

1 **TITLE: AN ELECTROSTRATIGRAPHIC CROSS-SECTION ACROSS THE**  
2 **CENTRAL PO PLAIN: BEARINGS ON SUBSURFACE GEOLOGY AND**  
3 **HYDROSTRATIGRAPHY.**

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12  
13 **ABSTRACT**

14 A 72-kilometers-long N-S cross-section was surveyed with Direct Current resistivity soundings through the  
15 Quaternary clastic infill of the Apennine foredeep in the Po plain of Lombardy (Northern Italy). The aims are: 1) to  
16 test the potential of DC resistivity methods at the regional scale; 2) to draw the electrostratigraphic picture of the basin  
17 fill, down to the pre-Quaternary substratum; 3) to refine and test the methodology and concepts of hierarchic  
18 electrostratigraphy at the basin scale; 4) to contribute to characterize the regional hydrostratigraphy of a relevant  
19 hydrogeological basin. 163 resistivity-versus-depth profiles with a maximum investigation depth of 450 m were  
20 obtained from Vertical Electrical Soundings. To draw the electrostratigraphic cross-section, the polarity of the  
21 resistivity contrast across resistivity interfaces (i.e., resistive over conductive layers or vice-versa) was considered and  
22 the discontinuities were correlated according to the persisting pattern from North to South. Doing so, the hierarchic  
23 assemblage of four major electrostratigraphic boundaries and the five intervening Groups of Electrostratigraphic Units  
24 (EsUs) was established. The resulting picture was compared to the available subsurface reconstructions from

literature, using the 1-D borehole data only to check the geophysical image at some random sample sites. The results show that the electrostratigraphic picture captures the geological and hydrostratigraphic complexity of the subsurface of the basin comparing well with the available direct subsurface geological and hydrostratigraphic reconstructions. At the regional scale of the cross-section, two hierarchic orders of EsUs and correlative boundaries could be drawn (1<sup>st</sup> order Groups and 2<sup>nd</sup> order individual EsUs), while the lowermost 3<sup>rd</sup> order rank, the electrolayer, is recognised at the single VES sites only.

Key-words: Electrostratigraphy, Hydrogeophysics, Hydrostratigraphy, Po Plain, Quaternary, Resistivity, VES.

## 1. INTRODUCTION

The subsurface of densely-populated alluvial plains of the world is the subject of geological, hydrogeological and geophysical studies, at both regional and local scales. Targets are both “deep” (for instance oil and gas reservoirs or high-temperature geothermal fields, hundreds to thousands of meters below the ground surface) and “shallow” (for instance groundwater reservoirs, low-temperature geothermal resources and so on, tens to hundreds of meters deep) and are related to a large number of diverse applications.

The shape of the basin-wide sedimentary units, their internal heterogeneities and the hierarchic arrangement of marine to continental clastic regressive sequences, that typically represent the shallow subsurface setting in alluvial basins, are the key-elements for a comprehensive characterization of these areas. Such a characterization can be approached by the integration of stratigraphic analysis and geophysical methods (Binley et al. 2010; Bridge and Hyndman 2004; Rubin and Hubbard 2005; Giudici 2010; Giudici et al. 2015).

To this purpose, ground-based Direct Current (DC) resistivity methods represent a cost-efficient tool to assist the hydrostratigraphical modelling of the alluvial stratigraphy. Thanks to the dependence of electrical properties on porosity, water saturation, pore water salinity, clay and silt content, grain size distribution, petrography and mineralogy of sediments (Keller and Frischknecht 1966; Reynolds 2011; Schön 2004; Slater 2007; Telford et al. 1990; Mele et al. 2014), DC methods allow the vertical survey of the subsoil by measuring the distortion of an electrical field applied at the ground surface by the variation of true electrical resistivity at depth.

Despite strong research and technological efforts, the reduction of the uncertainty on the geological interpretation of the subsurface resistivity images is still an open scientific problem. It greatly relies on the variation of the resolving

53 power of ground-based methods with the depth of investigation (Keller and Frischknecht 1966; Koefoed 1979) and,  
54 mostly, on the difficulty to match the electrical resistivity distribution in the subsurface with the geological data-set,  
55 such as fine-scale borehole-log stratigraphy.

56 Aiming to tackle these problems, in recent years an electrostratigraphic approach was set-up to manage resistivity  
57 data-sets in order to characterize geometries and internal properties of clastic, heterogeneous alluvial sequences  
58 (Bridge and Hyndman 2004; Huggenberger and Aigner 1999; Galloway and Sharp 1998). Mele et al. (2012)  
59 implemented the electrostratigraphic approach, describing the subsurface by DC methods in terms of 3-D volumes of  
60 sediments that, relatively with one another, maintain the same electrical resistivity contrast traceable in the subsurface  
61 wherever it exists. The resistivity contrast, in analogy to acoustic impedance for exploration seismic, is produced by  
62 the prominent geological and geometrical controlling factors on subsurface electrical conduction within the  
63 sedimentary sequence, i.e. gradual to sharp changes of clay/sand ratio, porosity, mineralogy of sediments, water  
64 content, water chemistry (mostly salinity) and temperature. These primary factors change through the subsurface in  
65 relation with the changes of thickness, shape, bedding styles and stacking patterns of the sedimentary bodies,  
66 including their pinch-outs, erosional truncations, folding and tectonic dips. Hence, the distribution of resistivity in the  
67 subsurface is expected to provide a proxy of the most relevant geological features at both the local and regional scales.

68 After a set of studies dedicated to improve and test the detailed resistivity imaging of the Po basin subsurface at the  
69 local scale (Bersezio et al. 2007; Mele et al. 2012, 2013, 2015), we now apply this approach to a wide scale case-  
70 study, that is the electrostratigraphy of a regional N-S cross-section across the Quaternary Po foreland basin in  
71 Northern Italy, East and South of Milan. The tectono-sedimentary setting of the basin is recorded by alluvial and  
72 glacio-fluvial clastic, regressive depositional systems, which prograde above shallow marine sediments, under the  
73 control of Pleistocene glacial cycles and Apennine-related tectonics. The resulting stacking patterns and the  
74 hydrogeochemistry of groundwater originate the geophysical contrasts between resistive (generally sands and gravels,  
75 i.e. coarse-grained “C”) and conductive intervals (clays and muds, i.e. fine-grained “F”, and the highly conductive  
76 connate waters). The magnitudes of these contrasts are suitable to be explored with ground-based DC methods.

77 Within a N-S strip across the central Po basin (Fig. 1) we formerly studied three fine-scale, key-sectors where we  
78 extensively acquired resistivity data with Vertical Electrical Soundings (VES; Mele et al. 2012, 2013, 2015). Our  
79 approach portrayed subsurface volumes of sediments that we informally named “Electrostratigraphic Units” (EsUs).

EsUs are characterised by specific, relatively small ranges of electrical resistivity and they are bounded by vertically- and laterally-persistent resistivity interfaces. In order to explain the results discussed in the paper, we introduce here the term “polarity” across a single resistivity interface (detectable by VES interpretation, see section 3.3) as the relative ordering of the resistivity overlap along the direction of increasing depth from earth surface, i.e. conductive-over-resistive (C-R pattern) or vice-versa (R-C pattern). In this way, EsUs are peculiar because they are defined on the basis of their resistivity, but the presence and nature of adjacent and overlapping units give rise to detectable electrical contrasts, traceable wherever their polarity is preserved, and permit the recognition of EsUs.

In particular, the results obtained at the key-sectors showed, as a whole, that a hierarchical structure of the EsUs emerges when exploring a sedimentary sequence; this structure is independent of any calibration between each VES and the lito-stratigraphy of a neighbouring 1-D borehole (Mele et al. 2012, 2013, 2015).

Owing to the expected decay of the VES vertical resolution with depth, the resistivity interfaces that bound the EsUs in the near-surface can be interpreted as individual and physically defined interfaces separating homogeneous sediments at the fine scale. On the contrary, at increasing depth, EsUs boundaries might be interpreted as *proxies* of the transition between sedimentary volumes with different styles of layering between conductive (clay-rich, i.e. fine-grained) versus resistive levels (sand-gravel rich, clay poor, i.e. coarse-grained), accounting for the variations of sediments’ fluid saturation and chemistry (Mele et al. 2015). Hence, electrical resistivity within the EsUs can be interpreted as a *proxy* of a volume-averaged ratio between the “shale”-dominated conduction volumes and the “electrolytic”-dominated conduction volumes of the corresponding stratigraphic units. This ratio is similar to the net-to-gross ratio adopted in petroleum geology to represent the quality of a reservoir zone (Pirson 1958) and it is linked, through empirical petrophysical relationships, to bulk resistivity and to average pore-water conductivity (Mele et al. 2012).

Starting from these site-specific results, we now extend the application of the electrostratigraphic approach up to the regional scale across the Po basin (Fig. 1) with the following aims:

- to obtain a regional electrostratigraphic cross-section of a wide part of the Quaternary Po basin, South and East of Milan, orthogonal to the regional structural grain of the basin (Fig. 1);
- to complement the picture of the Plio-Quaternary sequences and structures of the Po foreland basin in Lombardy which are shown at shallow depth with low-resolution and some uncertainties by the currently available deep seismic images (Bresciani and Perotti 2014; Burrato et al. 2003; Cassano et al. 1986; Fantoni et al. 2004; Francese

108 et al. 2005; Ghielmi et al. 2013; Livio et al. 2009; Pieri and Groppi 1981; Toscani et al. 2014; Turrini et al. 2014),  
109 providing new insights on the debated Plio-Quaternary tectono-sedimentary evolution of the Po foreland basin;  
110 • to generate electrostratigraphic images that can be interpreted in terms of hydrostratigraphy for the most relevant  
111 hydrogeological studies, showing the potential of the method in this field.

