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NWE-REGENERATIS
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D. I2.1.1. Site specific report on geophysical survey on Pompey site (FR)

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Summary

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3 INTRODUCTION

Pompey is one of the three pilot sites of the NWE-REGENERATIS project. It is a former tailing pond owned by the EPFGE (Etablissement Public Foncier de Grand Est, Public Real-Estate Company of Grand Est region). The site has been chosen for three main reasons: (1) it hosted various activities for iron based alloys production; (2) it was recently rehabilitated on surface, and (3) historic documentation and investigations are done with respect of the French legislation and threshold values. One of the interest of this site is that it allows testing the REGENERATIS methodologies developed within WPT1 and WPT2 on a site that has already been remediated.

Site works allowed on-site geophysical measurements and later provided access to material to perform lab trials. Geophysical data on site were acquired at two different times: (1) a first electrical profile, completed by magnetic susceptibility measurements in the trench pit were conducted in November 2020; (2) Measurements on 5 electrical profiles, 3 seismic profiles, an electromagnetic map and a magnetic map were led in March 2021.

This site-specific report is intended to provide specific data on geophysical characterization of the site including: (1) a location map; (2) the general geophysical methodology and methods used; (3) geophysical results and interpretations.

4 PRESENTATION OF THE POMPEY SITE

The Pompey site is a former tailing pond from the iron and steel complex of Pompey-Frouard-Custines, located 10 km North from Nancy (see deliverable DI2.1.1 and Huot, 2013). The steel complex was active from 1870 to 1986. It is renowned for producing cast iron and special steels, such as ferromanganese (ferro-alloy rich in manganese). The last blast furnace of the Pompey-Frouard-Custines iron and steel complex was stopped in 1986. Over time, a forest ecosystem developed on the former tailing pond. The dike delimiting the site was planted with a curtain of black locust trees in 1997. The rest of the pond gradually got covered with diversified deciduous vegetation, more or less dense depending on the area.

The geological substratum of the former tailing pond consists of the Lias marl formations (at 181 m NGF), which are covered by alluvium from the two rivers, composed of coarse siliceous materials (sands, gravel and pebbles) at the base over 3 to 6 m surmounted by finer materials (sands, silts and clays) on 1 to 3 m. These alluvial formations were locally exploited and backfilled with waste rock and iron and steel by-products.

The depth of the deposits in the basin is estimated at around 10 m. The surface of the former pond is estimated to 26 000 m^2, for a total estimated volume of wastes equal to 260 000 m^3.

The waters of the alluvial table would circulate from the channeled Moselle towards the Meurthe, whose level is lower. The piezometric levels measured in 2002 are 187.5 m NGF upstream (South-West of the island) and 184 m NGF downstream (East of the island), the basin surface being at 197 m NGF (ANTEA, 2002).

5 OBJECTIVES OF THE GEOPHYSICAL INVESTIGATIONS

Geophysical methods allow mapping the variations of geophysical properties that are indirectly linked to the physical and chemical nature of the formations in place, over the entire surface of the deposit. These methods provide very valuable and almost continuous information laterally and vertically. However, they are only indirectly linked with the targeted properties, such as concentration of metallic elements, size the metallic particles… Traditional sampling investigations on past metallurgical sites and deposits aims at characterizing the nature, physical and chemical composition of the wastes at a punctual location. The combination of the traditional sampling investigations and the geophysical imaging will allow interpreting in a semi-quantitative approach the geophysical observations, using the chemical and physical laboratory characterizations of the punctual samples.

The geophysical campaign will allow to:

- Better estimate thickness of the deposits, and thus volume of material to be revalorized
- Locate specific areas of interest with a higher revalorization potential (e.g. higher metallic particle concentration), that will be further studied through targeted sampling

6 INITIAL PROGRAM AND METHODS USED

6.1 TECHNICAL PROGRAM

In order to improve the characterization of the deposits stored on the Pompey site, the BRGM and the University of Liège carried out 2D electrical resistivity and induced polarization tomographies, combined with: (1) seismic tomographies, (3) electromagnetic mapping and (4) mapping of the gradient of the Earth's magnetic field. The use of each of these methods in the post metallurgical site and deposits context in detailed in deliverable DT1.3.1. Indeed :

- **The electrical resistivity profiles** are used to distinguish the different geological layers and the limit between waste deposits and natural formations
- **The induced polarization profiles** (carried out simultaneously to the electrical resistivity profiles), implemented in time domain (TDIP = Time Domain Induced Polarization), make it possible to identify the zones (in depth and laterally) of interest for post-sampling investigations. The characterization of the deposit is thus refined
- **The seismic measurements** are used to distinguish the different geological layers, using different ground properties (ability to propagate acoustic waves) than the electrical resistivity method. These results will be complementary to the electrical resistivity profiles to delineate the limit between the anthropic deposits and the natural alluvia layer.
- **The electromagnetic mapping** measures the same property than the electrical resistivity profiles (usually shown as its inverse: the electrical conductivity). It is used to identify the laterally interesting areas for the realization of targeted sampling and to provide cartographic information on the entire studied area and complete the lateral variations between the electrical profiles.
- **The mapping of magnetic fields** is complementary of the electromagnetic mapping. It is sensitive to magnetic susceptibility variations, which is a different geophysical property than the electrical resistivity/conductivity. It is used to identify the laterally interesting areas for the realization of targeted sampling and to provide cartographic information on the entire studied area.

6.2 VOLUME OF WORK

As part of this study, 6 electrical resistivity and TDIP tomography profiles were deployed (see Figure 1). In order to maximize the resolution of the measurements while ensuring a sufficient depth of investigation with regard to the anticipated depth of the substratum, the spacing between electrodes was set at 2 m. Indeed, the depth of investigation increases with the inter-electrode spacing (see deliverable DT1.3.1). The device used makes it possible to carry out measurements with 96 electrodes simultaneously, i.e. a 190 m long profile. Five profiles are parallel to each other (P1 to P5), oriented North-North West / South-South East, and one profile (P7) is perpendicular to the others, oriented East-NorthEast / West-SouthWest.

The three seismic profiles are aligned with the electrical profiles P1, P3 and P5. 91, 90 and 86 geophones were installed on profiles P1, P3 and P5 respectively, with a 2.5 m spacing between the geophones.

Two maps of: (1) electrical resistivity and (2) magnetic field gradients were also produced over the entire field site, partially covering an area of 51,141 m^2 (see Figure 1). The measurements were taken on profiles oriented West-South-West / East-North-East with a continuous measurement recording every 0.5 seconds and coupled to simultaneous GPS recording. The entire area could not be covered by the mapping methods, due to the dense vegetation.

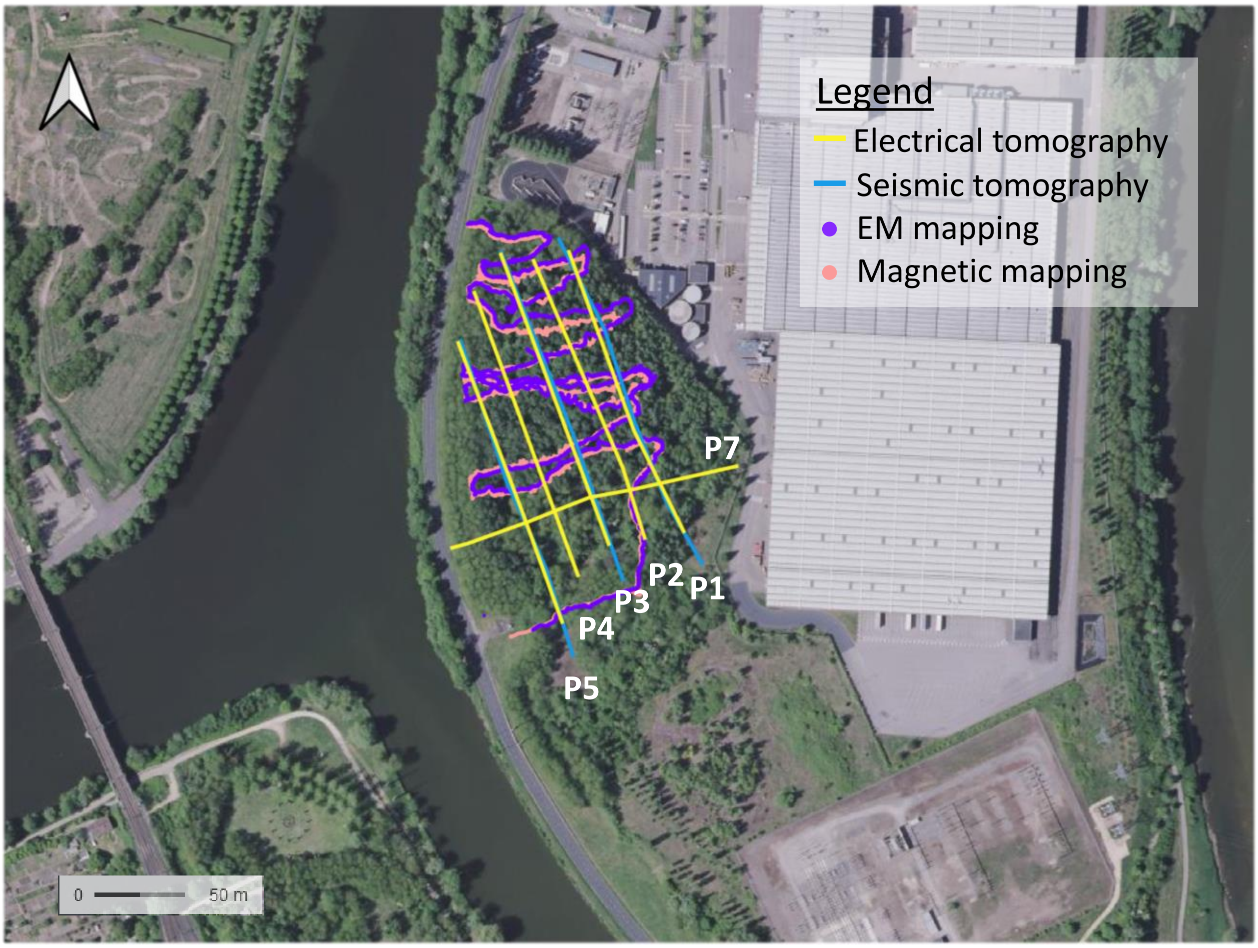

Figure 1: Location of the different geophysical profiling or mapping measurements. The profiles P1 to P7 are named for both the electrical and seismic tomography.

7 DATA ACQUISITION AND PROCESSING

Further details on each of the methods briefly described in this section can be found in the benchmark report on geophysics and non intrusive investigation techniques (deliverable DT1.3.1).

7.1 ELECTRICAL METHOD : TDIP (TIME DOMAIN INDUCED POLARIZATION)

7.1.1 Method description

Electrical resistivity and induced polarization, both measured by the TDIP electrical method, are two parameters widely used for subsurface metal detection. These are the main parameters measured for mining geophysical prospecting. The presence of metals, in the form of sulphides, oxides or carbonates, modifies the capacity of materials to conduct an electric current (resistive effect represented by electrical resistivity) and the capacity to temporarily store electric charges (capacitive effect, called the effect of induced polarization, or IP, represented by an electrical chargeability or a phase shift). These two parameters, electrical resistivity and chargeability, will be measured simultaneously using a so-called tomography configuration.

