven *Wen32* profiles were realised in the x direction. The
9 distance between two successive lines was 0.09 m. The recorded apparent electrical
10 resistivity measurements for one *Wen32* profile resulted in 129 measurements at six
11 pseudo-depths. The same measurement procedure with *Wen32* was repeated for the
12 B and C levels. The x and y coordinates of each *Wen32* array did not change.

13 For the A level, four *Wen16* profiles were realised in the y direction; these
14 profiles were perpendicular to the *Wen32* profiles. Seven *Wen16* profiles were
15 realised for the C level. For one *Wen16* profile, each experiment resulted in 34
16 measurements that were distributed across four pseudo-depths.

17 At the A and C levels, the square array (*Sqr32*) was used. This sequence
18 resulted in thirty measurements that were distributed across two pseudo-depths.

19 The temperature was recorded in the E&Bt horizon during the experiments
20 with PT100 probes. The temperature was constant during the electrical resistivity
21 measurements and was approximately 9°C. Thus, there is no need to consider
22 temperature effects on the electrical measurements.

23 24 **2.3. Data processing**

25 26 **2.3.1. 3D inversion of the electrical resistivity data**

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28 For each level, a complete dataset of georeferenced apparent resistivity
29 measurements was built. This dataset included measurements from the *Wen32*,
30 *Wen16* and *Sqr32* configurations. To obtain quantitative information regarding the
31 resistivity distribution at the actual investigated depths, the apparent resistivity
32 measurements were interpreted with the RES3DINV software (Geotomo Software,
33 Malaysia) based on the Loke and Barker (1996) inversion procedure. To help detect
34 the E&Bt horizon vertical structures, we chose a damping factor so that the vertical

1 flatness filter was twice the horizontal flatness filter. We used a model with narrower
2 cells, which is recommended when the resistivity varies greatly near the surface.

3 The 3D inversion of the electrical resistivity data provided a bloc diagram of
4 the interpreted electrical resistivity values for the three levels A, B and C.

5 6 2.3.2. Processing of the soil photographs

7
8 All of the photographs were ortho-rectified to the same (0, x, y, z) coordinates
9 of the electrical resistivity data so that they could be compared. On each photograph,
10 the ochre and white EPVs were separated by hand with a visual analysis. This
11 analysis created binary images that could be used to count the proportion of each
12 EPV and to evaluate the ability of the electrical resistivity measurements for
13 identifying ochre and white EPVs. As included in the ochres ones, the black
14 concretions were labelled as ochre ones in the binary images.

15 16 2.3.3. Comparison between the electrical resistivity data and the soil 17 photograph pictures

18
19 To compare electrical resistivity data, which were in 3D, and soil photographs,
20 which were in 2D, we extracted 2D planes from the 3D bloc diagram of inverted
21 electrical resistivity at a depth of 0.35, 0.41 and 0.47 m (i.e., at the A, B and C levels).

22 A variographic analysis was conducted on the three colour channels of the
23 photographs that were taken at the surface of each level and on the 2D resistivity
24 planes at depths of 0.35, 0.41 and 0.47 m. For each variogram, the local and regional
25 components were identified and used to create new datasets that corresponded to
26 each spatial component, except for nugget (see Appendix for the complete
27 description of the method).

Whatever the type of dataset (original dataset, local component dataset or
regional component dataset), 2D resistivity data were compared to each channel of
the photographs.

28 29 30 **3. Results**

3.1. Proportion of the EPVs at each level

The corresponding binary images of the photographs of the three levels were used to determine the proportion of ochre and white EPVs (Figure 3). The proportions of the ochre EPVs were 46, 45 and 55% for the A, B and C levels, respectively. A concentric zone (see the arrow symbol on the C level) with a higher proportion of white EPVs between 0.18 and 0.45 m along the Ox axis was observed, especially for the C level.