112 To all these purposes, here we describe and discuss a 72-kilometer-long regional resistivity cross-section, down to  
113 a maximum depth of 400 m below the ground surface (bgs from now on), in the central part of the Quaternary Po  
114 basin (Fig. 1). In this area, the cross-section crosses the Apennine foreland and extends from the buried front of the  
115 Northern Apennines, to the South, to the opposite flexured margin of Southern Alps to the North.

## 117 **2. GEOLOGICAL SETTING OF THE CENTRAL PO PLAIN IN LOMBARDY**

118 The Po plain represents the Neogene-Quaternary foreland basin shared by two opposite fold and thrust belts: from  
119 South to North, the Northern Apennines (verging North) and the Southern Alps (verging South; Fig. 1). In the  
120 subsurface of Lombardy, the buried frontal thrusts of the Apennine “Emilian Arc” interfere with the outermost  
121 Southalpine thrusts along an E-W belt, the Corneliano-Bordolano-Soresina interference zone (Bigi et al. 1990;  
122 Bersezio et al. 2001; Fantoni et al. 2004, Pieri and Groppi 1981). A gently South-dipping homocline of transgressive  
123 marine Pliocene sediments (“Pedialpine homocline”, Pieri and Groppi 1981; Fig. 1) developed on the northern side of  
124 the basin, in unconformity above the Southalpine structures. The S–N sequence of fault-propagation folds, shaped the  
125 buried morphology with uplifted dome culminations alternating with synformal depocentres, the most prominent of  
126 which is the “Lodi synformal depocentre” (Fig. 1), and originated a set of isolated relieves which elevate above the  
127 terraced plain of Lombardy, on both the Apennines and Southern Alps sides. Some of these relieves (Fig.1) are either  
128 directly crossed by the electrostratigraphic cross-section (Casalpusterlengo – Codogno high)) or emerge in the  
129 neighbourhoods (San Colombano al Lambro and Zorlesco highs); or at some distance, like the Romanengo, M.  
130 Netto/Capriano del Colle and Castenedolo highs (Alfano and Mancuso 1996; Anfossi et al. 1971; Baio et al. 2004;  
131 Bersezio et al. 2010, 2016; Boni, 1967; Bresciani and Perotti, 2014; Burrato et al. 2003; Castiglioni and Pellegrini  
132 2001; Cremaschi, 1987; Desio 1965; Livio et al., 2009; 2014; Pellegrini et al. 2003).

133 Deep seismic profiles showed the Messinian unconformity which truncates and seals the thrust-folded, syntectonic  
134 Tertiary clastic wedges and the overlaying marine Pliocene transgressive-regressive cycles (Cassano et al. 1986;  
135 Fantoni et al. 2001, Fantoni & Franciosi, 2010; Ghielmi et al. 2010, 2013; Pieri and Groppi, 1981; Rossi et al. 2015).

136 The Neogene succession is truncated after Apennine faulting and uplift as it is observed in outcrops (San Colombano  
137 hill; Zuffetti et al. 2018) and in the subsurface (Codogno, Casalpusterlengo, Zorlesco and Chiesiolo buried structures;  
138 Anfossi et al. 1971; Baio et al. 2004; Bersezio et al. 2010).

139 Four major seismic units, bounded by three regional unconformities, represent in the subsurface the transgressive-  
140 regressive cycles of the latest Pliocene and Pleistocene that progressively led to the basin fill, under the concurrent  
141 control of ongoing tectonics and glacio-isostatic evolution (Carminati et al. 2003; ENI- Regione Lombardia 2002;  
142 Muttoni et al. 2003; Ori 1993). Deep seismic interpretation by Ghielmi et al. (2010, 2013) shows two major  
143 unconformities, bounding three seismo-stratigraphic units, induced by the Early Pliocene (Zanclean) and Early  
144 Pleistocene (Gelasian) Apennine increments of Northwards thrusting. Early Pleistocene deep-water clastics  
145 unconformably overlay these former units (Ghielmi et al. 2010) and are covered by prograding fan deltas, coastal,  
146 deltaic and fluvial sediments (Ori 1993) both on the alpine and Apennine sides of the Po basin. The middle  
147 Pleistocene periglacial to glacio-fluvial successions spread all over the Lombardy Po plain (Bersezio et al. 2004; Bini  
148 et al. 2004; Bini 1997; Bini and Zuccoli 2001, 2004), sitting above a regional stratigraphic boundary attributed to 0.89  
149 Ma (“Red” surface, Muttoni et al. 2003; Scardia et al. 2006, 2012). After retreat of the LGM Alpine glaciers, post-  
150 glacial isostatic and tectonic uplift and climate-driven increase of riverine discharges induced the entrenchment of the  
151 river network, that is at present mostly confined within low-terraces metres to tens of metres below the average  
152 altitude of the plain (the so called “Livello Fondamentale della Pianura”, Castiglioni and Pellegrini, 2001).

153 The regional hydrostratigraphy of the central Po plain has been outlined by ENI-Regione Lombardia (2002), who  
154 identified four Aquifer Groups (labelled with the letters A to D from top to bottom). The middle – upper Pleistocene  
155 glacio-fluvial and alluvial aquifer groups (A and B) consist of multilayer aquifers saturated with freshwater (pore-  
156 fluids electrical conductivity ranging between 500  $\mu\text{S}/\text{cm}$  and 620  $\mu\text{S}/\text{cm}$ ; Mele et al. 2012) at the distal, Apennine  
157 side of the plain and correspond to a single coarse-grained aquifer at the northern Alpine side of the basin, inclusive of  
158 the phreatic and of a thick non-saturated zone at the top. Piezometric measurements from public datasets (the  
159 groundwater section of SIA, Environmental Information System of the Milan metropolitan city) show that the depth of  
160 the water table becomes shallow from North to South, from a depth of tens of meters to a few meters.

161 The lower Pleistocene – upper Pliocene marine to transitional aquifer groups (C and D) are confined to semi-  
162 confined, the regional aquicludes being represented by the fine-grained sediments of shallow marine to distal alluvial  
163 plain environment. Connate, high-density and salty pore waters represent a typical feature of the deepest aquifers

164 (group D). These marine waters, trapped at the bottom of the basin during late Messinian (Conti et al. 2000), rarely  
165 rise into the overlying transitional Group C (ENI-Regione Lombardia, 2002) that recurrently contains brackish waters.  
166 Uprising of these waters to shallow depths, at the southern side of the Po basin, is due to Apennine thrust faults and  
167 fault propagation folds.

168 This broadly summarised picture suggests the largest scale targets for the resistivity prospection along the North-  
169 South traverse across the basin: 1) the top of the highly conductive, fine-grained lower Pleistocene to Mio-Pliocene  
170 marine substratum, saturated by salt to brackish waters, which is uplifted and deformed by Apennine fault propagation  
171 folds; 2) the lower p.p. and middle Pleistocene syn-tectonic, folded and faulted clastic wedges, onlapping and  
172 downlapping the regional erosional unconformity that truncates the underlying marine sediments; the fresh/brackish  
173 water interface is contained in the lower part of this resistive succession 3) the middle p.p. – upper Pleistocene highly  
174 resistive, coarsening upwards clastic alluvial sequences, which rest on the whole above a regional unconformity and  
175 host the S-dipping phreatic surface in the uppermost stratigraphic units.  
176

### 177 **3. METHODOLOGY AND PRESENTATION OF THE DATA-SET**

#### 178 **3.1. GENERALITY OF VES SOUNDING AND MODELLING**

179 A VES consists of a sequence of measurements of apparent electrical resistivity ( $\rho_{app}$ ) with in-line, four-electrode  
180 array, coupled with the ground surface (Keller and Firschknecht 1966; Reynolds 2011). From the flowing current  
181 intensity injected through two current electrodes, the measured potential difference between two potential electrodes  
182 and a geometrical factor, which depends on the separation of current and potential electrodes and the general scheme  
183 of the array,  $\rho_{app}$  is computed. For a VES, consecutive measurements of  $\rho_{app}$  are collected by increasing the separation  
184 between the current and potential electrodes. Doing so, the measured electrical field is sensitive to an increasing  
185 volume of subsoil and, therefore,  $\rho_{app}$  is influenced by the resistivity distribution at increasing depths (Fig. 2).

186 Assuming no lateral resistivity transition (1-D assumption) and electrically homogeneous layers, numerical  
187 modelling of  $\rho_{app}$  is aimed to compute 1-D resistivity-versus-depth profiles that best fit the experimental data. This  
188 goal is obtained with inversion methods that, using resistivity and thickness of electrolayers as model parameters,  
189 minimize the root mean square relative error (RMS) between the observed and the modelled apparent resistivity. In  
190 this paper inversion is performed with the program RES1D (Loke 2001) which is based on a damped, non-linear least-

191 squares optimization method (Lines and Treitel 1984) and on the “linear digital filter” method (Koefoed 1979) for the  
192 forward modelling.

### 194 **3.2. VES DATA-SET AND FORMER RESULTS AT THE LOCAL-SCALE**

195 The data-set used in this work refers, in part, to the geophysical acquisition campaigns carried out from 2007 to  
196 2012 in three small key-areas (Fig. 1). The general results of these experiments were briefly summarized in the  
197 introduction of this paper and are discussed in details by Bersezio et al. (2007) and by Mele et al. (2010; 2012, 2013,  
198 2015).