An acquisition configuration is a way of geometrically arranging surface current and potential electrodes. There are several, each with advantages and disadvantages, including signal amplitude, depth of investigation, and resolution. Among these, the Dipole-Dipole configuration was implemented in this study. The dipole-dipole (DD) configuration is well resolved close to the ground surface and well suited to auscultation of vertical discontinuities. It is robust against lateral effects (structures parallel to the profile). It is well adapted to phase shift (or chargeability) measurements as the transmitter and receiver dipoles are well separated, thus limiting the electromagnetic coupling effects. On the other hand, the signal-to-noise ratio decreases rapidly, which limits its depth of investigation (compared to other more penetrating configurations).

Figure 2 : Electrical measurements running at the Pompey site:a) operator checking the recordings on the resistivimeter; b) operator recording the GPS location of an electrode.

7.1.2 Data acquisition

ERT and IP electrical data were taken with the Syscal Terra device (Iris Instrument, France) on profiles of 96 electrodes with a dipole-dipole configuration. The inter-electrode spacing of 2 m was chosen to ensure both an acceptable resolution of the surface terrains, and a maximum investigation depth of approximately 38 m (the thickness of the former settling pond to image is estimate to 10 m).

For the IP data, on all the profiles, the measurements were acquired in 50% duty cycle (one charging window, one dead time, one discharging window) with an acquisition time of 2 s. For profiles 1, 2 and 5 reciprocal data were acquired. For profile 5, data were also measured in full cycle (a charging then discharging window with no dead time between the two) with an acquisition time of 2 s; 1 sec; 500ms and 250ms. These data recorded only for profile P5 will not be discussed in this report.

Thanks to the presence of a layer of topsoil on all the deposits, the measurement conditions proved to be ok (see Figure 2 and Figure 3). As a precaution, when the resistance of the electrodes was too high compared to the average contact resistance values (greater than 10 kohm), water saturated with salt was added to the foot of each electrode in order to improve their contact with the ground and so to increase the signal-to-noise ratio.

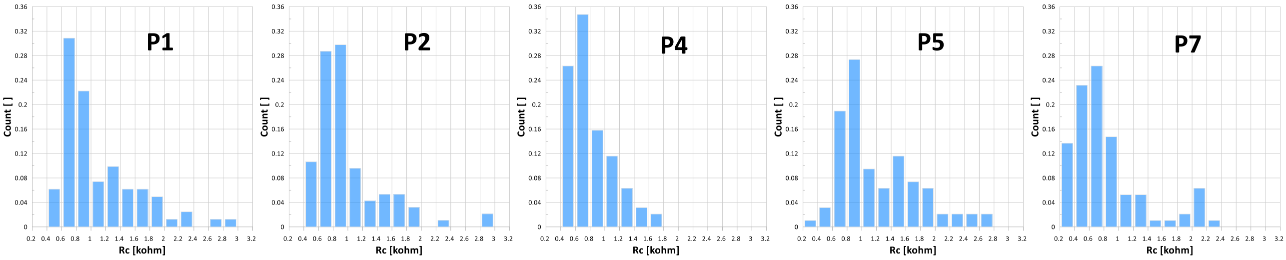

Figure 3 : Histogram of the contact resistances Rc measured for the different TDIP profils (P1 to P7). The corresponding histogram for the P3 profile is not represented because the contact resistances were not stored in November 2020.

7.1.3 Data treatment

7.1.3.1 ProsysIII filtering

The raw electrical measurement data were filtered with the following parameters (for both resistivity and IP inversions):

- |V|> 0.1 mV (V: measured potential),
- Q < 1%, (Q = quality factor, repeatability error during the stack phase).
- IAB > 0.1 mA (IAB: intensity of the injected current)
- M > 0 mV/V (M: apparent global chargeability)

Treatment with ProsysIII also allowed us to:
- Visualize the pseudo-sections of apparent resistivity and chargeability,
- Remove outliers,
- Integrate the topography to the data.

This type of filtering is consistent with the instrumental characteristics provided by the manufacturer, and complies with AGAP recommendations (BRGM et al., 1992). The Tableau 1 summarizes the number of measurements kept after filtering for each profiles. The initial number of measurements is different for P1 and P3 because they have both been used as tests to define the best measurement sequence for the Pompey site (P3 measurements were run in November 2020, and P1 was the first profile to be tested in March 2021).

Tableau 1 : Statistics on the electrical measurements taken and stored after filtering.

Profil	Length (m)	Nb of electrodes	Nb of measurements	Nb of kept measurements	% of kept measurements
P1	190	96	6552	6438	98.3
P2	190	96	3659	3589	98.0
P3	190	96	2837	2541	89.6
P4	190	96	3659	3624	99.0
P5	190	96	3659	3565	97.4
P7	190	96	3659	3500	95.7

7.1.3.2 BERT inversion

The "Boundless Electrical Resistivity Tomography" (BERT) software is a free software for modeling and inversion of complex electrical resistivity imaging (ERI). It includes both resistivity and Induced polarization (both in the time (TDIP) and in the frequency (FDIP) domains) tomography data based on the pyGIMLi library. It is available either in Python with the pyGIMLi and pyBERT libraries, or with command lines in bash script (e.g. Günther, 2021a and 2021b). It allows modeling and inversion in 2D and 3D of complex ERI data.

Here, the bash version of BERT was used to invert all the pseudo-sections of apparent resistivity and chargeability. The inversion was done with the default settings proposed by BERT. A first inversion is performed on the resistivity data alone. The results of this inversion are then used as a first guess in the chargeability inversion. Whatever the performances of the convergence algorithms, in the absence of calibration (calibrated resistivity, depth of the geoelectrical interfaces), the results provided by the inversion are not defined unequivocally (there are several solutions satisfying the same dataset). This indetermination can only be assessed by testing different solutions or by constraining the inversion using parameters (resistivities, thicknesses, depths) obtained by other means (other geophysical method, logs, drilling, observations of outcrops, etc.).

The "true" resistivity and chargeabilities sections, results of the inversion, are then used for the interpretation in terms of the structure of the deposits and geological formations. They provide quantitative information (resistivity, geometry and depth, dip) to characterize the origin of the various anomalies highlighted. The inversion results are presented in the form of a section showing the distribution of resistivities and chargeabilities along the profile as a function of depth.

The inversion performed in BERT specifies several parameters describing the data fit: (1) an absolute root-mean square (rms) (in Ohm.m for the resistivity, and in mV/V for the chargeability), (2) a relative rms (rrms) (in %), (3) the error-weighted chi-square fit $\chi^2 = \phi_d/N$,and (4) the objective function ϕ consisting of the data misfit ϕ_d ($\phi_d = \sum\left((d_i - f_i(m))/\varepsilon_i\right)^2$), plus the regularization parameter λ, times the model roughness. The closer χ^2 is from 1, the better the fit is between the model and data.

For the resistivity inversions, the maximum number of iterations ranges from 3 to 5 minimum before they reach a satisfactory criteria. The rrms is the highest for P3 (8.4%), and lowest for P1 (4.9%). The profile P3 has also the χ^2 that is the furthest from 1 (1.8). This profile was measured in November 2020, and was used as a test to define an optimized measurement sequence for the rest of the measurements.

For the chargeability inversions, the results are classically not as efficient as the resistivity inversions. Indeed, the maximum number of iterations ranges from 4 to 13. The rrms is very high for P2 and P5 (above 200%), and is the lowest for P1 (4.4%). P2 and P5 also have χ^2 values that are the furthest from 1 (155 for P5, and 255 for P2). The chargeability tomography obtained for P2 and P5 should thus be interpreted with care.

7.2 ELECTROMAGNETIC METHOD

7.2.1 Method description

The electromagnetic (EM) method used uses an active Slingram transmitter coil and a parallel receiver coil. The acquisition principle is the following (see deliverable DT1.3.1):

- a primary EM field is generated by a transmitter coil and propagates in all direction;
- the primary field induces Eddy currents in the subsurface whose intensity is directly proportional to the electrical conductivity of the medium crossed by the waves;
- these currents in turn induce a secondary EM field which can be detected by a receiver coil. The receiver detects both the primary (that is emitted by the transmitter) and the secondary EM fields. The secondary EM field differs in amplitude and phase compared to the primary field.

The in-phase component with the primary field gives information about the magnetic susceptibility of the medium (i.e. presence of metallic object/structures) whereas the quadrature component is directly proportional to its electrical conductivity.

Given the properties targeted (electrical conductivity and magnetic susceptibility) the method is well suited to investigate past metallurgical sites and deposits (PMSD) in search for mineral resources but also to map contaminated land. Indeed, the presence of metals, in the form of sulphides, oxides or carbonates, modifies the capacity of materials to conduct an electric current. Moreover, the presence of ferro- or ferri-magnetic materials (typically iron alloys) also impact the magnetic susceptibility of the ground.

7.2.2 Data acquisition

The electromagnetic data were acquired using a CMD Mini-explorer from GF Instruments with one transmitter coil and three receiver coils in horizontal coplanar (HCP) configuration. Thanks to its three receiver coils at three different distances from the transmitter coil, the Mini-explorer allows exploring simultaneously geophysical properties of soil layers with a thickness of 0.5 m, 1 m and 1.8 m. Both quadrature (proportional to the electrical apparent conductivity) and in-phase (related to the apparent magnetic susceptibility) components were recorded.

In addition, a GPS Trimble R10 (without RTK correction) was connected to the system for accurate positioning. Whenever possible, an acquisition grid is setup over the area to cover with an interline spacing depending on the size of the structure/object to detect. In the case of Pompey, the vegetation was very dense, so the acquisitions were run using all the available areas and paths within the field site (see Figure 1 and Figure 4 b). The data points will be directly presented and no interpolation of the data is possible in this case as the data points are not covering the area with a dense enough grid.

Figure 4 : Data acquisition on the Pompey site using: a) the G858 magnetometer for magnetic measurements and b) the CMD mini-explorer for electromagntic measurements.

7.3 Magnetic method

7.3.1 Method description

This method consists of measuring the magnetic field on the surface of the Earth: a change in magnetic property (magnetization) in the subsoil generates a variation in the recorded signal, this is called a magnetic anomaly. The objective is to estimate the distribution of magnetizations in the subsoil from surface measurements. In general, the data will be presented in the form of maps in the horizontal plane or along a profile. During the interpretation step, a magnetic anomaly will be seen as an association of positive and/or negative parts in the signal. However, the shape and arrangement of these positive or negative lobes provide information on the source present in the subsoil. Indeed, the geometry of a magnetic anomaly will depend on several parameters, including the location of the source in the subsoil, its geometry, its magnetic properties (magnetization) and finally the place where the magnetic measurements were acquired (regional magnetic field).

7.3.2 Data acquisition

The magnetic data were acquired using the G858 Cesium Vapor Magnetometer at a frequency of 0.5 s in vertical gradient. GPS coordinates were taken simultaneously.

The measurements were taken using a G-858 cesium vapor magnetometer (GEOMETRICS, USA) coupled with a Trimble Geo7X GPS. The two magnetometer sensors were mounted in vertical gradiometer mode with a spacing of 60 cm between the top sensor and the bottom sensor (see Figure 4 a) in order to limit the influence of magnetic noise sources such as metallic fences and railway tracks surrounding the field site.

Since the vegetation is very dense on site, the data points will be directly presented and no interpolation of the data is possible in this case as the data points are not covering the area with a dense enough grid.

7.3.3 Data treatment

A first filtering of the magnetic measurements was carried out using the MagMap software (GEOMETRICS) with a “Despike” filter (threshold: 5000nT, max spike lim.: 5).