3.2. 3D electrical resistivity

The graphic representations of the planes that corresponded to the A, B and C level depths were obtained from the first layer of each inverted dataset for each A or B or C levels (Figure 4). They exhibited resistivity values of between 15 $\Omega.m$ (i.e. 66 $mS.m^{-1}$) and 80 $\Omega.m$ (i.e. 12 $mS.m^{-1}$). Generally, the resistivity values decreased with depth. For example, the resistivity values were higher for the A level (40 $\Omega.m$ on average i.e. 25 $mS.m^{-1}$) than for the B and C levels (30 $\Omega.m$ on average i.e. 33 $mS.m^{-1}$). At each level, the resistivity values varied spatially.

On the C level, a more resistive zone of approximately 45 $\Omega.m$ (i.e. 22 $mS.m^{-1}$) was observed between 0.20 and 0.40 m along the Ox axis (see the arrow symbol), which corresponded to the location of the concentric zone that was previously described in section 2.2.

3.3. Comparison between the electrical resistivity data and the photographs

3.3.1. Variographic analysis

To compare the soil photographs at the three levels to the 2D planes from the 3D electrical resistivity inversion, the original, local component and regional component datasets were analysed. Figure 5 provides an example for level C.

We then analyse the coefficient correlation between the soil photograph pixel values for each colour channel and the 2D electrical resistivity values of the 2D planes that were extracted by 3D inversion for the A, B and C levels (Table 2). These correlation coefficients were calculated for the original, local component and regional

1 component datasets. The correlation coefficients were not significant (lower than
2 0.40) for the original or local component datasets for any of the colour channels or
3 levels.

4 In contrast, for levels B and C, the correlation coefficients between the
5 regional components of the photographs and the spatial components of resistivity
6 maps were considered significant for all colour channels.

8 3.3.2. Creation of a 3D soil structure image

9
10 The 3D inverted resistivity values were interpolated using a 3D kriging routine.
11 In addition, we proposed the following methodology to transform the electrical
12 resistivity values into ochre and white EPVs. At each level, we separated the
13 electrical resistivities into two classes with different threshold values and calculated
14 the resulting proportions of ochre and white. The best threshold value should provide
15 the ochre and white proportion that is closest to the one calculated from the binary
16 photographs. For each level, the best agreement was observed when the threshold
17 value corresponded to the mean resistivity value. Next, we used the mean value of
18 the entire 3D resistivity dataset to discretise the 3D data into white and ochre EPVs.

19 Figure 6 contains the maps of agreement between the binary electrical
20 resistivity data and the binary soil photographs. A large zone of agreement between
21 0.20 and 0.40 m along the Ox axis was observed that corresponded to the concentric
22 zone position of the white EPVs.

23 This 3D discretisation (Figure 7) was composed of 43.8 and 56.2 % of white
24 and ochre electrical EPVs, respectively, which is consistent with the values obtained
25 from the soil photographs at the three levels. In addition, these results were
26 consistent with those were obtained by Montagne et al. (2007), who used image
27 analysis on large impregnated blocks.

28 29 **4. Discussion**

30 31 **4.1. The structure of the heterogeneous horizon: what do we learn from** 32 **electrical measurements?** 33

1 The use of electrical resistivity in soil science studies has one considerable
2 advantage over the use of geological studies because non-destructive and rapid
3 observations of the structure are feasible. The E&Bt horizon appears to be a good
4 case study because the electrical resistivity values are highly heterogeneous.

5 For our experiment, several soil characteristics, including the bulk density, the
6 clay content and the water content, were determined. The clay contents were
7 significantly higher in the ochre than in the white EPVs, which should result in lower
8 resistivity values in the ochre EPVs. For the water and the bulk density, the maximum
9 differences between the white and ochre EPVs were 0.005 g.g^{-1} and 0.06 g.cm^{-3} ,
10 respectively (Table 1). Such small variations cannot be detected by the electrical
11 resistivity measurements (Seladji et al., 2010). Thus, we can assume that only the
12 soil texture (due to its clay content) would induce large soil electrical variations.
13 Incidentally, soil texture measurements throughout the soil profile indicated that the
14 clay content increased with depth due to the decreasing white volumes. This finding
15 is consistent with the general decrease in resistivity with depth.