199 At these sites, VES exploration yielded quasi-3D information about subsurface with a high horizontal data density,  
200 comparable with the characteristic scale lengths of the alluvial depositional systems. The VES clusters were located,  
201 from North to South, at three hinge zones in the geological architecture of the basin (Fig. 1):

- 202 1) the Northern hinge between the uplifted middle-late Pleistocene proximal glacio-fluvial sandur and the central to  
203 southern distal alluvial depositional systems, where the thick freshwater phreatic aquifer group splits into phreatic  
204 and semiconfined aquifer systems (Cassano d’Adda-Pozzuolo Martesana cluster, 24 VES; Mele et al. 2015);
- 205 2) the central area corresponding to the Lodi synformal depocentre of the Pleistocene clastic wedges, which host  
206 freshwater into semi-confined to confined aquifer groups (Lodi Vecchio cluster, 89 VES; Bersezio et al. 2007;  
207 Mele et al. 2012);
- 208 3) the Southern area where Apennine tectonics affected the Pleistocene sediments, uplifting and locally exhuming  
209 the marine sequences, logged by high-conductive brackish to salt-waters and associated to local geothermal  
210 anomalies (Casalbusterlengo-Zorlesco cluster, 36 VES; Mele et al. 2013).

211 Apparent resistivity data were acquired with a four-channel PASI 16G georesistivity-meter and Schlumberger  
212 array. Using a maximum half-spacing (i.e. half the distance between the current electrodes) equal to 300 m (Lodi  
213 Vecchio and Cassano d’Adda-Pozzuolo Martesana cluster) and to 500 m (Casalbusterlengo-Zorlesco cluster), we  
214 explored the upper portion of the alluvial stratigraphy: 1-D resistivity-versus-depth profiles obtained after complete  
215 curve matching yielded an estimated maximum depth respectively of 100 m and 250 m bgs. Notice that the maximum  
216 current intensity injected into the Earth to obtain reliable data was of the order of almost 600 mA.

217 The purpose of scaling-up the electrostratigraphic analysis to the regional scale requires a larger investigation  
218 depth than that of the former exploration campaigns, in order to reach the deepest Quaternary succession.



219 To do so, we integrated the available data-set with 15 VES, which were performed with the same instrumental  
220 setting and were located in-between and partially overlying the three mentioned VES clusters, from the northern  
221 deeply weathered Pleistocene terraces to the southern present day Po valley. The entire data-set has been acquired at  
222 the top surface of the uppermost morphological terrace, skipping the entrenched post-Glacial to Holocene valleys  
223 (Fig.1), having care to investigate comparable stratigraphic sequences at every site. The separation between VES  
224 acquisition station ranges from 1.5 km to 5.5 km; relatively large half-spacings (up to 1,000 m) permitted deep  
225 investigation. The numerical interpretation yielded 1-D resistivity-versus-depth profiles down to an estimated  
226 maximum depth of 450 m bgs. The RMS obtained after inversion of the VES apparent resistivity curves with RES1D  
227 was lower than 2.8% with up to 11 electro-layers.

### 229 **3.3. 1-D MODELLING AND REGIONAL HIERARCHIC ELECTROSTRATIGRAPHY**

230 The specific basin-scale application along the North-South cross-section of the Po basin was performed with a two-  
231 step, geophysical and geological procedure to manage 1-D resistivity-versus-depth profiles.

232 At the first step, we focused on the number and on the polarity of the interfaces, as both these properties concur in  
233 the identification of the local vertical electrostratigraphic sequence, which in turn controls the shape of the apparent  
234 resistivity field curves. This approach was implemented by inverse modelling of VES field curves, with the tools  
235 described in the previous section, and by evaluating the numerical fit between experimental and modelled data as a  
236 function of the number and the polarity of interfaces at each VES. In Fig. 3 is shown an illustrative example of the  
237 multiple interpretation with equivalent electrostratigraphies at VES T7 (location in Fig. 1), and the corresponding  
238 values of RMS error, obtained for three- to seven-layer models. At the end of this step, for each VES we considered  
239 satisfactory the resistivity-versus-depth profile obtained when no appreciable decrease in RMS error is generated by a  
240 focused addition of an electrolayer. In particular, an additional layer was inserted with the specific aim to reduce the  
241 misfit of the most loosely fitted parts of the field curve (see caption of Fig. 3). This procedure can be illustrated by  
242 means of the example in Fig. 3. The addition of layers for the models with a number of layers up to 6 is aimed to the  
243 improvement of the field-curve fit for long half-spacing of the current dipoles. On the other hand, the decrease in RMS  
244 error between six- and seven-layer models is due to the addition of a low-order interface (see later for details) at  
245 shallow depth for the best fitting of the initial part of the field curve (half-spacing less than 30 m), which shows some  
246 oscillations, symptoms of fall of 1-D assumption for possible shallow lateral heterogeneities.

247 Of course, the interpretation of a single VES is affected by equivalence, i.e., multiple, layered structures with  
248 different thicknesses and resistivities might fit the field data with a similar RMS error. Geoelectrical equivalence is  
249 still an open scientific problem and it could be reduced by independent data (for example, the exact depth of calibrated  
250 interfaces inferred from borehole logs) or could be managed with different techniques of inversion in case of multiple  
251 data-set (e.g., laterally constrained inversion; Auken et al. 2005; Christiansen et al. 2007). This important issue is  
252 beyond the scope of this paper and here is considered in an indirect way only, through the check performed during the  
253 following step of the procedure.

254 At the second step, we traced the interfaces between adjacent VES stations along the North-South cross-section,  
255 according to their polarity, i.e. the mentioned R-C and/or C-R patterns, and to the horizontal trend of variation of the  
256 local electrostratigraphy (Fig. 4). We conducted a critical evaluation of the validity of the subsurface geometries in  
257 terms of hierarchic electrostratigraphic interfaces and EsUs by matching non-contradiction, internal consistency,  
258 simplicity and likelihood criteria. At this stage, the electrostratigraphic results obtained at the three small-scale key-  
259 sectors were incorporated (see section 3.2, Fig. 1 and references therein). At the end of this analysis, we eventually re-  
260 evaluated the equivalent models obtained at step 1 in order to choose those which provide the identification of the  
261 major order electrostratigraphic interfaces and the smoothest geometries.

262 The resulting cross-section is presented in Fig. 5 and the detailed description of EsUs can be found in Tab.1. In the  
263 cross-section we represent the VES with the largest exploration depth (>100 m bgs), complemented by a limited  
264 number of shallow (<100 m bgs) resistivity-versus-depth profiles. Considering the quasi-3D results at the three fine-  
265 scale key-sectors (Fig. 1; see references therein) it should be noted that, while the regional cross-section shows EsUs  
266 in 2D, the 3-D distribution of VES stations across the basin and the adopted electrostratigraphic criteria allow to  
267 consider EsUs as the expression of 3-D electrostratigraphic bodies.

268 The calibration of the cross-section has been obtained at the three key-sectors using: 1) correlation panels from  
269 lithological logs (boreholes; see Fig. 1 for location); 2) short and long normal resistivity logs from a deep hydrocarbon  
270 well (within the Casalpusterlengo-Zorlesco cluster); 3) the electrical conductivity of groundwater and 4) the depth of  
271 the water table in the LFP. This matter is presented and discussed in details by Bersezio et al. (2007) and Mele et al.  
272 (2010, 2012, 2013, 2015). In the cross-section of Fig. 5 we show, as a reference, a limited number of litho-textural  
273 logs from water wells (less than 170 m bgs) to facilitate comparisons with the regional subsurface stratigraphy.

274 At the regional scale portrayed by the resistivity cross-section, four laterally persistent, resistivity discontinuities  
275 have been mapped. They were informally named S1 to S4 from top to bottom (Fig. 5; see also the discussion of the  
276 results in the following section). In the hierarchic electrostratigraphic architecture we assigned them the highest-rank  
277 (1<sup>st</sup> order). According to the polarity, lateral persistence and vertical resistivity trends, S1 to S4 1<sup>st</sup> order  
278 electrostratigraphic discontinuities bound five highest-rank Groups of EsUs, numbered in increasing order downwards  
279 from the ground surface from Group 1 to 5 (Tab. 1; Fig. 5). The electrical resistivity ranges estimated for the EsUs  
280 forming each Group are comparable with those previously obtained at the key-sectors and are listed in Tab. 1.