The magnetic measurements were carried out continuously, accompanied by differential GPS measurements. In order to reposition the magnetic field measurements obtained, a resynchronization was carried out between the data acquired with the magnetometer and those acquired with the GPS using a dedicated script in python.

7.4 SEISMIC METHOD

7.4.1 Method description

Seismic techniques utilize the ways in which vibrations travel through materials. The seismic methods can provide elements of interest to derive the subsurface layering and the physical properties of the different materials present, including mechanical characteristics and the state of cracking, fractures and other discontinuous elements.

In Pompey, two active source methods were used, seismic refraction tomography and multiple analysis of surface waves (see Figure 5). A series of geophones were installed at the same locations than the electrical profiles P1, P3 and P5 (see Figure 1). They measured the propagation of seismic waves generated by an artificial source : a sledgehammer struck against a plate. Data were first treated using seismic refraction tools, and then using multichannel analysis of the surface waves (MASW). These two methods are used in near-surface applications where the surface and refracted waves often mask the reflected waves:

- **The Seismic refraction technique** consists in measuring the time required by the P-waves refracted at the interface between materials with different acoustic impedances to reach the geophones. The technique is used to estimate the seismic velocities of the subsurface layers from which important factors such as rippability, rock strength or fluid content can be derived. Both P (primary or pressure) waves and S (secondary or shear) waves can be targeted by Seismic refraction.
- **The MASW technique** measures the surface waves generated from a source to derive a S-wave velocity (V_s) model of the subsurface. Under most circumstances, V_s is a direct indicator of the ground strength (stiffness) and therefore is commonly used to derive load-bearing capacity.

Figure 5 : Seismic measurements running at the Pompey site:a) operator checking the recordings on the acquisition station; b) operator using the hamer to create a vibration in the ground.

7.4.2 Data acquisition

The seismic data were taken on profiles P1, P3 and P5 with respectively 91, 90 and 86 geophones (the vegetation does not allow other geophones to be planted to obtain the same length for the three profiles) and a spacing of 2.5 m between the geophones, arranged in a roll-along:

- Geophones 1 to 48, 1 shot every 4 geophones from geophone 1
- Geophones 24 to 72, 1 shot every 4 geophones from geophone 24
- Geophones 48 to 91, 1 shot every 4 geophones from geophone 48

The choice of one shot triggered every four geophones is a compromise between the measurement time available for each seismic profile and the lateral resolution reached along the seismic profile.

7.4.3 Data treatment

The seismic data were first treated with classical seismic refraction tools (Pickwin^{TM} module from SeisImager/2D^{TM}, Geometrics), by picking the first arrival times of the waves. The vertical profiles can then be directly interpreted, or inverted to retrieve the wave speed of the different layers. The data being noisy and the wave speed in the ground lower than the one in the air, the procedure was very difficult to apply (see Figure 6a).

The multichannel analysis of the surface waves (MASW) method was thus used instead (see Figure 6b). The software SurfSeis was used to invert the data and obtain a seismic tomography profile of Vs.

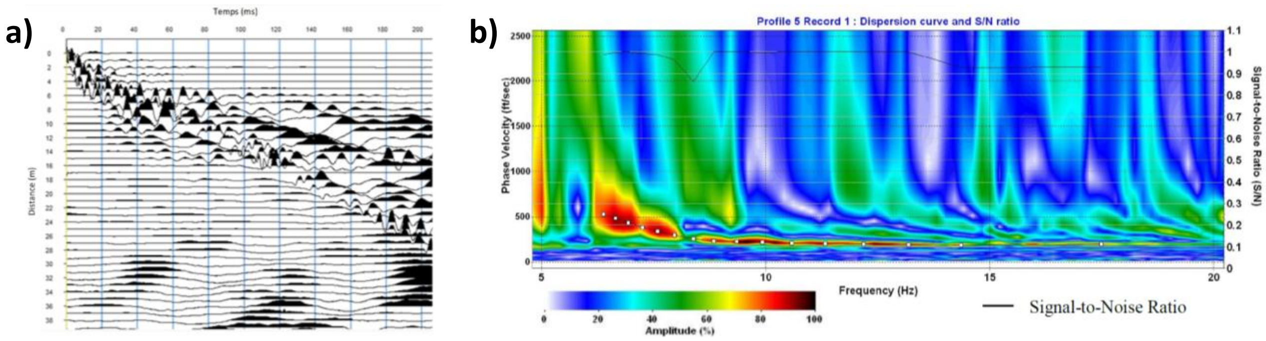

Figure 6 : a) Example of raw signal obtained from record 1 for profile P5; b) Example of a dispersion curve and signal-to-noise ratio (black curve) obtained using SurfSeis from the same dataset (record 1, profil P5).

7.5 MEASUREMENT POSITIONING

All the geophysical methods used were positioned with a Trimble Geo7X GPS associated with an external Zephyr type antenna. This receiver can pick up GPS satellites as well as GLONASS satellites (on average between 14 and 20 satellites). The values obtained were corrected in post-processing, using IGN ephemerides. This post-processing makes it possible to achieve centimetric precision in X and Y (under optimal conditions of use).

The precision on the altimetric surveys (Z) is a function of the vegetation cover and the topography. The values of Z, affected by an abnormally high precision, and/or which seemed aberrant (compared to the DTM and compared to field observations), were rejected, and were therefore not taken into account in the construction of the topographic profile. The final precision on Z is of the order of a few tens of centimeters in absolute terms (under optimal conditions of use).

The geographic reference system is Lambert 93 and/or WGS84.

8 RESULTS

8.1 TDIP PROFILES

8.1.1 Electrical resistivity – profiles P1 to P5

The electrical resistivity results of profiles P1 to P7 highlight the following succession of geoelectrical horizons (see Figure 7), from bottom to top:

- **A layer of medium resistivity R3**, with a top from 192 to 180 m of altitude. The values of resistivity are ranging from 40 to 150 ohm.m. This layer could correspond to the natural formations in which the waste was deposited: Quaternary alluvium from the Meurthe and the Moselle surrounding the site.
- **A conductive layer C3** with a thickness ranging from 4 to 10 m. The values of resistivity of this layer are ranging from 5 to 40 ohm.m. The layer is limited laterally for several profiles (e.g. for P1, the layer extends from the distance 30 m to the distance 170 m). For P5, the thickness of the layer is decreasing to 2m in the N-NW side of the profile, probably indicating the lateral edge of the layer. This layer could correspond to a layer of anthropogenic deposits, part of the former settling pond deposits.
- **A layer of medium resistivity R4**, that runs from the surface of the ground to a maximum thickness of 3 m. The values of resistivities range from 40 to 80 ohm.m. This layer could also correspond to a layer of anthropogenic deposits, part of the former settling pond deposits. As they are more resistive, the nature of the deposits might be different. They could potentially contain less metallic elements
- **A resistive layer R1**, that is located in the S-SE corner of the site. It runs from the ground surface to a maximum of 4 m thick. Its resistivity is ranging from 40 to 1500 ohm.m. The center of this layer corresponds to a mound (see P7 location on all the profiles), probably indicating that this deposit is subsequent to the settling pond deposits. From observations in the field, this layer might be composed of civil engineering wastes with concrete blocks and rebars.
- **A resistive layer R5**, that is located in the N-NW corner of the site. This layer is a little more resistive than the layer R3. It is not distinguishable for P4 and P5. The boundary between the layers R3 and R5 is not very visible. This layer might be part of the natural alluvia formation, or another layer of anthropic deposits subsequent to the settling pond deposits.
- **A resistive anomaly R6**, only visible on P3, that is located in the N-NW corner of the profile. The anomaly corresponds to a topographic high at the surface (a mound). From observations

in the field, this layer might be composed of all comers household and construction wastes. It is probably the youngest deposit on the field site.

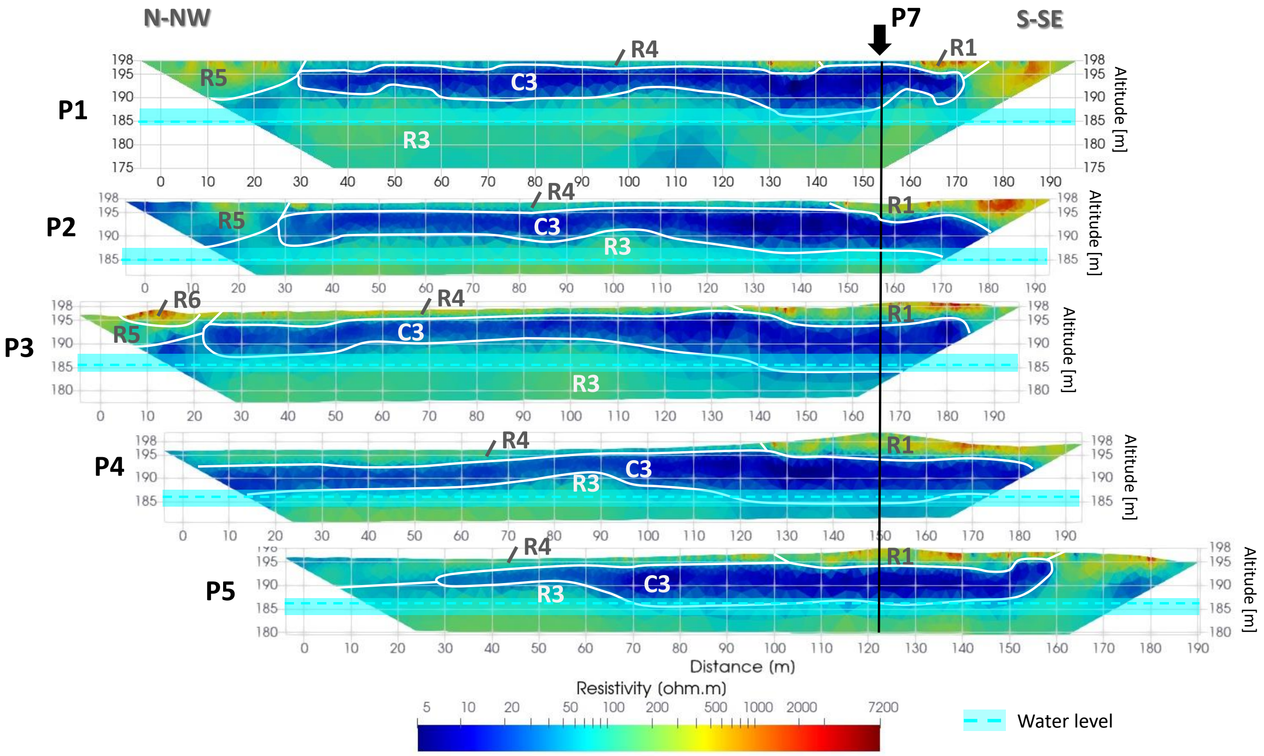

Figure 7 : Electrical resistivity tomography results for profiles P1 to P5, all oriented N-NW / S-SE (see Figure 1). The black arrow and line represent the position of the perpendicular profile P7. The turquoise rectangle and associated dotted line corresponds to the known range of the water level that is higher in the W-SW side (profile P5, close the Moselle river) and lower in the E-NE side (profile P1, close to the Meurthe river). White lines corresponds to interpreted limits of electrical resistivity layers named Cn or Rn, depending on their resistive or conductive relative nature.

