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NEAR-SURFACE ELECTROSTRATIGRAPHY AS A TOOL TO DETECT THE CONNECTIVITY OF THE SEDIMENTARY BODIES

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Summary. The results of near-surface Direct Current surveys have been interpreted with the analysis of 1-D and 2-D resistivity datasets and sediments' and pore fluids electrical properties, in order to obtain 3-D models of sand-gravel and silt-clay alluvial bodies of an area of the Po plain south of Milan (Italy). The definition of the hierarchical scales of the sedimentary bodies permits the integration between hydro- and electro-stratigraphy and to gain a valid representation of heterogeneities of alluvial aquifers necessary for a reliable conceptualization of the groundwater reservoirs needed for the mathematical modelling of flow and transport processes.

1 INTRODUCTION

1.1 Integrated approaches to aquifer characterization

The representation of heterogeneity of aquifers at different scales is a key topic for the evaluation of the lateral and vertical extent and the connectivity of the sedimentary bodies in order to develop quantitative flow and transport models for the management and protection of ground water resources. The identification of aquifer geometries and facies organization is strictly dependent on direct methods such as continuous recovery boreholes (geognostic, water-well), especially in alluvial plains characterised by extensive human activities.

Integrated methods which involve stratigraphy, sedimentology and near-surface geophysical techniques[1,5,8,12] help to describe the spatial variation of the porosity and the permeability of alluvial aquifers in order to improve the 3-D stochastic modeling of (hydro)-facies distribution, porosity and hydraulic conductivity (K) fields. Starting from the assumption that sedimentary heterogeneity in the subsurface can be described with hierarchical elements at different scales[8,11], an integrated geological-geophysical approach can lead to a better assessment of the sensitivity and spatial resolution of near-surface geophysical techniques, with respect to the variation of the sediments' properties at depth and the relationship between petrophysical properties and pore-fluid saturation. This approach represents a link among spatial variations of permeability, hierarchical scales and variations of geophysical parameters, such as electrical resistivity (ρ). The survey design should take into account the characteristics (limits, external geometry and internal facies organization) of the sedimentary bodies, which could be successively traced in the subsurface following distinctive geophysical patterns. The latter, when joined with the geological interpretation, can be considered as signatures of specific sedimentary facies or their major associations (hydrofacies, hydrostratigraphic system/complex[1,7,10]).

Direct Current (DC) methods[6] supply the ρ of porous aquifers (sand, gravel) and aquitards (silt, clay), mainly controlled by the prevailing process of current conduction ("shale" vs. electrolytic conduction) and by the pore-fluids electrical conductivity. The aim of this work is to improve the integration between fast, cheap and non-invasive DC methods, the conceptual models of sedimentary architecture and the relationship between litho-textural properties, groundwater content and geophysical properties in order to obtain 3-D models that provide a valid representation of heterogeneity of aquifers, useful to constrain the successive mathematical modelling of flow and transport processes in the porous media.

1.2 Case study

The case-study is represented by the Quaternary sedimentary fill of the Po plain, in Northern Italy, in the valley of the palaeo-Sillaro extinct meandering river belt (Fig. 1) of LGM-post glacial age, entrenched in the local plain level ("*Livello Fondamentale della Pianura*" *Auct* - LFP) of the interfluve between Adda (on the eastern flank) and Lambro (on the western flank) major alluvial valleys.