16 The comparisons between the photographs of each level and the interpreted
17 electrical resistivity measurements did not lead to significant results when the raw
18 values or the local components of the two datasets were considered. Indeed, the
19 precise geometrical limits of the EPVs were not detected by the electrical resistivity
20 because of either the inter-electrode spacing or the loss of information with depth. In
21 contrast, because the ERT method is integrative, these comparisons were more
22 relevant for the regional components of the two datasets. The current lines are three-
23 dimensional and represent a certain soil volume whose size increases and resolution
24 decreases as the inter-electrode spacing increases. As a result, this method is
25 efficient for locating large areas (several centimetres) of white or ochre soil volumes
26 without determining their exact local geometry. Regarding geometry, the electrical
27 structure exhibits large electrical resistivity values that correspond to white volumes
28 near the surface and along the Ox axis (i.e., parallel to the surface plane). Deeper,
29 the large resistivity values are organised by geometrical volumes and are oriented
30 more along the Oz axis (i.e., along a vertical axis). This orientation is consistent with
31 the general organisation of the E&Bt horizon in an Albeluvisol. Near the soil surface,
32 the amount of white EPVs (i.e. albeluvic tongues) is greater. These white volumes
33 are less numerous and more vertical. In addition, they occur in tongues that range
34 from a few centimetres to several tens of centimetres in size (WRB, 1998). These

1 tongues have a higher hydraulic conductivity than the ochre volumes and constitute
2 preferential pathways for water transfer (Frison et al., 2009). According to the field
3 observations of several authors, the functionality of some of these tongues depends
4 of their texture (Diab et al., 1988). However, these differences are difficult to identify
5 from soil profile photographs. Based on the electrical structure analyses of the
6 tongues, lower electrical resistivities corresponded to higher hydraulic conductivities.
7 To interpret the electrical resistivity in terms of hydraulic conductivity, some
8 complementary measurements are necessary, such as the water content and the
9 resistivity of several soil volumes. Nevertheless, the 3D structure of a heterogeneous
10 horizon, which is derived from electrical measurements, contains a relevant 3D
11 structure of the hydraulic properties. Thus, this 3D structure could be used to model
12 the water transfer at this scale, as demonstrated by Samouëlian et al. (2011).

14 **4.2. Determination of the structure's Representative Elementary Volume** 15 **(REV)**

16
17 Modelling the hydric function of the horizon with albeluvic tonguing is only
18 feasible if (i) the structure is studied in 3D and, (ii) the volume of studied soil is
19 greater than the Representative Elementary Volume (REV). It is possible that the
20 REV of some hydric properties is different than the REV of some structural
21 characteristics. However, we can determine if this difference occurs by determining if
22 the volume analysed by electrical resistivity is greater than the REV that is necessary
23 to describe the horizon morphology (i.e., the 3D geometrical arrangement of the
24 ochre and the white EPVs).

25 From the 3D resistivity values, a variogram was calculated for each direction
26 (Ox, Oy, Oz) (Figure 8) to represent the distribution of the ochre and white EPVs
27 based on distance. A limit value was observed at a distance of 0.25 m for both
28 variograms in the Ox and Oz directions. This result indicated that the REV for the
29 horizon structure was reached. In addition, this value was consistent with the value
30 obtained by Montagne et al. (2007) from 2D images of the same horizon. In contrast,
31 the REV was not reached in the Oy direction. Thus, further investigations are needed
32 to determine the exact structure in the Oy direction.

34 **5. Conclusions**

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ERT surveys were conducted on a highly heterogeneous horizon over a surface area of approximately one square metre. The E&Bt horizon of an Albeluvisol was studied with 3D electrical resistivity prospecting.