8.1.2 Chargeability – profiles P1 to P5

The chargeability results complement the electrical resistivity results of profiles P1 to P5. Several observations can be added to the first descriptions of the layers using only electrical resistivity:

- **For layers R1 and R5:** the highest chargeabilities are measured. The values are ranging from 5 to 92 mV/V, with an average value of 30 mV/V. The highest values of chargeability corresponds to the most resistive parts of the layers. In the field, we observed massive metal bars (3-5 cm diameter) pointing out of the mound constituting layer R5. These layers might be composed of all comers household and construction wastes, including massive blocks of concrete (explaining the high resistivities) and metal bars – embeded or not in the concrete (explaining the high chargeability).

- **Layer R3** has the lowest values of chargeabilities, ranging from 0.2 to 1.5 mV/V. This layer interpreted as a layer of natural alluvium. It is not expected to contain high concentration of metallic particles. The low values of chargeability gives another clue towards this interpretation.

  For profile P1, the values of chargeability for the layer R3 are increasing with depth. These variations are not interpreted as real variations. They are probably artefacts of the TDIP inversion, because of the lower quality of the data in this area.

- **Layers C3 and R4** are the layers interpreted as being constitutive of the anthropogenic deposits from the former settling pond. The values of chargeability are higher for C3 (between 3 and 86 mV/V, with an average value of 5 mV/V) than for R4 (between 0.1 and 3 mV/V, with an average value of 1 mV/V). These differences brings another piece of evidence that the layer C3 (more conductive and higher chargeability) is probably the most interesting one of the deposit in terms of metal concentration.

- **The limit between R3 and C3** is not detected at the same depth than for the resistivity profiles for profiles P3 and P5. The C3 layer thickness is lower when taking into account the chargeability. This is especially the case when the limit is deeper and closer to the water level (S-SE part of the profiles). The electrical resistivity is more sensitive to water changes in the pores. The higher thickness of C3 observed in the resistivity profiles might come from a highly charged water (high ionic strength) that percolates through the anthropic deposits (with metallic elements dissolving into the water) to the natural alluvium. New limits of the C3 layer are proposed with the metal factor profiles (see Figure 9).

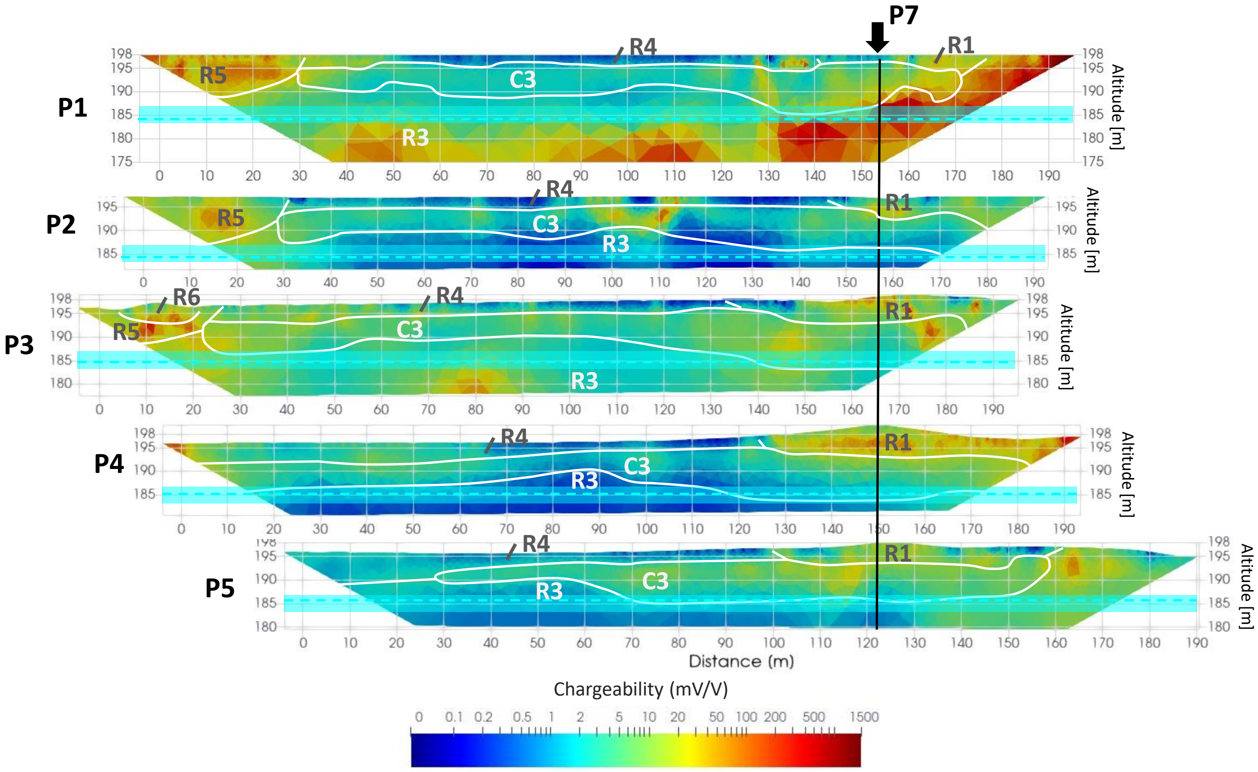

Figure 8: Chargeability tomography results for profiles P1 to P5, all oriented N-NW / S-SE (see Figure 1). The black arrow and line represent the position of the perpendicular profile P7. The turquoise rectangle and associated dotted line corresponds to the known range of the water level that is higher in the W-SW side (profile P5, close the Moselle river) and lower in the E-NE side (profile P1, close to the Meurthe river). White lines corresponds to interpreted limits of electrical resistivity layers named Cn or Rn, depending on their resistive or conductive relative nature (see Figure 7).

8.1.3 Metal factor – profiles P1 to P5

The metal factor MF is a parameter that summarizes the variations observed in terms of electrical resistivity and chargeability. It can be expressed as a ratio between chargeability M and resistivity ρ. Here it is taken as:

$$MF = 2000.\frac{M}{\rho}$$

With MF in 1/(ohm.m), M in mV/V and ρ in Ohm.m

The same observations than for the electrical resistivity and chargeability profiles can be made in terms of layers' identification. We made an attempt to refine some of the limits between the natural formations R3 and the anthropogenic deposits from the tailing pond (supposedly) C3 (see dotted lines in Figure 9). With these new observations, the thickness of the C3 deposits decreases from 2 to 3 m and the limit between R3 and C3 remains in majority above the water level.

Zones of particular interest for the REGENERATIS project are the ones were the electrical resistivity is the lowest and the chargeability is the highest, i.e. where the metal factor is the highest. We identified several of these zones (see Z1 to Z4 in Figure 9). Targeted sampling close to these particularly interesting areas will bring additional data that will be very useful to interpret these highly conductive and chargeable areas.

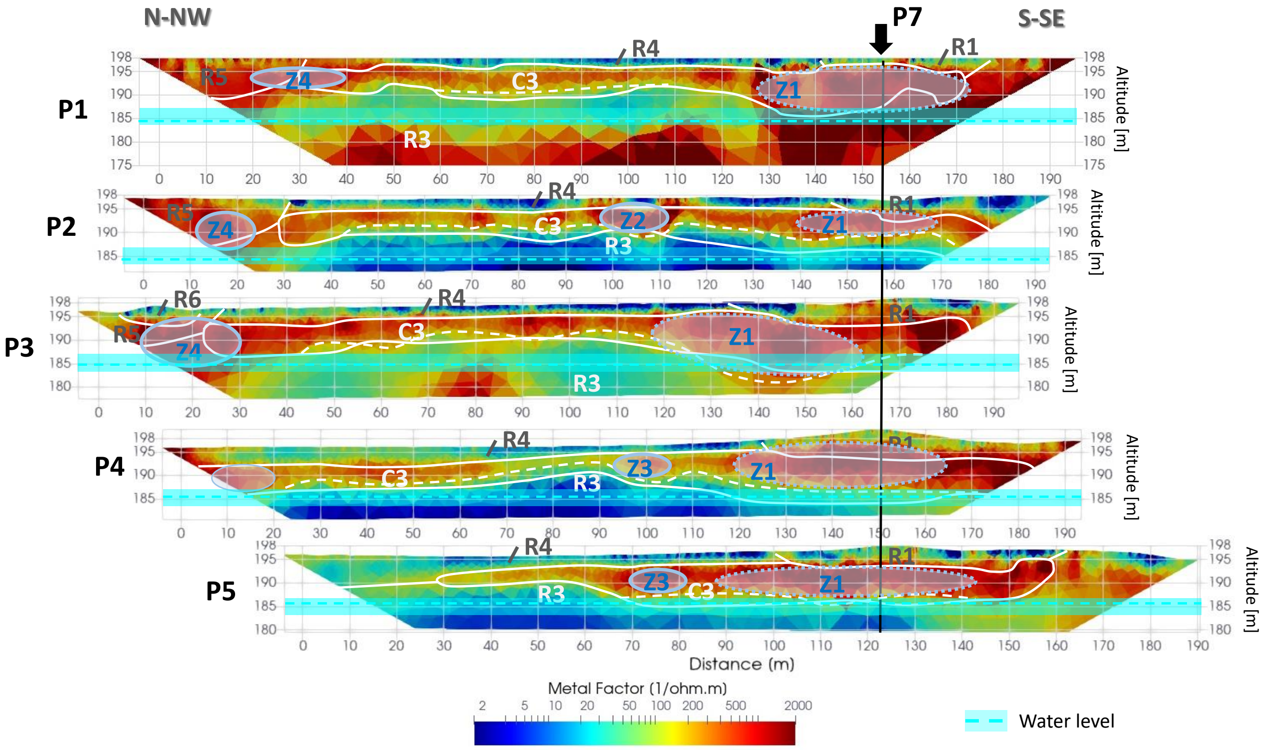

Figure 9 : Metal factor tomography estimations for profiles P1 to P5, all oriented N-NW / S-SE (see Figure 1). The black arrow and line represent the position of the perpendicular profile P7. The turquoise rectangle and associated dotted line corresponds to the known range of the water level that is higher in the W-SW side (profile P5, close the Moselle river) and lower in the E-NE side (profile P1, close to the Meurthe river). White lines corresponds to interpreted limits of electrical resistivity layers named Cn or Rn, depending on their resistive or conductive relative nature (see Figure 7). Dotted white lines correspond to the limits interpreted from the metal factor variations. Light blue circles highlight zones of particular interest called Zn, with the highest MF values.

8.1.4 TDIP parameters – profile P7

The profile P7 is crossing the five other TDIP profiles perpendicularly (see Figure 1). It gives insight on the lateral extent of the layers identified in the 5 other profiles, towards the East and the West. At the crossing locations between P7 and the other profiles, the correlations in terms of resistivity and chargeability values, and thus in terms of identified layers, are good (see Figure 11). Several observations can be made:

- **The layers R1, C3 and R3** can be identified within the same altitude range than on the 5 other profiles.
- **A new conductive layer C1** is observed on the Western part of the profile. It has a resistivity range and thickness close to the ones from layer R4: (1) maximum thickness of 2 m; (2) resistivity range from 30 to 120 ohm.m. This layer could be a lateral extension of the layer R4. It could correspond to a layer of anthropogenic deposits, modified by the plant cover and the site rehabilitation. As the resistivity is higher in C1 than in C3, these deposits could potentially contain less metallic elements.
- **A conductive anomaly C2** is observed on the East of the resistive layer R1. It corresponds an observed local depression at the ground surface, potentially indicating the presence of a stream of water at the surface. No water was observed during the field work in March 2020.