281 Intermediate-rank discontinuities (2<sup>nd</sup> order) delimit individual 2<sup>nd</sup>-order EsUs preserving the polarity (C-R or R-C)  
282 between adjacent and overlapping units (Fig. 4 and Fig. 5). The lowest-rank interfaces (3<sup>rd</sup> order) represent internal  
283 heterogeneities within the individual EsUs, i.e. they bound sub-volumes within the EsUs showing the lowest variation  
284 of electric resistivity (electrical homogeneity criteria; Fig. 4). This is the rank of the individual electrolayers in the 1-D  
285 interpretation of a VES. In 2-D and 3-D, at regional scale, their lateral continuity and overall geometry are highly  
286 uncertain, in particular for lense-shaped units detected in single VES (for example, in T6 and T8; Fig. 5), due to the  
287 intrinsic limit of vertical resolution at increasing depth for VES interpretation. Hence only their inferred boundaries  
288 are drawn in the regional cross-section (Fig. 5, dotted lines) and they are not considered in Tab.1. To resolve the third  
289 order resistivity heterogeneity at shallow depth, more detailed surveys, like 2-D resistivity imaging and Ground  
290 Penetrating Radar (Mele et al. 2012), are necessary, and should be applied to a much finer scale than the basin-wide  
291 scale. On the other hand, at greater depth, the third order units could be resolved only by independent data  
292

## 293 **4. DISCUSSION OF RESULTS**

### 294 **4.1. THE REGIONAL RESISTIVITY CROSS-SECTION**

295 The resistivity cross-section is represented in Fig. 5 using 23 selected resistivity-versus-depth profiles. The five 1<sup>st</sup>  
296 order groups of EsUs describe an overall, large-scale, upwards increasing trend of electrical resistivity that is  
297 associated to important changes in the staking patterns of the 2<sup>nd</sup> order EsUs. This pattern compares to the regional  
298 regressive trend from marine sediments (initially and still partly logged by saltwater) to the coarsest-grained  
299 prograding glacio-fluvial units (freshwater logged) known from literature, and summarised in section 2. Vertical and  
300 horizontal internal resistivity trends do exist also within the Groups of EsUs (Fig. 6a and b respectively). The observed  
301 vertical resistivity trends are of three types: upwards increasing, upwards decreasing and stationary. In the

302 stratigraphic setting of the study area these trends mimic respectively the typical coarsening/thickening,  
303 fining/thinning and stationary stacking pattern trends of sedimentary units. Also southward and northward horizontal  
304 trends of resistivity could be detected and traced within and across the 2<sup>nd</sup> order EsUs and 1<sup>st</sup> order Groups (Fig. 5 and  
305 6b). Hence, Fig. 5, Fig. 6 and Tab. 1 permit to read and interpret the combination of the array of electrostratigraphic  
306 features that could be detected: the geometry of the electrostratigraphic units of the 1<sup>st</sup> and 2<sup>nd</sup> order and of their  
307 boundaries, the spatial assemblage of the EsUs and their mutual relations, the vertical and horizontal resistivity trends  
308 within the units and through their assemblage.

309 Considering the calibration procedure which was adopted (section 3.3), the resistivity field responds to the  
310 heterogeneous distribution of the litho-textural properties of the sedimentary bodies showing the strong analogy of the  
311 reconstructed electrostratigraphic architecture with the known geological and hydrogeological/hydrogeochemical  
312 features, which was described in section 2. This permits to interpret the electrostratigraphic cross-section in terms of  
313 subsurface geology, including the simplest and most obvious tectonic and stratigraphic features and the relative  
314 chronology from which they derive. At last the stratigraphic interpretation can also be transposed to a  
315 hydrostratigraphic architecture, which is one of the expected applications of this implementation of the  
316 electrostratigraphic prospecting method. The stack of 1<sup>st</sup> order Groups of EsUs can be summarized as follows,  
317 descending from the ground surface.

318 Group 1 (red-pink-white colours in Fig. 5) is the shallowest and therefore the best resolved EsU, which justifies a  
319 more detailed interpretation compared to the underlying units. It is bounded at the base by electrical discontinuity S1  
320 and consists of a stack of interfingered, wedge-shaped and southward-dipping, resistive and conductive EsUs,  
321 delimited by 2<sup>nd</sup> order surfaces. These EsUs show a decreasing tilt toward South and an apparent downward  
322 termination above the gently curved and southwards-dipping S1 and/or above one another. These features mimic the  
323 typical depositional geometry of a downlapping, progradational stacking pattern, as it might be interpreted in terms of  
324 physical stratigraphy from a seismic line or from a borehole stratigraphic correlation panel. Between VES T16 and  
325 T22 (Fig. 5), acquired in the area of the southern Casalpusterlengo and Zorlesco structural highs (Desio 1965;  
326 Cremaschi 1987; Bersezio et al. 2010), the basal resistive EsU of Group 1 shows an upward curvature, mimicking a  
327 folded synformal-antiformal pattern, while the overlaying EsUs follow up-section without bending. In geological  
328 terms we could interpret this electrostratigraphic pattern as the image of the relationships between less deformed  
329 sediments sitting above a folded stratigraphic unit. Highly uncertain third order resistivity interfaces are mapped

330 within the resistive EsUs, aiming to highlight the lateral resistivity transitions at the horizontal scale of tens of  
331 kilometres (Fig. 6b). On the opposite, conductive units are tabular, quite homogeneous and show northward stepping  
332 terminations, mimicking a retrogradational stacking pattern of fine grained, transgressive, depositional packages, if  
333 compared to the southward “prograding” pattern of the resistive 2<sup>nd</sup> order EsUs. The overall electrostratigraphic  
334 sequence of Group 1 shows small-scale, upward-decreasing resistivity cycles (see VES T3, T6, and T9 in Fig. 5 and  
335 Fig. 6a) that are delimited at their top by the surface topography. The average modelled thickness of this group is  
336 about 50 m along the central and the southern part of traverse, while it thickens to North up to about 100 m (T1 in Fig.  
337 5).

338 Group 2 (dark and light yellow colours in Fig. 5) sits above electrostratigraphic discontinuity S2 and consists of a  
339 couple of EsUs revealed by VES between T7 and T20, in the region of the Lodi synformal depocentre adjacent to the  
340 North and to the South the Casalpusterlengo – Zorlesco structural highs. Group 2 depicts a large, upward decreasing  
341 resistivity trend, characterized by a resistive EsU at the base and a conductive EsU at the top (VES T12 in Fig. 5).  
342 Both units form two lenses which wedge-out northwards and southwards, where S2 reaches its shallowest depth and  
343 joins S1 from below. In geological terms, these features could be interpreted as folding and subsequent erosional  
344 truncation (S1 truncating S2 and Group 2) of a fining-upwards large-scale sedimentary sequence. The geometry of the  
345 EsUs, their mutual relationships and the relations between Group 2 and the underlying Groups suggest progressive  
346 southwards and northwards onlaps of Group 2 EsUs onto the top of Groups 3 and 4, as it is apparent in the vicinity of  
347 the Casalpusterlengo and Zorlesco structural high (T16 – T22, Fig. 5).

348 Group 3 (dark and light green colours in Fig. 5) consists of curved EsUs lying above electrostratigraphic discontinuity  
349 S3, forming one large-scale upwards-decreasing resistivity cycle (Fig. 6a). The lower resistive EsU shows a lateral  
350 resistivity decrease from North to South, i.e. toward the Lodi synformal depocentre that reverses close to the  
351 Casalpusterlengo and Zorlesco structural highs (Fig. 6b). Southwards of VES T10, the lower resistive EsU looks to be  
352 uplifted and sealed by the upper conductive EsU, plunging toward South, whereas it is truncated by S2 (Fig. 5,  
353 complete truncation of Group 3 occurs between VES T13 and T16). Two resistive lenses tens of meters thick are  
354 interpreted with some uncertainty at VES T6 and T8 within the upper conductive EsU.

355 Group 4 (dark - light blue and cyan colours in Fig. 5) is a widespread conductive interval which embeds resistive  
356 wedges and lenses. The overall geometry of Group 4 is comparable to kilometre-scale folds, forming a synform  
357 (North) – antiform (South) pair. The buried antiformal bend develops below the surface expression of the

358 Casalpusterlengo – Zorlesco structural high. In the northern part of the electrostratigraphic cross-section (VES T1 -  
359 T4; Fig. 5), a South-dipping, wedge-shaped, resistive EsU is present in the core of Group 4. In correspondence of the  
360 Casalpusterlengo and Zorlesco structural high, a curved, lens-shaped, resistive EsU is mapped (VES T19 - T23; Fig.  
361 5). Both these wedge-shaped EsUs thin and wedge-out towards the central synform that broadly corresponds to the  
362 Lodi synformal depocentre. Group 4 reaches its maximum modelled thickness (about 300 m) towards the northern end  
363 of the cross-section. The stacking of the EsUs gives origin to a lower trend of increasing resistivity, that is followed  
364 upwards by an opposite trend above the resistive lenses (Fig. 6a). A trend of decreasing resistivity can be observed  
365 from North to South, leaving from the northern resistive lens-shaped EsU (Fig. 6b).

366 Group 5 (grey colour in Fig. 5) consists of extremely-high conductive EsUs, revealed in the central and southern parts  
367 of the electrostratigraphic cross-section. These EsUs could be reached either at the sites where the deepest  
368 investigation depth was attained (between T6 and T9, T15; Fig. 5) or where they are uplifted close to the ground  
369 surface (T16 – T21, Fig. 5; Casalpusterlengo structural high area). The extremely-high conductive EsUs correspond to  
370 the core of the antiformal bend portrayed in the most uplifted sector of the Casalpusterlengo structural high. These  
371 features might be interpreted, in geological terms, as the result of synclinal-anticlinal folding of the marine, highly  
372 conductive substratum of the Pleistocene elastic sequence.

373  
374

## 375 **4.2. HYDROSTRATIGRAPHIC INTERPRETATION**

376 The regional electrostratigraphy of the Po plain in central Lombardy shows a general upwards-increasing resistivity  
377 trend. This is in accordance with the regional, coarsening-upwards depositional trend, from the lowermost fine-  
378 grained, well-bedded and conductive units of the (Mio)-Plio-Pleistocene marine-to-transitional depositional systems to  
379 the progressively more coarse-grained, massive and resistive fluvial and glacio-fluvial depositional systems of the  
380 Middle–Late Pleistocene (Ghielmi et al. 2013; Ori 1993). Pore-water chemistry and saturation changes contribute to  
381 this pattern, salt- to brackish water being confined to the deepest Group 5 and to part of the overlying Group 4, while  
382 freshwater saturates Group 3, Group 2 and the lower part of Group 1, which contains the phreatic surface (Fig. 5;  
383 compare with the fresh-saltwater interface depth reported from ENI oil wells in ENI-Regione Lombardia, 2002).