The studied horizon had a complex structure composed of a juxtaposition of silty white and clayey ochre EPVs. We demonstrated that the resistivity of the white EPV was larger than the resistivity of the ochre EPV. In addition, the structure of the soil horizon can be derived from electrical resistivity data. Nevertheless, to obtain accurate electrical measurements that could describe the horizon structure, our work required the destruction of the studied soil. Other destructive methods, such as serial sectioning with numerical photograph analysis, could also be used to produce the 3D structure of the studied horizon. However, more electrodes could be used in the future to improve the accuracy of the ERT measurements without disturbing the soil horizon.

The resistivity was higher in the upper portion of the studied horizon. In this layer, zones were identified that were parallel to the surface and corresponded to the white EPVs. The resistivity was lower at depth due to the higher amount of ochre EPVs. However, the white EPVs occurred in structures that were predominantly orientated perpendicular to the soil surface, similarly to tongues. Depending on their actual texture, these tongues may or may not transfer water. Electrical resistivity measurements could enable the identification of functional tongues if they are collected several times during infiltration or evaporation periods. In the future, the 3D structure of such a complex horizon obtained by electrical resistivity measurements will improve water and solute transport models.

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- 17

1 **Appendix**

2 Indeed, a spatial random process can be a combination of several constituent
 3 random processes one nested within another and acting different characteristic
 4 spatial scales. In these circumstances the variogram of a random function $Z(\mathbf{x})$ is a
 5 nested combination of two or more individual variograms leading to so-called nested
 6 variogram that displays different structures (e.g. different ranges of spatial
 7 dependence). The variogram can thus be modelled as the sum of $L + 1$ basic
 8 variograms (e.g. Goovaerts, 1997; Bourennane *et al.*, 2012), each corresponding to a
 9 distinct spatial structure:

10
$$\gamma(\mathbf{h}) = \sum_{l=0}^L \gamma_l(\mathbf{h}) = \sum_{l=0}^L b_l \gamma_l(\mathbf{h}) \quad \text{with } b_l \geq 0 \quad (1)$$

11 where b_l is the variance of the corresponding basic variogram model $\gamma_l(\mathbf{h})$.

12 The variance corresponding to $l = 0$ is called nugget and represents the spatial
 13 unstructured part of the total variance. Based on the linear model of regionalization
 14 (1), the random function $Z(\mathbf{x})$ can be decomposed into a sum of $(L+1)$ independent
 15 random functions, called spatial component, and its local mean $m(\mathbf{x})$:

16
$$Z(\mathbf{x}) = \sum_{l=0}^L Z_l(\mathbf{x}) + m(\mathbf{x}) \quad (2)$$

17 where $Z_l(\mathbf{x})$ is the l th spatial component corresponding to the variogram model
 18 $\gamma_l(\mathbf{h})$. Each spatial component can thus be individually mapped by filtering out the
 19 other components. The estimator of the l th spatial component of variable Z at
 20 location \mathbf{x}_0 is:

21
$$Z_i^*(\mathbf{x}_0) = \sum_{\alpha=1}^n w_{\alpha,l} Z(\mathbf{x}_\alpha) \quad (3)$$

22 with n the number of observations around \mathbf{x}_0 involvd in the estimation where
 23 each observation receiving a weight $w_{\alpha,l}$. As the available observations $z(\mathbf{x}_\alpha)$
 24 contain the contribution of all $L + 1$ components which are considered mutually
 25 independent, only the contribution of the l th component must be taken into account in
 26 the right hand side term of the kriging system. Moreover to ensure unbiased
 27 estimations and provided the variogram model $\gamma_l(\mathbf{h})$ is bounded (stationary case), the