- **A new resistive layer R2** is observed on the Eastern part of the profile. It was very hard to place the electrodes in this area of the site. A continuous concrete layer was observed at the Eastern part of this layer close to the surface of the ground. This layer might correspond to the location of a former building.
- **The metal factor variations suggest that the limit between the layers R3 and C3** is located at a shallower depth than estimated using only the electrical resistivity results. The new limit is almost always close or above the water level altitude (except close to the P4 profile, at the top of the mound). This variation in the altitude estimation might come from a highly charged water (high ionic strength) that percolates through the anthropic deposits (with metallic elements dissolving into the water) to the natural alluvium, decreasing the resistivity of the top of the natural alluvium.
- **The zone Z1** of particular interest in terms of metal concentration (high metal factor, low resistivity, high chargeability) can be identified and extends laterally further than profiles P1 and P5 (see Figure 10).

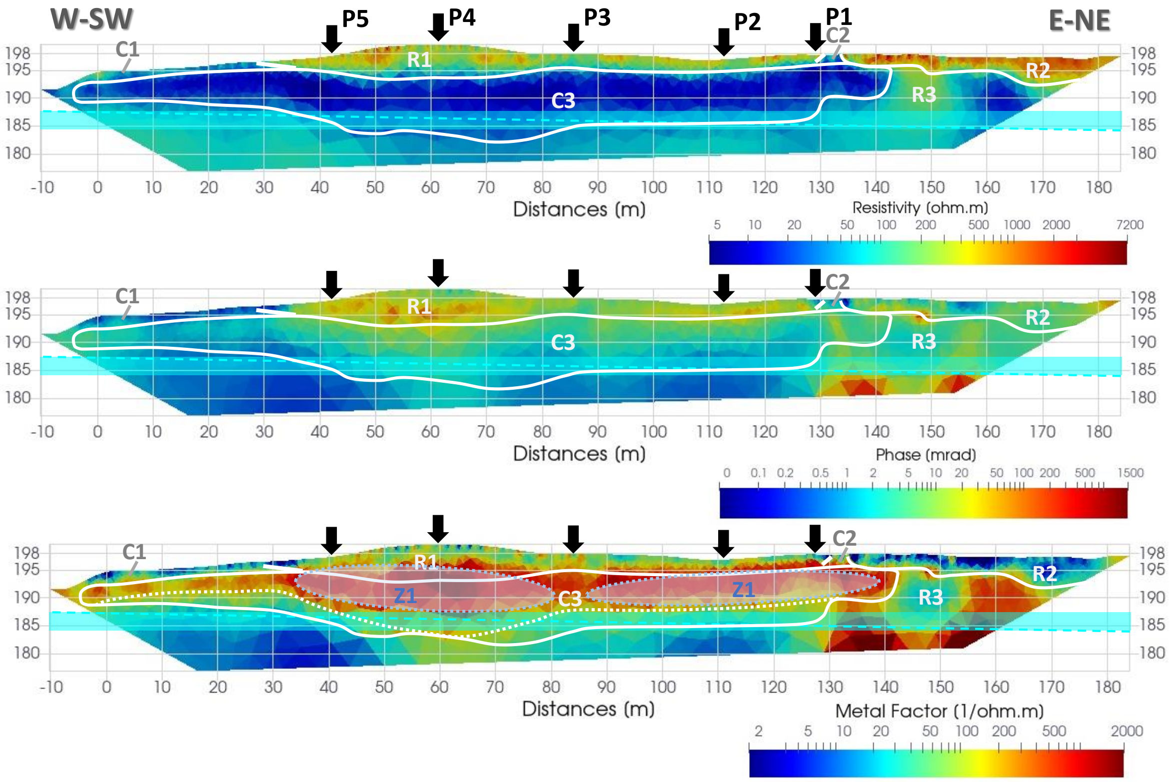

Figure 10 : Tomography results for profile P7 (see Figure 1). The parameters inverted are: a) the inverted electrical resistivity, b) the inverted phase-shift, c) the estimated metal factor. The black arrow and line represent the position of the perpendicular profile P7. The turquoise rectangle and associated dotted line corresponds to the known range of the water level that is higher in the W-SW side (profile P5, close the Moselle river) and lower in the E-NE side (profile P1, close to the Meurthe river). White lines corresponds to interpreted limits of electrical resistivity layers named Cn or Rn, depending on their resistive or conductive relative nature (see Figure 7). Dotted white lines correspond to the limits interpreted from the metal factor variations. Light blue circles highlight zones of particular interest called Z1 (see Figure 9), with the highest MF values.

8.2 EM AND MAGNETIC MAPPING

The EM mapping tool used gives information on variations of magnetic and electrical properties for grounds with a maximum investigation depth of 1.8 m. Since the thickness of the deposits is estimated to approximately 10 m, the variations observed with the EM method are only available for the shallowest part of the deposits. Furthermore, the dense vegetation made it hard to measure EM parameters over a regular, dense grid. The EM and magnetic data are thus sparse and not regularly taken.

The in-phase component measured gives information about the magnetic susceptibility of the medium (i.e. presence of metallic object/structures), whereas the quadrature component is directly proportional to its electrical conductivity, and can thus be directly converted into electrical conductivity (or resistivity) values.

In terms of resistivity variations, several observations can still be made (see Figure 11 and Figure 12):

- The values of resistivity measured using the EM device and the ones obtained through TDIP measurements are very similar at the same depth. The results are thus very coherent and trustworthy from one method to the other
- Three zones can be distinguished laterally within the deposit shallow layer:
  - **Z1 in the northern part:** this area corresponds to a more conductive layer in the first 50 cm (the electrical resistivity $\rho \in [10;33]$ ohm.m), and then a more resistive layer down to 1.8 m approximately (the electrical resistivity $\rho \in [50;500]$ ohm.m). This area is not well covered by the TDIP profiles. It could correspond to the ***layers named R5 and/or R6*** (see Figure 7). This shallow layer might be composed of all comers household and construction wastes, including metal bars, concrete blocks that could explain the observed switch between conductive and resistive anomalies.
  - **Z3 in the southern part:** The same variations than in the Z1 zone can be observed in the south corner of the field site. The delimitation of the area corresponds to the limit of the ***layer R1*** identified from TDIP data (see Figure 7). From observations in the field, crossed by TDIP results, this layer might be composed of civil engineering wastes with concrete blocks and rebars, explaining the observed switch between conductive and resistive anomalies.
  - **Z2 in the center of the deposit:** this area corresponds to the layer R4 identified using TDIP results (see Figure 7). The values of resistivities range from 100 to 500 ohm.m in the first 50 cm, and then reach 20 to 50 ohm.m down to 1.8 m approximately. This layer could also correspond to a layer of anthropogenic deposits, part of the former settling pond deposits.

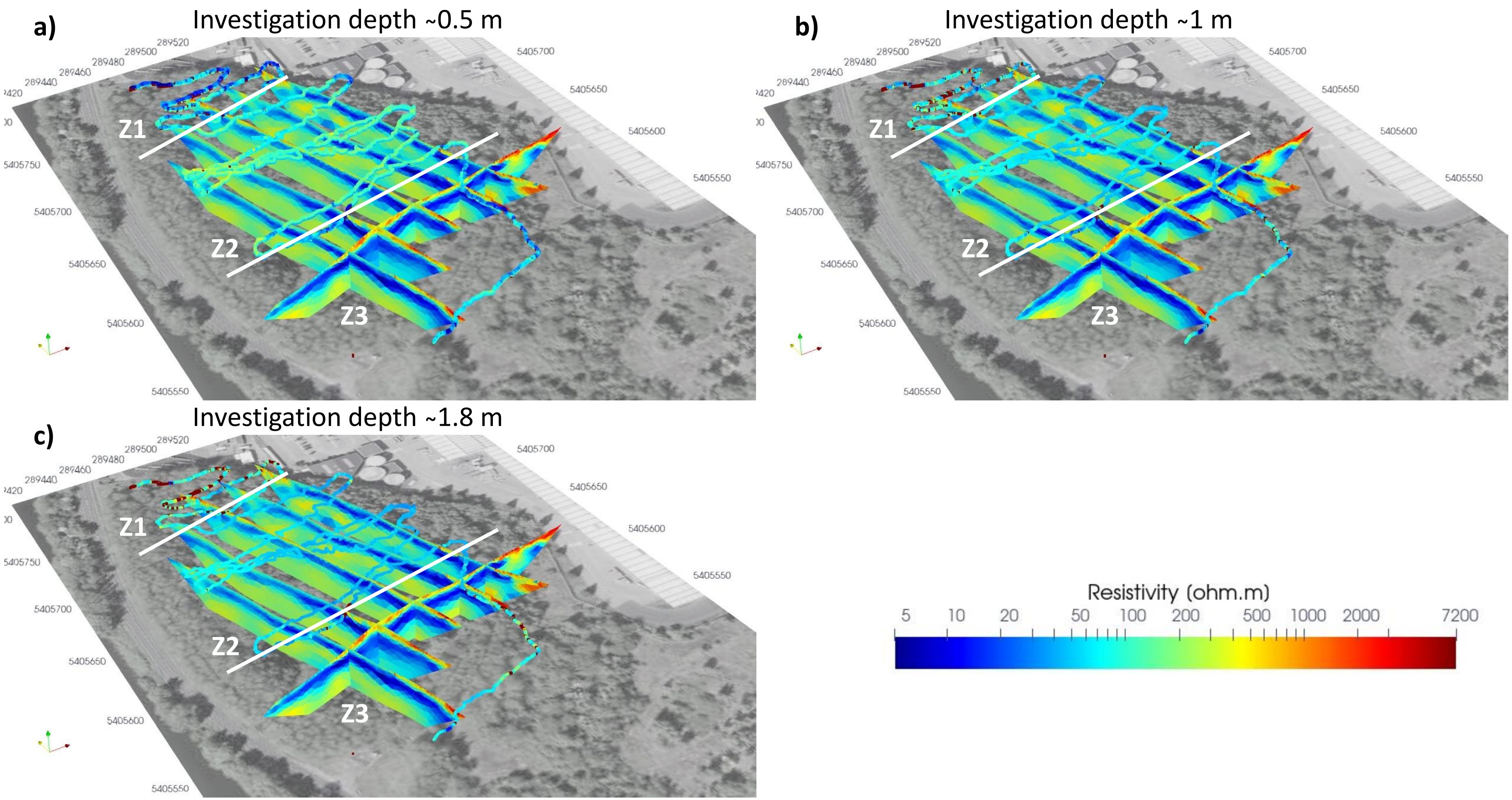

*Figure 11: 3D representation of the electrical resistivity estimated through: (1) TDIP measurements (the 6 profiles - see Figure 7); and (2) EM measurements (cartographic info. represented by points/path data). **a)** Representation of EM results for the 0.5 m investigation depth; **b)** Representation of EM results for the 1 m investigation depth; **c)** Representation of EM results for the 1.8 m investigation depth (see part 7.2). The white lines indicate the interpreted limit between three zones with different resistivity variations.*

These three zones also have distinct magnetic signatures (see Figure 12 and Figure 13):

- **Zones Z1 and Z3** are showing the highest magnetic contrasts, both in terms of in phase EM measurements and of magnetic vertical gradient. This observation is in good correlation with the previous interpretation of areas containing recent all comers household and construction wastes, including metal bars and concrete.
- **Zone Z2** is containing middle range in phase measurements and very low vertical gradient measurements. This layer could correspond to the latest deposits from the former settling pond.