384 If these interpretations are correct, the resistivity image of Fig. 5 and Fig. 6 represents a proxy of the  
385 hydrostratigraphic architecture, showing that the Northern, single, large-scale and thick aquifer (about North of T6 in

386 Fig. 5) splits progressively southwards into thin, coupled, aquifers and aquitards (South of T6 in Fig. 5; compare with  
387 the hydrostratigraphic cross-sections in Bersezio et al. 2004, 2010 and ENI-Regione Lombardia 2002).

388 At increasing depth below Group 1, the resolution decreases and a progressively less detailed image must be  
389 interpreted. Freshwater-logged, regressive aquifer systems, partly or totally confined by the intervening transgressive  
390 fine-grained aquitard/aquiclude systems are confidently interpreted from the stack of folded resistive and conductive  
391 EsUs shown by the electrostratigraphic image of Groups 3 and 4 below S2.

392 Below S3 the most conductive 1<sup>st</sup> order Groups 4 and 5 occur. Both are uplifted close to ground surface by the  
393 Casalpusterlengo ramp-fold at the southern end of the cross-section, as it is confirmed by borehole stratigraphy at  
394 Casalpusterlengo-Zorlesco (Bersezio et al. 2010) and outcrop geology at the neighbouring San Colombano relief  
395 (Desio 1965; Anfossi et al. 1971; Boni, 1967; Bersezio et al. 2016). The top boundary of the deepest 1<sup>st</sup> order Group 5  
396 (the most conductive unit) most plausibly represents the salt/brackish water interface. Inside Group 4, lens-shaped  
397 freshwater aquifers are confined within the marine aquitard, conductive fines with a repetition of the  
398 brackish/freshwater interface.

### 400 **4.3. GENERAL REMARKS ON ELECTROSTRATIGRAPHY**

401 The Po Plain electrostratigraphic cross-section shows that the hierarchically arranged electrostratigraphic units  
402 (EsUs, EsUs Groups and the corresponding resistivity boundaries) clearly have different expression, extension and  
403 modelled thicknesses, i.e. different sizes. Electrical resistivity can be considered as an equivalent volume-averaged  
404 physical property between the “shale”-dominated conduction volumes and the “electrolytic”-dominated conduction  
405 volumes (Mele et al. 2012, 2014, 2015), and therefore it bears extremely different geological and hydrostratigraphic  
406 information for subsurface reconstruction.

407 This is important in terms of the prominent geological controlling factors on subsurface electrical conduction  
408 because it directly implies that when observed regardless of their physical scale, the resistivity volumes appear similar  
409 to one another, because the corresponding stratigraphic units are characterized by comparable styles of propagation of  
410 the internal heterogeneities affecting the bulk electrical conduction.

411 At the fine-scale, typically investigated by high-resolution borehole logs, laboratory experiments (Inzoli and  
412 Giudici 2015; Mele et al. 2014) or ground-based DC methods focused to the near-surface (Bersezio et al. 2007), the  
413 transition between sediment volumes with homogeneous electrical properties mainly occurs at definite physical

414 interfaces. This is the case of sedimentary facies transition, corresponding to a resistivity contrast whose magnitude is  
415 linked to the textural parameters concurring to the variation.

416 On the contrary, when electrical resistivity ground-based methods are used to explore large volumes of stratified  
417 sediments, the electrical equivalence restricts the size of the vertical heterogeneities that can be resolved. As a  
418 consequence, the interpreter is forced to consider the vertical sequences of thin strata at depth as a single electrically  
419 macro-anisotropic entity (Christensen 2000). In this way the sediments are depicted as a function of the resolving  
420 power of the method, which acts as a low-pass filter with respect to the vertical wavenumber components of electrical  
421 resistivity, enabling to detect only low-wavenumber resistivity variations related to the sediments' nested hierarchy  
422 that emerged at different depths (and physical scales) of observation.

## 424 5. CONCLUSIONS

425 A 72-kilometer-long cross-section, based on electrostratigraphic correlation of resistivity-versus-depth profiles  
426 obtained by VES soundings, has been portrayed across the Po plain in central Lombardy, down to 300 m below sea-  
427 level, to investigate the architecture of the Quaternary fill of the Po Apennine foreland basin.

428 The test shows that:

- 429 1) the survey permits to depict the subsurface geology of the uppermost 400 m of the basin stratigraphy. In the  
430 densely populated alluvial plains of the world, this depth interval is of paramount relevance for many  
431 applications (e.g. hydrogeology, geothermal exploitation, quarrying and digging, subsidence problems and so  
432 on), but it is often poorly understood yet. In the case of the Po plain, the new generation of electrostratigraphic  
433 cross-sections permits to start closing the gap between deep seismic images by the oil-industry, that are still  
434 poorly oriented to show in detail the shallow geology, and the very shallow water wells and borehole-derived  
435 stratigraphic reconstructions (Cassano et al. 1986; ENI-Regione Lombardia 2002; Fantoni et al. 2004; Ghielmi  
436 et al. 2013; Pieri and Groppi 1981);
- 437 2) The cross-section has been obtained thanks to the refinement of the concepts and methodology of  
438 “electrostratigraphy”, after a set of studies dedicated to improve and test the detailed resistivity imaging of the  
439 Po basin subsurface at the local scale. The wide physical scale of the experiment is relevant for this test. As a  
440 matter of fact, such a large volume in a tightly constrained tectono-sedimentary framework involves large-scale  
441 changes of the prominent controlling factors on electrical resistivity (i.e. gradual to sharp changes of texture



442 and composition of the investigated sediments and rocks, changing water saturation, changing underground  
443 water chemistry and temperatures, gradual to abrupt changes of shape, bedding styles and stacking patterns of  
444 the sedimentary bodies, pinch-outs, erosional unconformities, folds and tectonic dips and so on). These  
445 remarks now permit to conclude that electrostratigraphic units can represent a category of geophysical-  
446 stratigraphic units, comparable to seismic units or to some of the traditional categories like allostratigraphic or  
447 lithostratigraphic units (NASC 2005). Provided that the resistivity method permits to interpret the sediments as  
448 a function of the resolving power, and that the resolution lowers with depth, the survey demonstrates that: i)  
449 EsUs have boundaries, that are detectable resistivity interfaces preserving the polarity wherever they exist; ii)  
450 EsUs are formed by sediment/rock volumes showing a relatively narrow range of resistivity values, admitting  
451 lateral and vertical trends (upwards and/or laterally increasing, decreasing or stationary); when pore fluids'  
452 chemistry is constant, the latter plausibly relate directly to the stacking pattern of sedimentary bedsets (i.e.  
453 fining/coarsening, thinning/thickening and stationary trends); iii) EsUs are hierarchically arranged, the basic  
454 unit being the EsU that contains sub-units (1-D electrolayers, hardly traceable at regional scale) and can be  
455 clustered into Groups of EsUs; iv) they are related to some fundamental features of the stratigraphic sequences  
456 (i.e. the composition of sediments, the net-to-gross ratio, the fluid chemistry and saturation, hence they can be  
457 calibrated to the known local stratigraphic and structural settings, rather than to individual borehole data-  
458 points); v) they have external geometry and mutual relationships, so the calibrated electrostratigraphic picture  
459 can be interpreted, with the proper caution, in terms of geological architecture, relative chronology and  
460 evolution;

- 461 3) The electrostratigraphic cross-section shows the most relevant stratigraphic and tectonic features of the  
462 Quaternary fill of the central Po plain, along a traverse sitting on the structural fronts of both Alps and  
463 Apennines, in satisfactory agreement with the available literature. A synthetic list of such features includes: i)  
464 the frontal salient of the Northern Apennines, represented by the Casalpusterlengo thrust-propagation anticline,  
465 that folds the ESUs of Groups 4 and 5, the deepest, which might correspond to the (Mio)-Pliocene - Calabrian  
466 marine to transitional fine-grained succession and contain the present-day saltwater and brackish-freshwater  
467 interfaces; ii) the on-lapping, off-lapping and truncated EsUs of Group 3, which could correspond to the  
468 Calabrian alluvial to littoral regressive – transgressive cycle. Group 3 is interpreted as affected by ongoing syn-  
469 to post-depositional folding; iii) the fill of the Lodi synformal depocentre, i.e. Group 2, that is interpreted as the

470 expression of the Calabrian – middle Pleistocene distal alluvial and glacio-fluvial sequence, related to the  
471 Verbanò and Lario amphitheatres. The electrostratigraphic image permits to infer that this Group underwent  
472 syn-depositional folding and subsequent truncation to the South (Casalpusterlengo, Zorlesco and related thrust-  
473 propagation folds) concurrent with uplift and erosion at the northern side, that sits above the Southalpine  
474 thrusts at that time involved as the peripheral bulge of the Apennines, iv) the prograding – retrograding EsUs  
475 of Group 1, the shallowest one, sitting on an “electrical unconformity” (1<sup>st</sup> order surface S1) that truncates the  
476 underlying groups both on the crest of the Casalpusterlengo anticline (South) and on the uplifted ramp to the  
477 North. This Group, that contains the phreatic surface, is calibrated to the Middle – Late Pleistocene glacio-  
478 fluvial to post-glacial alluvial sediments. The uppermost EsU seals unconformably the southernmost tectonic  
479 structures. Within this group, the geophysical resolution which could be attained at shallow depth, permits to  
480 recognize at least three cycles of resistive and coarse-grained sediments prograding from North to South above  
481 more conductive, fine-grained deposits, which are finally cut and filled by the ESUs hosted into the post-  
482 Glacial to Holocene Po terraced valley. Group 1 ESUs might represent the major Middle – Late Pleistocene  
483 glacial advance and retreat cycles of the Lario amphitheatre (Binago-Specola, Besnate, and Cantù/LGM  
484 glaciations; Bini et al. 2004). At last, it might be observed that the interpretation of the electrostratigraphic  
485 cross-section in terms of geological evolution provides an additional validation tool of the geophysical image,  
486 by comparison with the current geological reconstructions, if available.