- 1 kriging weights $w_{\alpha,l}$ must sum to zero, and not to one as in ordinary kriging
2 (Wackernagel, 1998). This leads to the following kriging system for lth component:

$$\begin{cases} \sum_{\beta=1}^n w_{\beta,l} \gamma(\mathbf{x}_\alpha - \mathbf{x}_\beta) + \phi_l = b_l \gamma_l(\mathbf{x}_\alpha - \mathbf{x}_0) & \text{for } \alpha = 1, \dots, n \\ \sum_{\beta=1}^n w_{\beta,l} = 0 \end{cases} \quad (4)$$

- 3
4 where ϕ_l is the Lagrange parameter for the lth component. This system of
5 n+ 1 equations must be solved to find the weights $w_{\beta,l}$ that are then inserted into
6 equation (4) to estimate the lth spatial component of variable Z at location \mathbf{x}_0 . The
7 operation is repeated for all locations where such decomposition is required.
8

1 **Figures captions:**

2 **Figure 1:** 3D representation of the soil profile. The underlined white zones
3 correspond to some white EPVs. The ochre EPVs were juxtaposed to the
4 white ones.

5 **Figure 2:** Experimental design. Location of the *Wen32*, *Wen16* and *Sqr32* electrodes
6 at each studied level.

7 **Figure 3:** Photographs of the three surface levels (-a-, -c- and -e-) and their
8 corresponding binary representations (-b-, -d- and -f-) for white and ochre
9 EPVs after the visual analysis. The surface proportions of the white and ochre
10 EPVs are mentioned.

11 **Figure 4:** Interpreted electrical resistivity for the three levels extracted from the
12 inverted electrical resistivity 3D data.

13 **Figure 5:** Comparisons of the electrical resistivity planes and the real surface level
14 photographs. For example, the C level between the resistivity plane that was
15 extracted from the 3D data and the blue channel of the real photograph were
16 compared. The comparisons are made on the original images (-a- and -d-)
17 and on the local (-b- and -e-) and regional components (-c- and -f-) that were
18 obtained from variographic analysis. For conductivity equivalent values, see
19 Figure 4.

20 **Figure 6:** Map of agreement between the binary classifications that were determined
21 from visual analysis and from electrical resistivity maps separated by the
22 threshold value.

23 **Figure 7:** A 3D representation of the electrical structure discretisation in two EPVs.

24 **Figure 8:** Variograms of the 3D block of the electrical resistivity discretised for the
25 three Ox, Oy and Oz directions.

26
27

1
 2 **Table 1:** Soil characteristics for the white and ochre EPVs. The standard errors of
 3 measurements are presented in brackets.

Depth (m)	Bulk density (g cm ⁻³)		Clay content (g kg ⁻¹)		Field water content (g g ⁻¹)	
	White EPV	Ochre EPV	White EPV	Ochre EPV	White EPV	Ochre EPV
0.35-0.45	1.61 (0.06)	1.63 (0.02)	182	248	0.211 (0.01)	0.206 (0.01)
0.45-0.55	1.59 (0.02)	1.65 (0.03)	213	322	0.209 (0.01)	0.205 (0.01)

Table 2: Correlation coefficients between the colour channel pixels of the numerical photographs and the interpreted resistivity of the x-y maps that were extracted from the 3D data in the A, B and C levels (at z coordinates of 0.35, 0.41 and 0.47 m respectively). The comparisons were made for the raw data, the local and regional components of each level.

Level A (0.35 m)			
Correlation	Red channel	Green channel	Blue channel
Raw data	0.05	0.09	0.08
Local component	0.01	0.02	0.02
Regional component	0.14	0.21	0.20

Level B (0.41 m)			
Correlation	Red channel	Green channel	Blue channel
Raw data	0.23	0.27	0.27
Local component	0.08	0.15	0.18
Regional component	0.55*	0.64*	0.64*

Level C (0.47 m)			
Correlation	Red channel	Green channel	Blue channel
Raw data	0.32	0.40	0.39
Local component	0.21	0.33	0.35
Regional component	0.71*	0.75*	0.76*

* correlation coefficient considered as significant

4
 5
 6