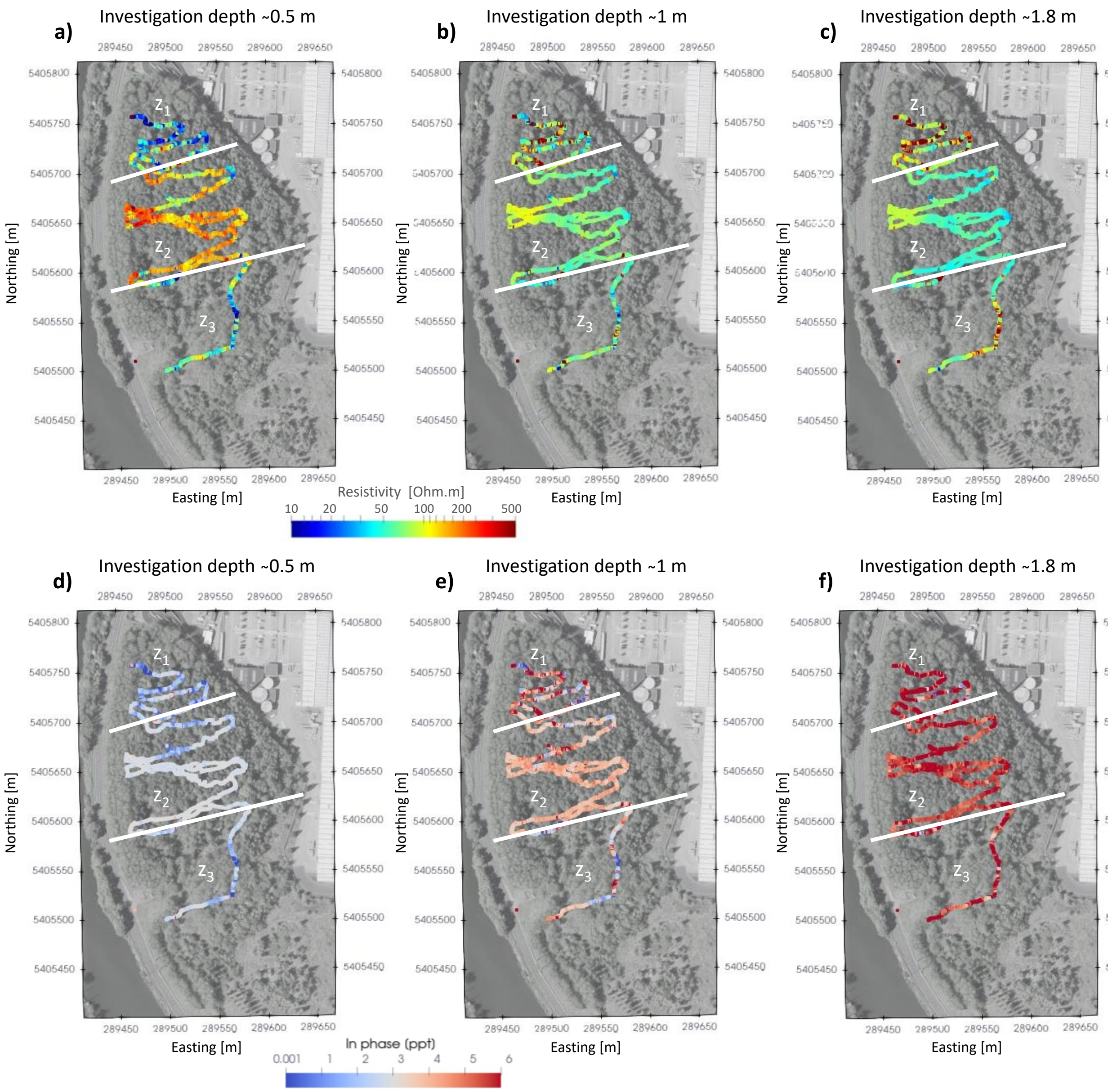

*Figure 12 : EM measurements (cartographic info. represented by points/path data). **a)** Representation of electrical resistivity for the 0.5 m investigation depth; **b)** Representation of electrical resistivity for the 1 m investigation depth; **c)** Representation of electrical resistivity for the 1.8 m investigation depth (see part 7.2); **d)** Representation of in phase results for the 0.5 m investigation depth; **e)** Representation of in phase results for the 1 m investigation depth; **f)** Representation of in phase results for the 1.8 m investigation depth (see part 7.2) The white lines indicate the interpreted limit between three zones with different resistivity variations.*

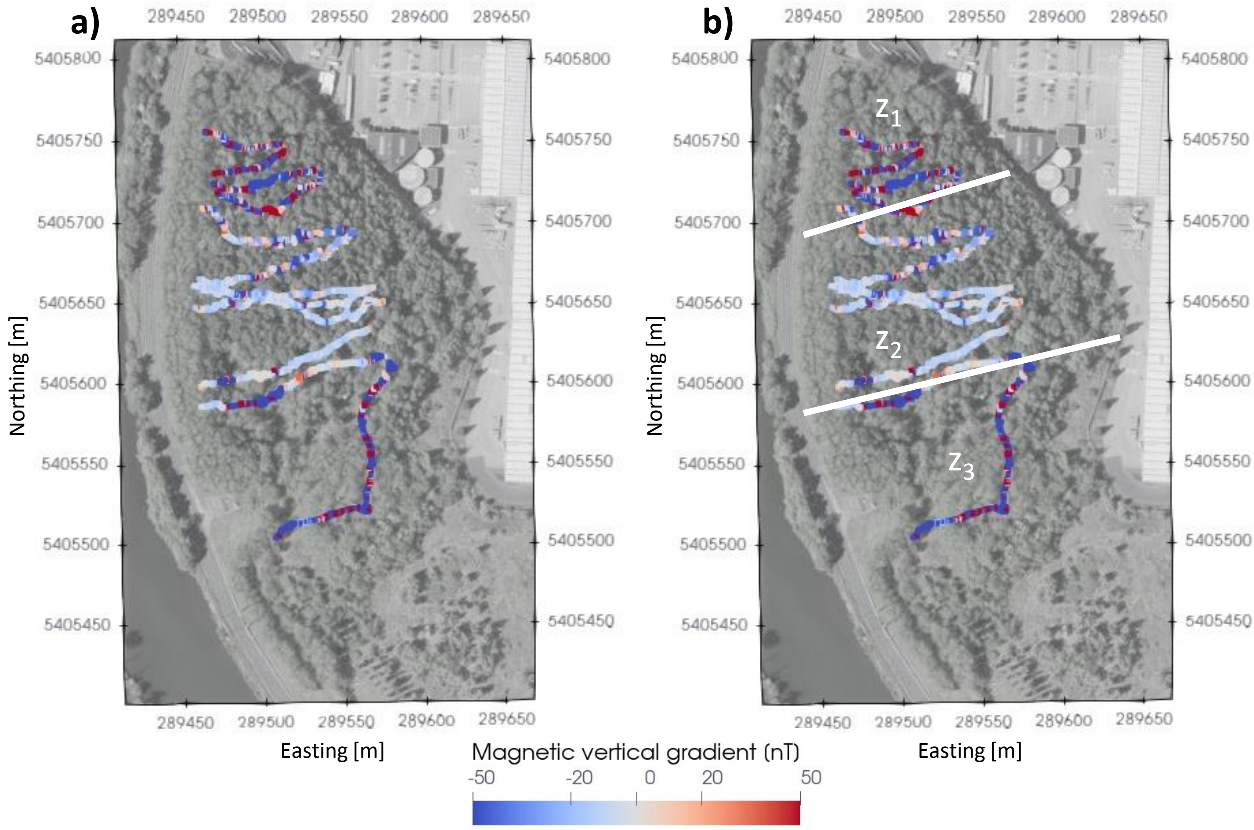

*Figure 13 : Magnetic measurements of the vertical gradient (cartographic info. represented by points/path data). **a)** Data alone; **b)** Data with interpreted areas. The white lines indicate the interpreted limits between three zones with different resistivity variations (see Figure 12), that also correspond to magnetic gradient variations.*

8.3 Seismic profiles

Three of the TDIP profiles have been chosen to also run seismic measurements. The data were inverted using the MASW method to retrieve variations of shear waves velocity. The interpretation of the TDIP results have been superimposed to the inverted sections in order to ease the comparison (see Figure 14). Several observations can be made to complete the interpretation of the electrical data:

- The limit between the natural geological formation (R3 where Vs $\in$ [350; 600] m/s) and the anthropic deposits (Vs < 300 m/s) is well defined and close to the one interpreted using the electrical results
- Within the anthropic deposit layers, the distinctions between the different layers and anomalies (C3, R1, R4, R5 and R6) is not so clear and other patterns are observed. The seismic data quality was not very good (e.g. low wave speed) because of the heterogeneity of the materials present close to the surface (domestic and civil engineering wastes). We will thus focus the interpretation on the electrical results rather than on the seismic ones.

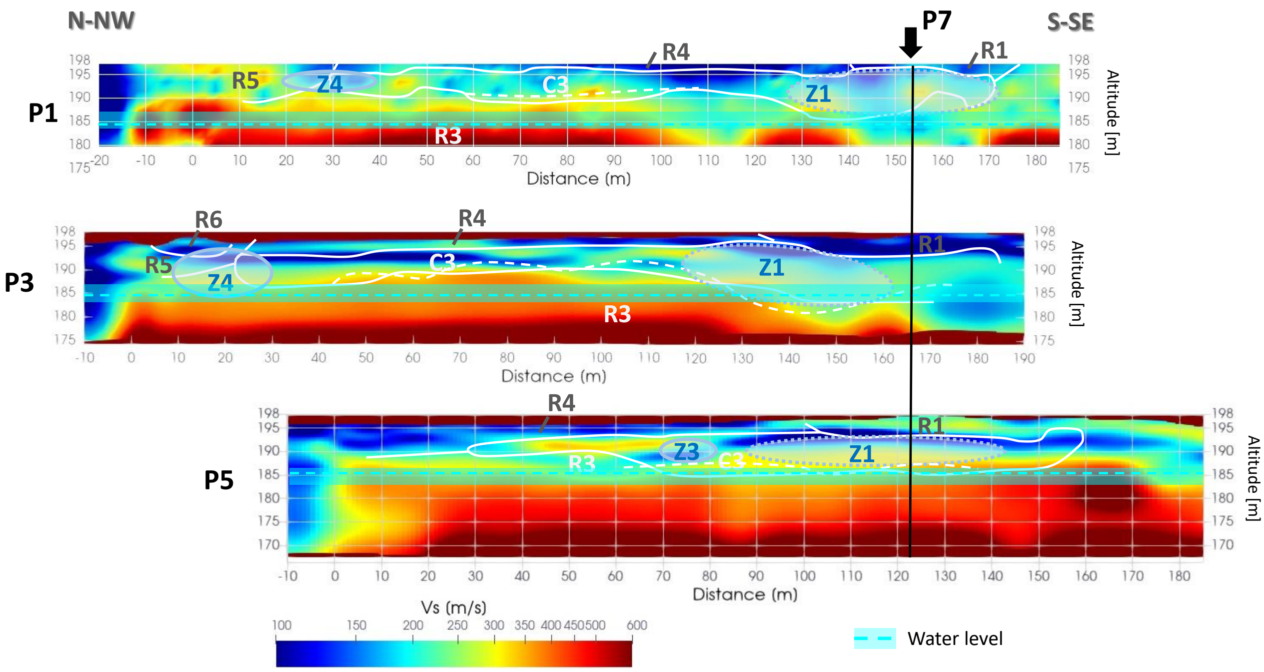

Figure 14 : Shear waves speed tomography results for profiles P1, P3 and P5, all oriented N-NW / S-SE (see Figure 1). The black arrow and line represent the position of the perpendicular profile P7. The turquoise rectangle and associated dotted line corresponds to the known range of the water level that is higher in the W-SW side (profile P5, close the Moselle river) and lower in the E-NE side (profile P1, close to the Meurthe river). White lines corresponds to interpreted limits of electrical resistivity layers named Cn or Rn, depending on their resistive or conductive relative nature (see Figure 7, 6 and 7). Dotted white lines correspond to the limits interpreted from the metal factor variations. Light blue circles highlight zones of particular interest called Zn, with the highest MF values (see Figure 9).