- 487 4) The electrostratigraphic image is a picture of the resistivity distribution that can be interpreted in terms of  
488 petrophysical properties of the subsurface succession, like hydraulic conductivity, hence it might represent a  
489 good proxy of the hydrostratigraphic structure of the central Po plain. Fig. 5 shows that Group 4 represents the  
490 basal confining layer that sustains the confined aquifers represented by the overlying EsUs of Groups 3 and 2.  
491 Group 4 also contains large-scale isolated lenticular aquifer systems and the related multiple base of the  
492 freshwater aquifers. The fine-grained top EsUs of Groups 3 and 2 represent the aquitard-aquiclude layers  
493 which confine the aquifers hosted by Group 1. The top EsUs of Group 1 contain the piezometric surface and  
494 the related flowing wells, that form a well-known E-W trending belt at the northern side of the Po plain.
- 495 5) The DC survey complemented with the electrostratigraphic interpretation and calibration yields promising  
496 results, at low-cost and with almost no environmental impact, concerning that depth range which often escapes  
497 the other geophysical techniques. The application to a regional case study, which is typical of the very common

498 and diffuse geological setting of an alluvial plain within a foreland basin, suggests that this approach could  
499 yield good results in many other regions, assuming a general validity. In any case, in order to obtain plausible  
500 pictures and interpretations and to reduce the uncertainties on the final reconstruction, the geoelectrical results  
501 must always be integrated with the existing geological knowledge and with any other independent geophysical  
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## 670 **8. FIGURE CAPTIONS**

671 Fig. 1. Simplified geomorphological map and main subsurface tectonic features of the Quaternary Po foredeep  
672 basin in Lombardy (after Bigi et al. 1990; Castiglioni and Pellegrini 2001; Fantoni et al. 2004). The map shows the  
673 location of VES surveys and the trace of the resistivity cross-section (black line) in the interfluvium between the Adda  
674 and Lambro Holocene valleys. Location of the map in Northern Italy is indicated in the top left insert.

675 Fig. 2. Box A) Apparent resistivity curves of VES along the resistivity cross-section (location in Fig. 1). Box B)  
676 Horizontal variation of apparent electrical resistivity measured along the cross-section for a Schlumberger array and  
677 half-spacings between the current electrodes equal to 10 m (red line), 60 m (green line), 300 m (blue line).

678 Fig. 3: Example of multiple electro-layer interpretation at VES T7 (location in Fig. 1). On the left: the resistivity-  
679 versus-depth profile is shown with the hierarchic interfaces traced along the cross-section shown later in Fig. 5 and the  
680 litho-textural logs for comparison. On the right: multilayer interpretation obtained by complete curve matching (from  
681 3- to 7- layers models, reducing RMS % error), showing the comparison of subsurface structure in terms of pattern of  
682 the interfaces and the corresponding depth variability.

683 Fig. 4: Example of the hierarchical procedure to trace the electrostratigraphic interfaces starting from 1-D models  
684 obtained by curve-matching of single VES (zoom in from the northern and shallower sector of the regional resistivity  
685 cross-section, zoom box shown in Fig. 5). The modelled 1-D resistivity for individual electro layers is displayed at  
686 each VES location; the polarity across individual electrostratigraphic interfaces (relative resistive over conductive or  
687 vice-versa) is also represented with double coloured lines (red and blue, respectively, along the resistive and  
688 conductive faces). Note that high-, intermediate- and low-order electrical interfaces bound adjacent and overlapping  
689 units of comparable rank preserving the reciprocal polarity wherever it is traceable.

690 Fig. 5: Electrostratigraphic cross-section across the Po plain (location in Fig. 1) showing the architecture of  
691 electrostratigraphy (see legend for hierarchy of units). Litho-textural logs are orthogonally projected from a maximum

692 distance of 300 m (litho-textural classes: G: gravel; S: sand, L: silt; C: clay; f: fine; m: medium, c: coarse). Vertical  
693 exaggeration: 100×.

694 Fig. 6: Box A) Vertical resistivity trends of 1<sup>st</sup> order groups of EsUs. Box B) horizontal resistivity trends within  
695 individual 2<sup>nd</sup> order EsUs. Resistivity trends are represented with coloured triangular sticks with apex in the direction  
696 of decreasing resistivity. Colours help to differentiate the 2<sup>nd</sup> order more conductive EsUs (same as Fig. 5). The S1-S4  
697 1<sup>st</sup> order boundaries between 1<sup>st</sup> order Groups are coloured as in Fig. 5.

698

## 699 **9. TABLE CAPTIONS**

700 Tab. 1: Electrostratigraphic sequence of the central Po Plain in Lombardy. Refer to Fig. 4 and 5 to visualize  
701 individual EsUs, EsU Groups and the relative Bounding Surfaces (1<sup>st</sup> order: S1 to S4) and to Fig. 6 for Vertical vs.  
702 Horizontal Resistivity trends. Two orders of the hierarchic assemblage are shown: Groups of EsUs (1<sup>st</sup> order) and  
703 EsUs (2<sup>nd</sup> order).

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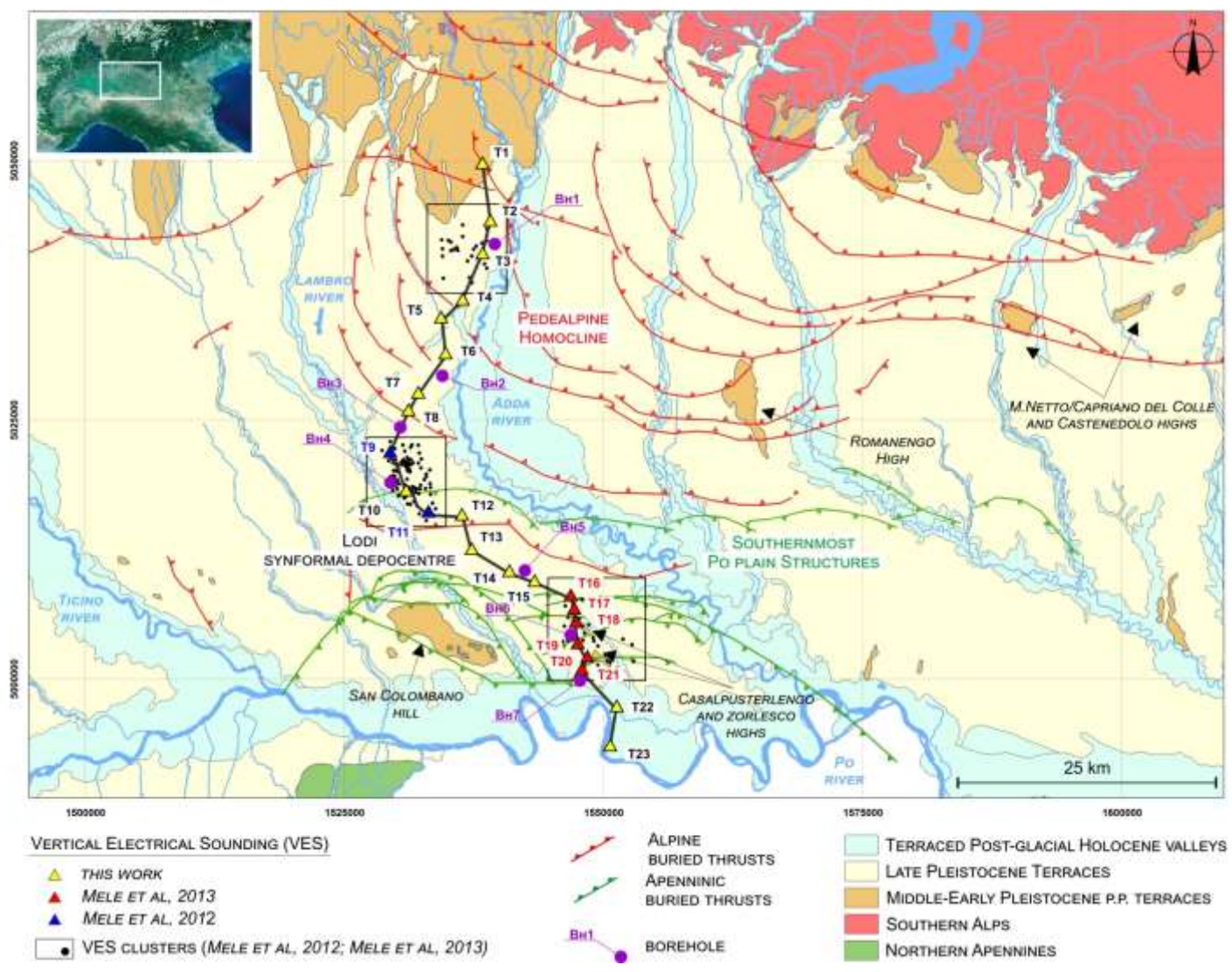
Table 1

GROUP OF ESUS (1 <sup>ST</sup> ORDER)	RESISTIVITY RANGE IN $\Omega$ m OF THE 2 <sup>ND</sup> ORDER ESUS	GEOMETRY & STACKING PATTERN	INTERPRETED HYDROSTRATIGRAPHY
1	25 to 67, red in Fig.4	Gently dipping, alternating R/C wedges with decreasing vs. increasing upward resistivity trends	Phreatic to semi-confined freshwater aquifers/aquitards
	71 to 192 pink in Fig.4		
	72 to 1109, white in Fig.4		
2	33 to 93 dark yellow in Fig.4	Curved resistive wedge with upward decreasing resistivity trend	Semi-confined freshwater aquifers
	99 to 173 light yellow in Fig.4		
3	25 to 69 dark green in Fig.4	Curved resistive body with upward decreasing resistivity trend and intervening resistive lenses with homogenous resistivity values	Confined freshwater aquifers.
	81 to 214 light green in Fig.4		
4	14 to 26 dark blue in Fig.4	resistive lenses within widespread conductive	Basal confining layer with fresh- brackish water isolated aquifers.
	21 to 48 cyan in Fig.4		
	65 to 217 light blue in Fig.4		
5	< 9 grey in Fig.4	Curved, up-doming conductive layer	Saltwater basal aquitard

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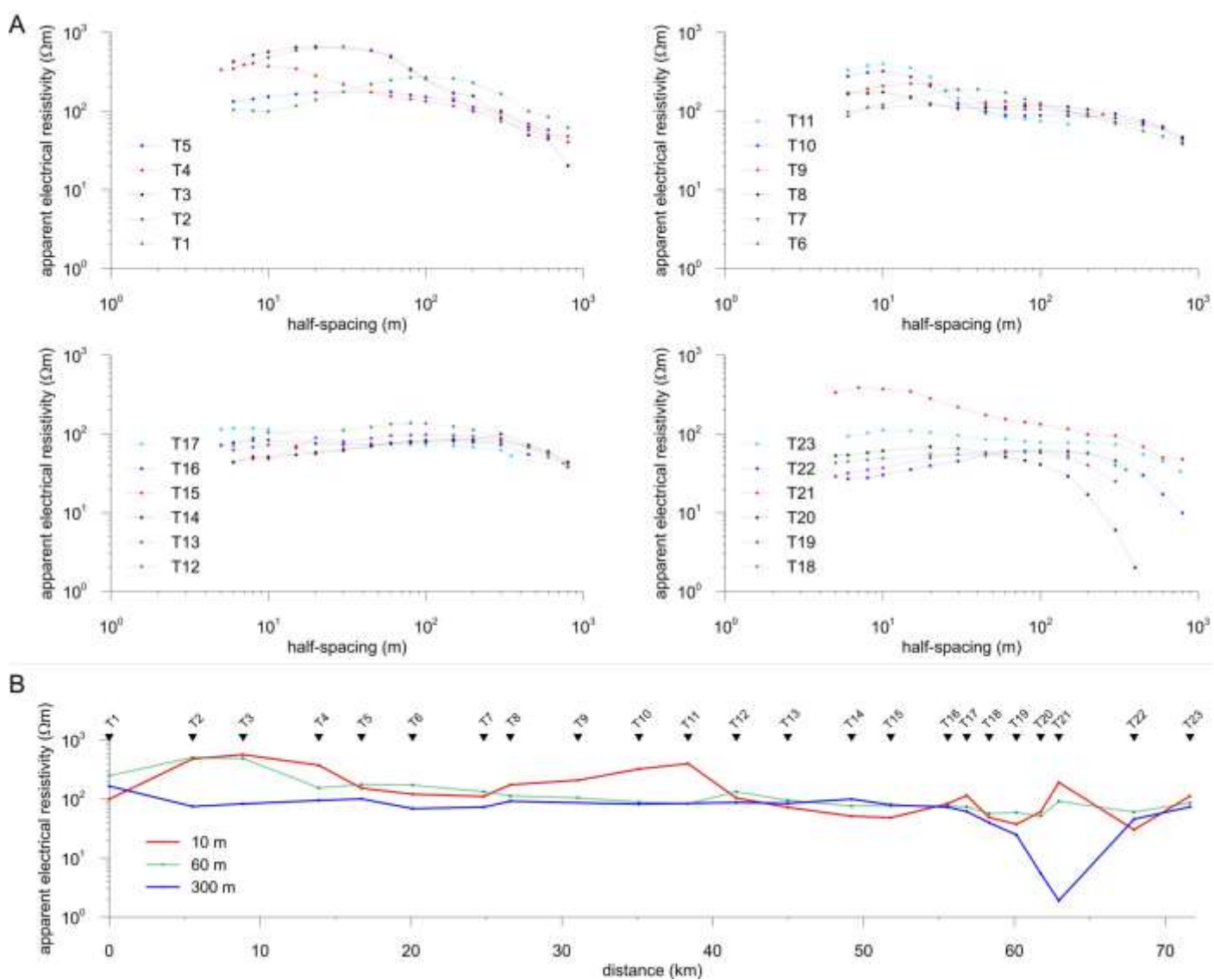
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Figure 1