9 INTERPRETATION AND RECOMMENDATIONS

The geophysical results highlight the following succession of horizons (see Figure 7), from bottom to top:

- **A layer R3** of medium resistivity, low chargeability and high Vs, with a top limit varying from 192 to 180 m of altitude. This layer could correspond to the natural formations in which the waste was deposited: Quaternary alluvium from the Meurthe and the Moselle surrounding the site.
- **A layer C3** that is conductive, with a higher chargeability and lower Vs. Its thickness is ranging from 4 m (in the Northern part of the site) to 10 m (in the southern part of the site). This layer could correspond to a layer of anthropogenic deposits, part of the former settling pond deposits. The layer is limited laterally for several profiles (e.g. for P1, the layer extends from the distance 30 m to the distance 170 m), indicating the limit of the former settling pond. Because of its electrical properties, it might be the most interesting layer in terms of metal content.
- **A layer R4**, that is more resistive, with lower chargeability signature and low Vs. It runs from the surface of the ground to a maximum thickness of 3 m. This layer could also correspond to a layer of anthropogenic deposits, part of the former settling pond deposits. As they are more resistive, the nature of the deposits might be different. They could potentially contain less metallic elements (maybe linked with the vegetation cover and its root network)
- The layer R4 is edged by **resistive layers: R1 in the S-SE corner, R5 and R6 in the N-NW corner, R2 in the E-NE corner.** These layers are probably of anthropic origin, but not part of the former settling pond deposits. For R1, R5 and R6, they are interpreted as all comers household and construction wastes, including metal bars, concrete blocks explaining the presence of magnetic dipoles in these areas.

In order to go further in the interpretation of the geophysical results, four sounding locations are suggested (see Tableau 2):

- The location of **FP1** and **FP4** are chosen to investigate a volume of particularly interesting geophysical properties Z1 (see Figure 9 and Figure 10)
- The location of **FP3** is chosen to investigate another volume of particular interest Z4 (see Figure 9)
- The location of **FP2** is chosen to be in the center of the settling pond, and representative of the average geophysical signature of the former settling pond. It could be used as a reference to compare the other sounding's results to.

Tableau 2 : Recommended GPS coordinates of the four sounding

Sounding name	Latitude [°]	Longitude[°]
FP1	48.76755883	6.135278975
FP2	48.7682648	6.135338145
FP3	48.76890601	6.134964081
FP4	48.76773870	6.136143922

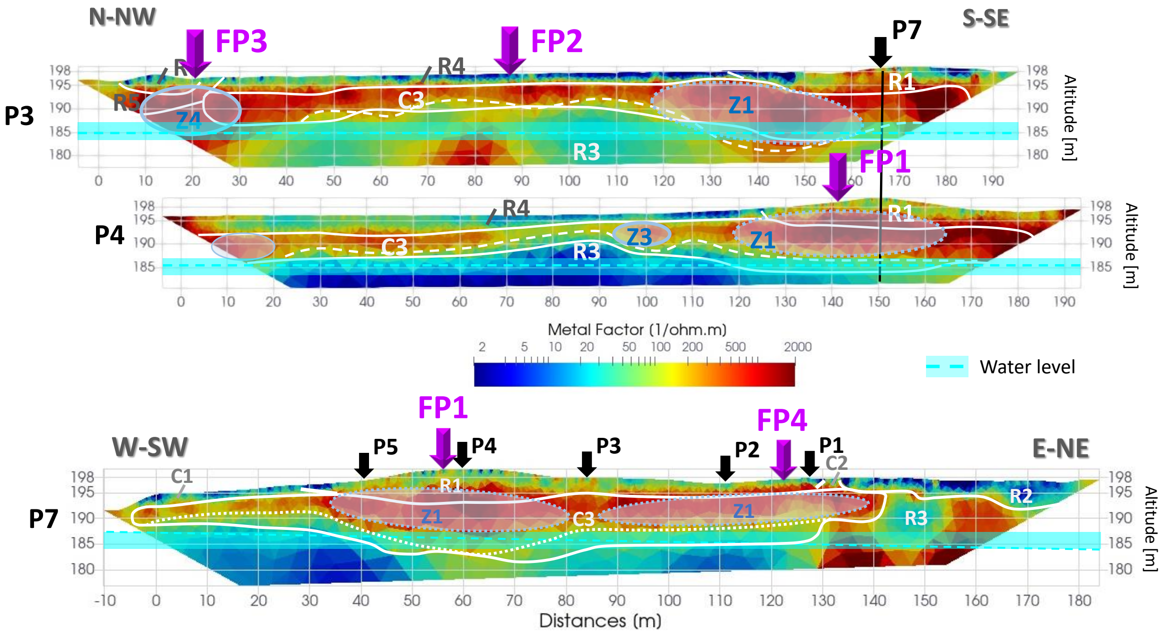

Figure 15 : Location of the 4 recommended sounding points, placed on the metal factor tomography estimations for profiles P3, P4 and P7 (see Figure 9 and Figure 10Figure 1). The black arrow and line represent the position of the perpendicular profile P7. The turquoise rectangle and associated dotted line corresponds to the known range of the water level that is higher in the W-SW side (profile P5, close the Moselle river) and lower in the E-NE side (profile P1, close to the Meurthe river). White lines corresponds to interpreted limits of electrical resistivity layers named Cn or Rn, depending on their resistive or conductive relative nature (see Figure 7). Dotted white lines correspond to the limits interpreted from the metal factor variations. Light blue circles highlight zones of particular interest called Zn, with the highest MF values.

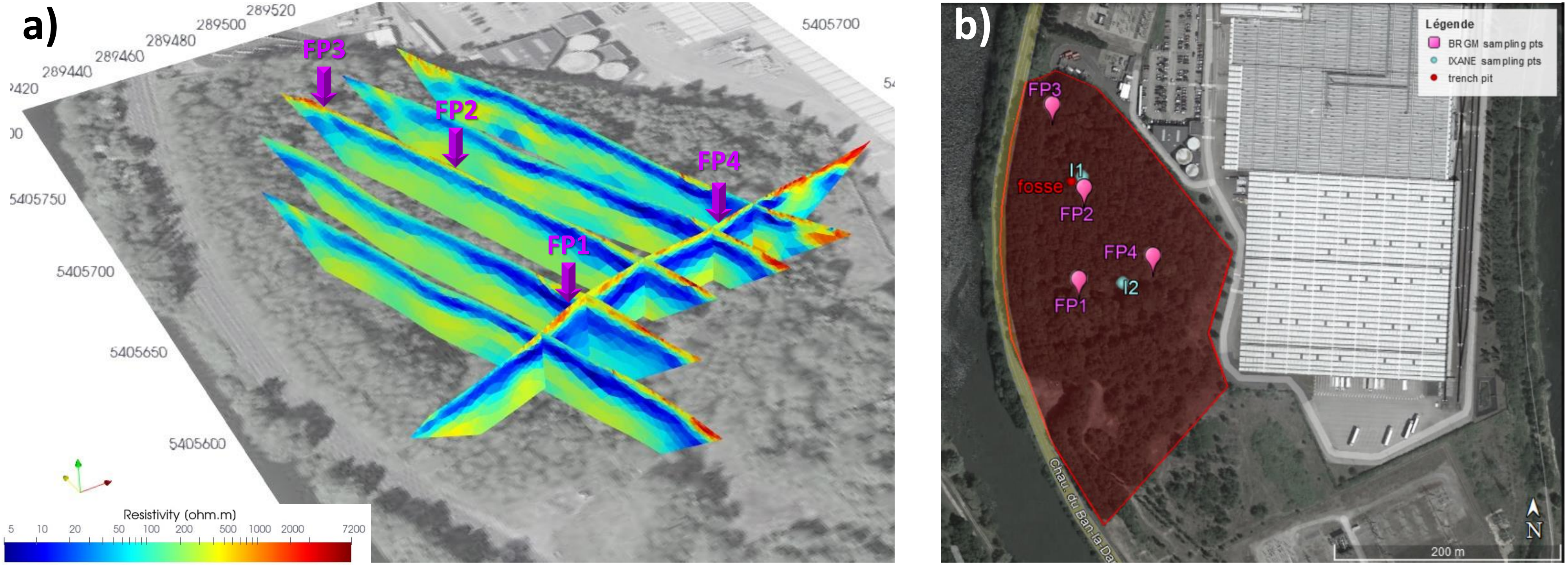

Figure 16 : Location of the 4 recommended sounding points, placed on: a) a 3D representation of the electrical resistivity estimated through TDIP measurements (the 6 profiles - see Figure 7); b) the map of the field site with the different sampling locations.

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BASOL: database on polluted or potentially polluted sites and soils calling for action by public authorities, for preventive or curative purposes, http://basol.developpement-durable.gouv.fr/

Community of communes of the Pompey basin website: http://www.bassinpompey.fr/

Géoportail: website of the National Institute of Geographic and Forest Information (IGN), http://www.geoportail.gouv.fr

Infoterre : website gathering all available BRGM data: geological maps from 1: 1,000,000 to 1: 50,000, files from the Basement Data Bank and geological logs, maps of natural and industrial risks, data on groundwater, etc., https://infoterre.brgm.fr/

11 APPENDIX 1: RAW INVERTED ELECTRICAL PROFILES

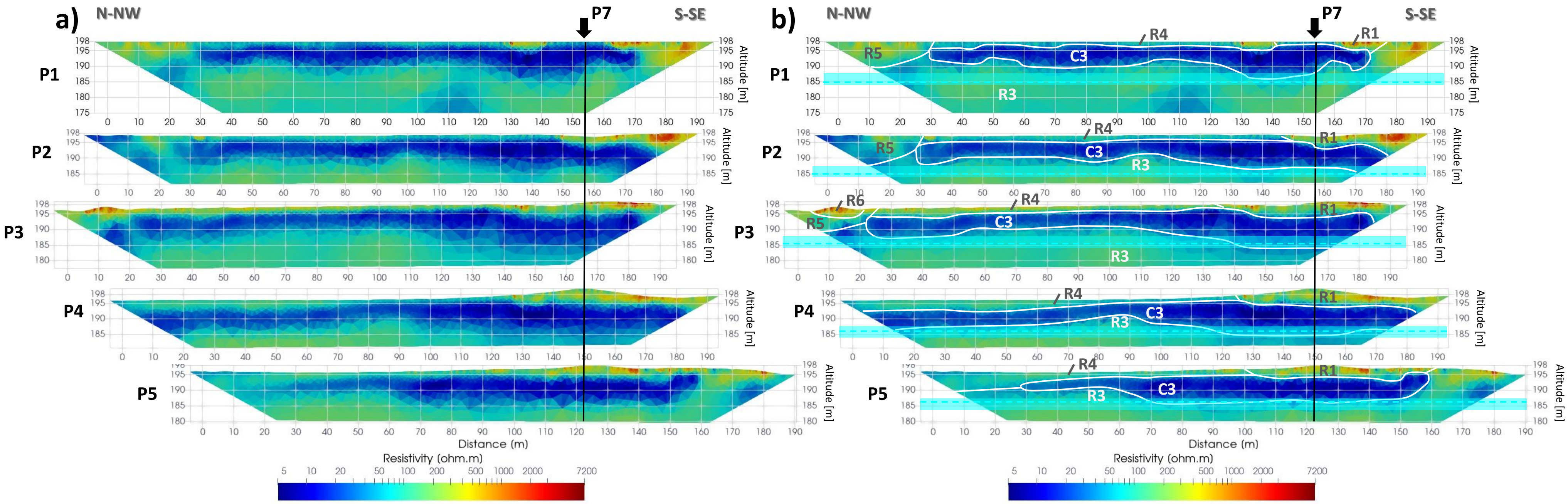

Figure 17 : Inverted electrical resistivity tomographies for profiles P1 to P5 : a) without interpreted layers ; b) with interpreted layers.