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Figure 2

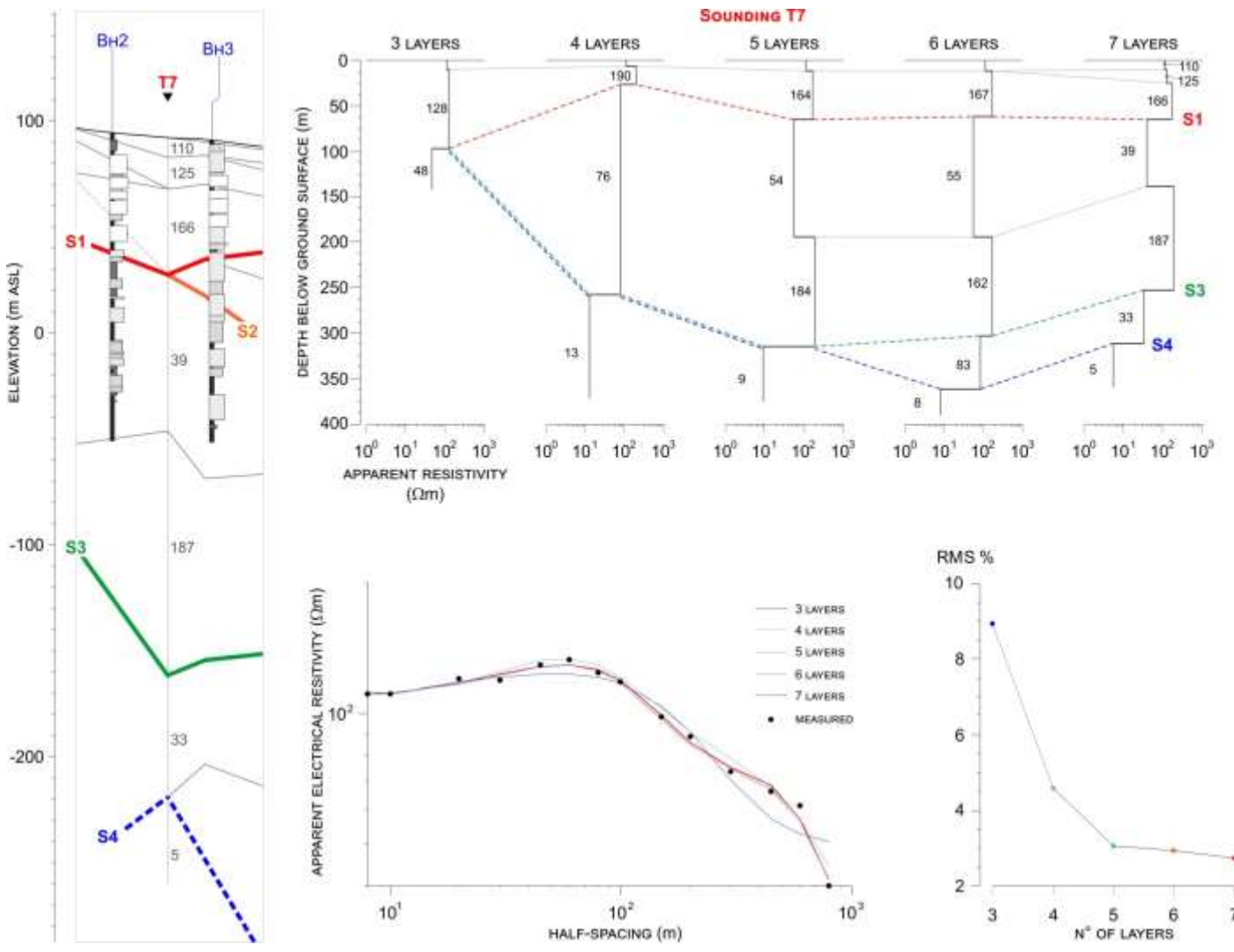


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Figure 3

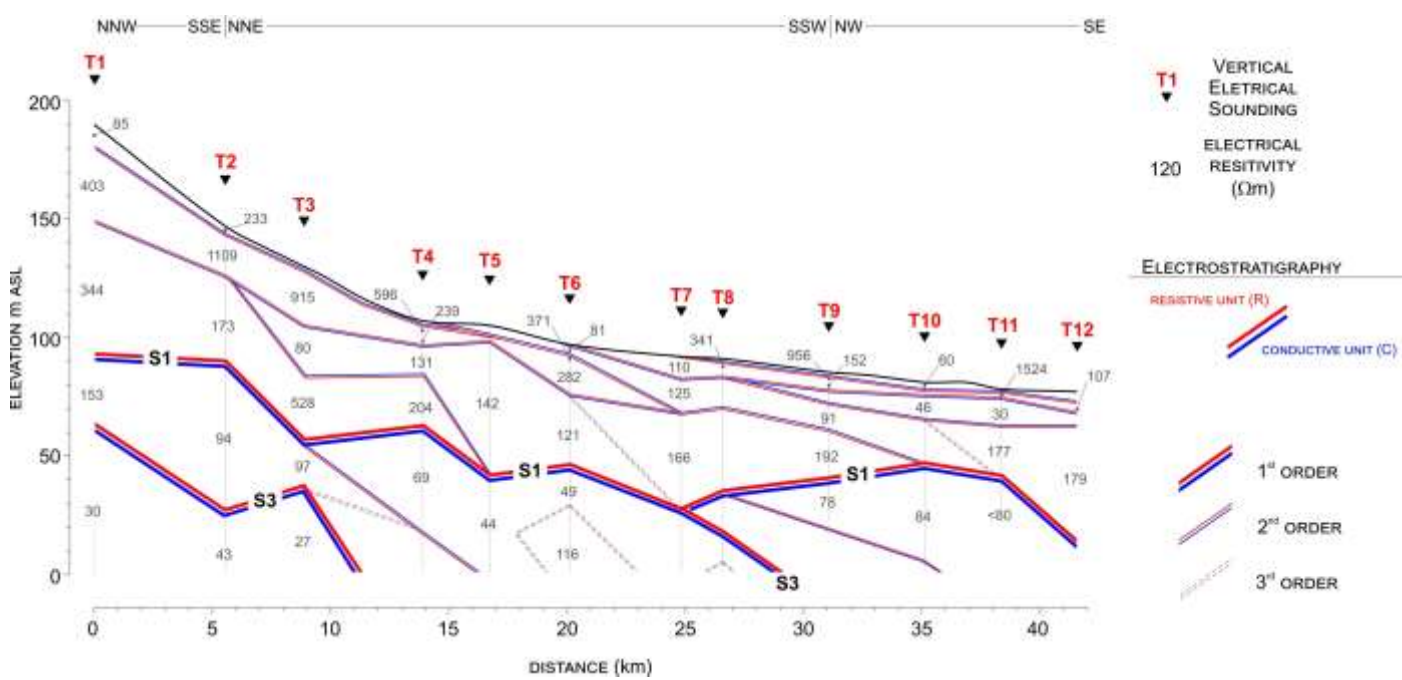


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Figure 4



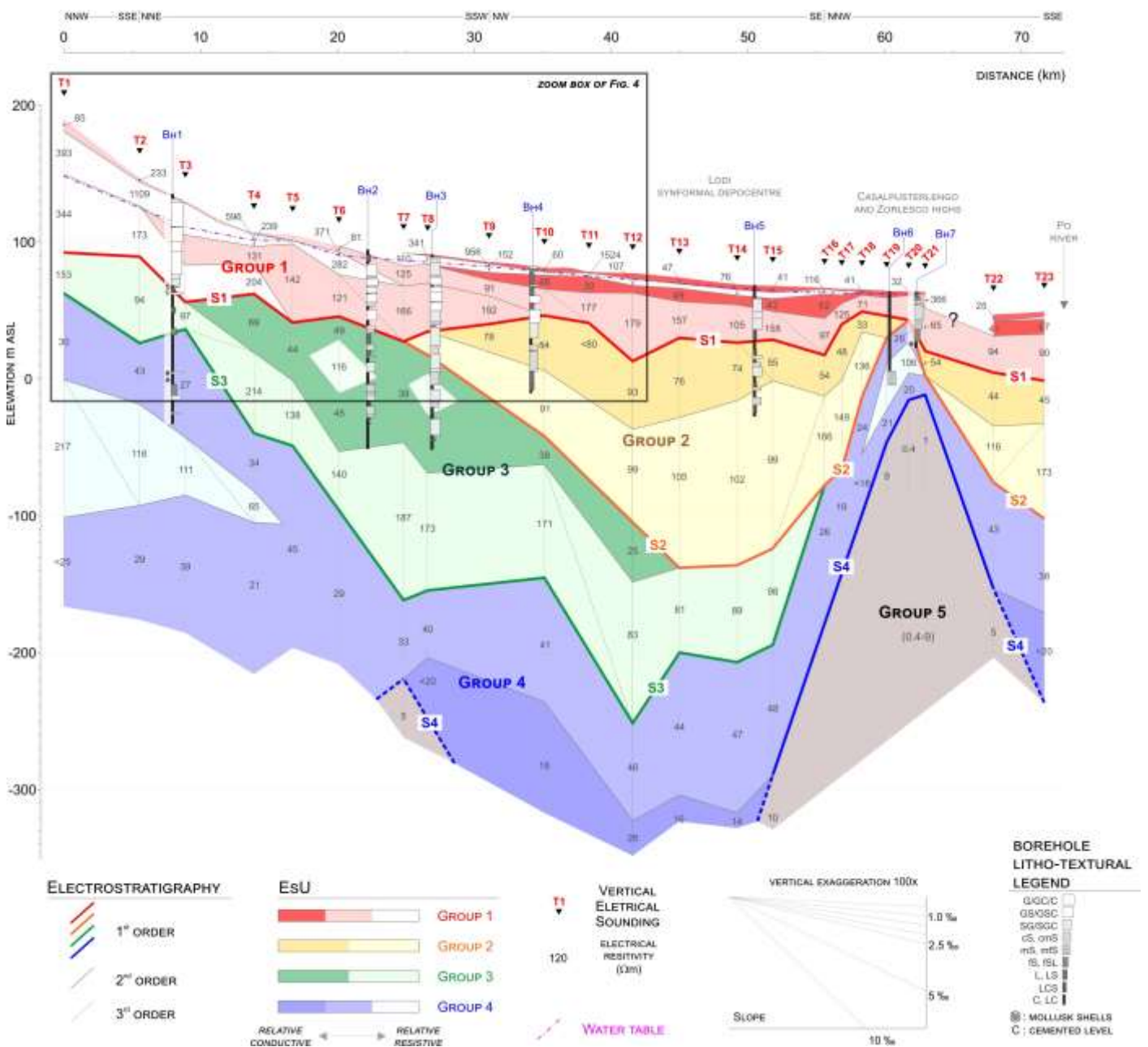
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Figure 5

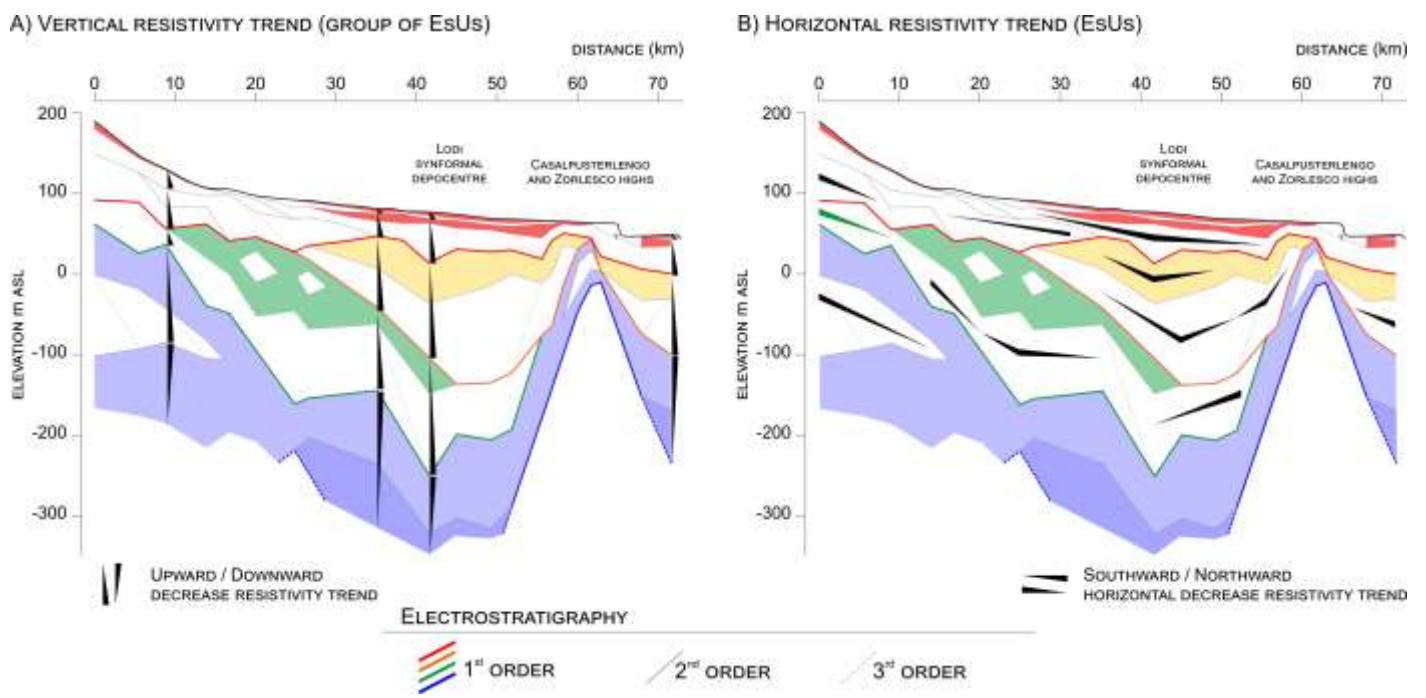


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Figure 6



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