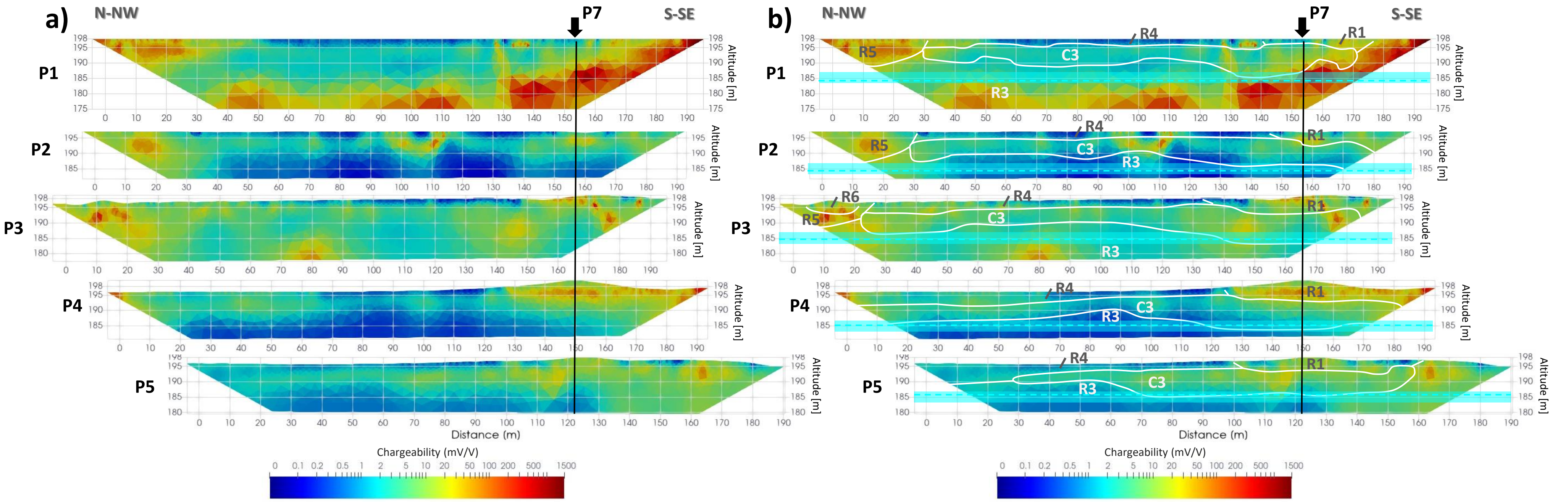

Figure 18 : Inverted chargeability tomographies for profiles P1 to P5 : a) without interpreted layers ; b) with interpreted layers.

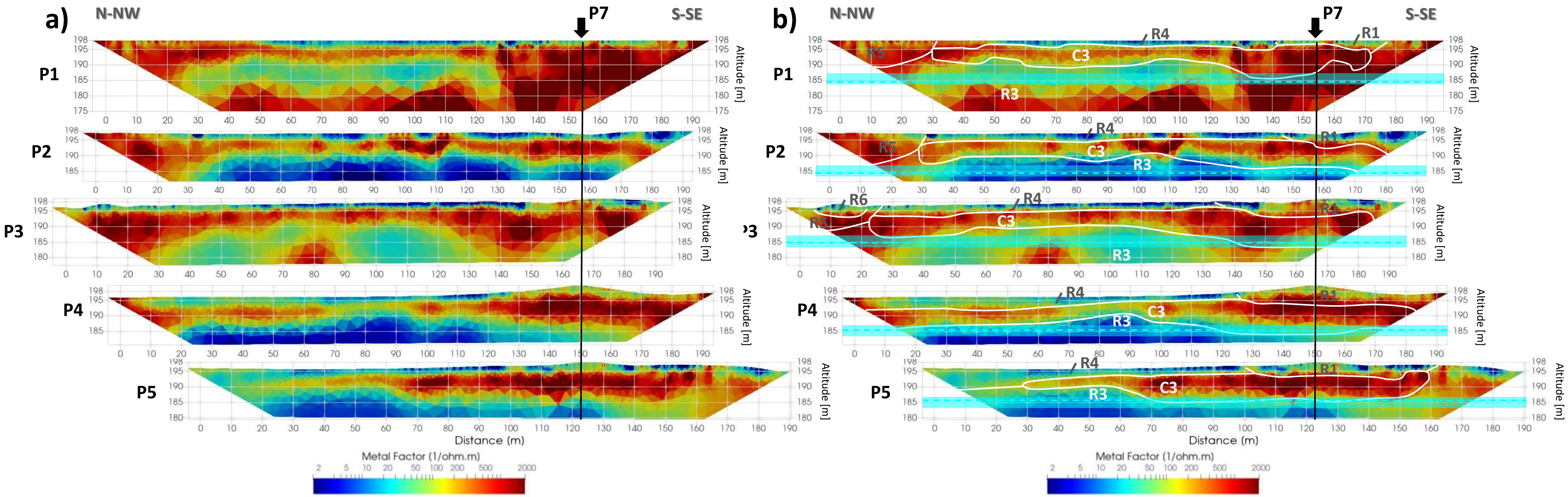

Figure 19 : Estimated metal factor tomographies for profiles P1 to P5 : a) without interpreted layers ; b) with interpreted layers.

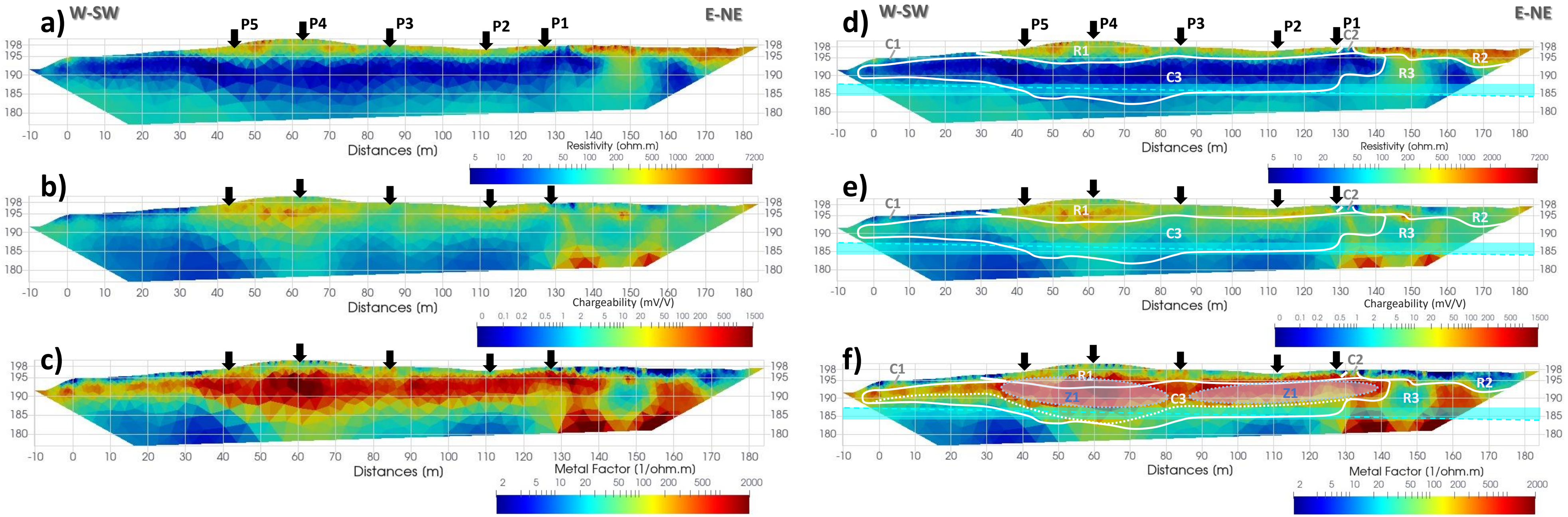

Figure 20 : Estimated electrical resistivity (a) and d); chargeability (b) and e); metal factor (c) and f)) tomographies for profile P7, without interpreted layers (a), b) and c)); and with interpreted layers (d), e) and f)).

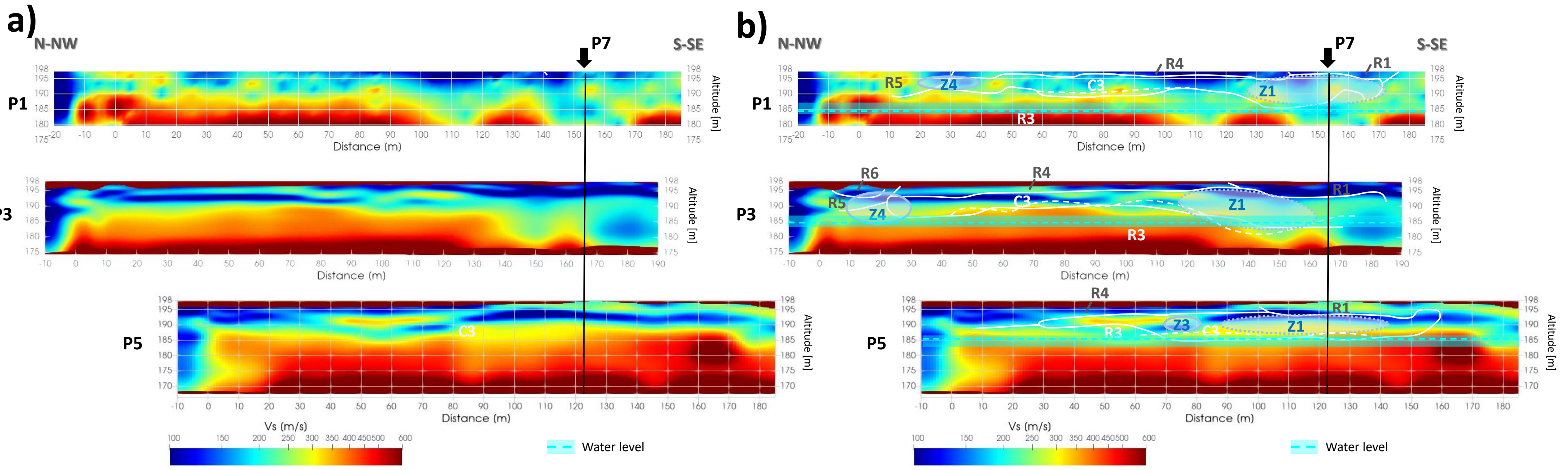

Figure 21 : Estimated Vs tomographies for profiles P1, P3 and P5 : a) without interpreted layers ; b) with interpreted layers.