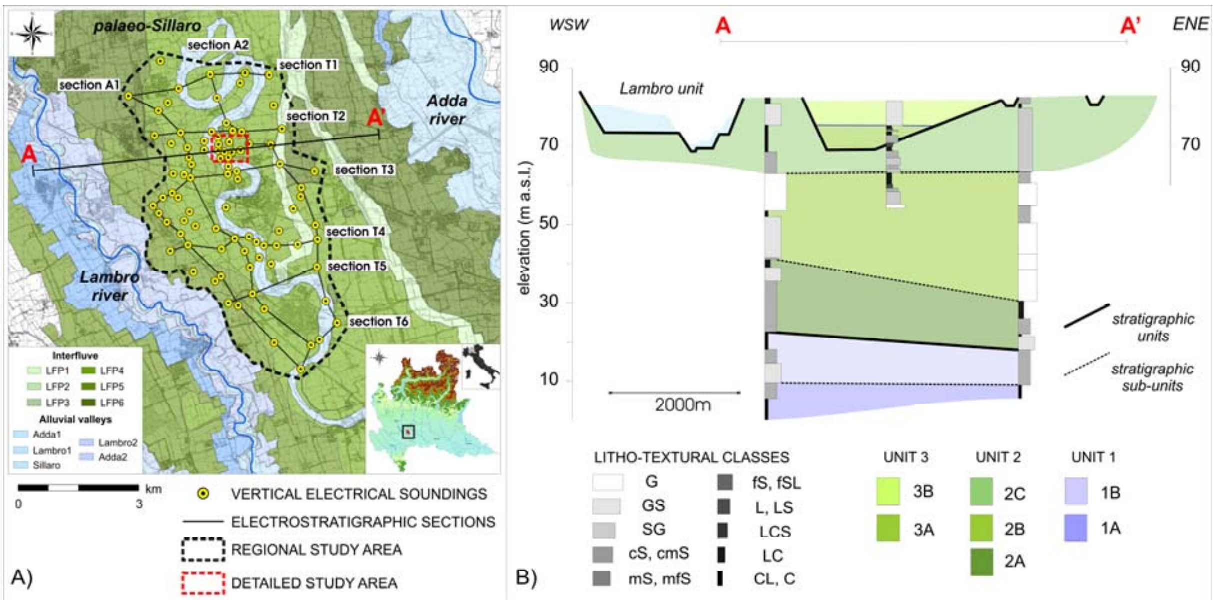

Figure 1: *A*) geomorphological map of the palaeo-Sillaro meandering river belt showing VES location into the regional study area (black dashed box) and the detailed survey area (red dashed box); *B*) simplified geological section accros palaeo-Sillaro (ubication in Fig.1A).

The detailed hydrostratigraphic model of the Adda-Lambro interfluve is carried out on the basis of the available borehole data to a maximum depth of 100 m. The low rank hierarchical units (hydrofacies), their evolutive trends (fining/coarsening upwards sequences) and their assemblage into high rank units (hydrostratigraphic systems) at regional scale have been identified. The local stratigraphy consists (Tab. 1[4]) of *i*) LGM sand-gravel point bar and channel bodies (aquifer system S4) overlying *ii*) clay to fine sand aquitard system (S3) of an Upper Pleistocene flood plain, *iii*) alternating gravel-sand aquifer bodies and fine sand to silty-clay drapes formed by Middle-Upper Pleistocene braiding to meandering depositional systems that represents the main aquifer (S2) and which developed above *iv*) a basal aquiclude (S1) of silty-clays formed by pre-Middle Pleistocene transitional-to-marine facies which hosts the salt-fresh water interface.

Stratigraphic Units (age)	sub-units	Minimum genetic units	Thickness (m)	Hydrostratigraphic units
Unit 3 (Latest Pleistocene, LGM)	3B	silt to clay fining upwards sequences; clayey silt lenses	3 - 8	aquifer system S4
	3A	gravelly sand to silt and clay fining upwards sequences; clayey silt lenses;	5 - 10	
Unit 2 (Middle-Late Pleistocene)	2C	sand to silt fining upwards sequences; organic-rich clayey silt lenses	5 - 20	aquitard system S3
	2B	non-cyclical gravel bodies; gravel to sand fining upwards sequences; clayey silt lenses	15 - 25	aquifer system S2
	2A	gravel to sand fining upwards sequences; clayey silt lenses	5 - 15	
Unit 1 (Middle Pleistocene)	1B	sand to silt and clay fining upwards sequences; clayey silt lenses	10 - 15	
	1A	clayey silt lenses	10 - 15	aquitard system S1

Table 1: stratigraphy and hydrostratigraphy in the palaeo-Sillaro valley.

3 NEAR-SURFACE ELECTROSTRATIGRAPHY

3.1 Regional study area

89 VES[6] were collected with Schlumberger array and a maximum half-spacing of 300 m over a 30 km^2 wide area across the palaeo-Sillaro meandering river belt (Fig. 1A), with an exploration depth of about 80 m below ground surface. Correlation of 1-D models obtained from field data inversion across the regional study area is based on two criteria: *i*) the discontinuities between electrolayers are characterized on the basis of the vertical polarity of the resistivity contrast (vertical stacking of resistive above conductive layer or vice versa) determining the local vertical electrostratigraphic sequence; *ii*) the polarity of resistivity contrasts between electrolayers is correlated among the 1-D models in order to delimitate the subsurface sediment volumes with the lowest internal variation of electrical resistivity. These two criteria allow to recognize the 3-D geoelectrical bodies in the subsurface (Fig. 2), informally defined “electrostratigraphic units” (EsUs), that can be traced through the investigated volume by the horizontal variation of the vertical electrostratigraphic sequence and are characterized by an increasing thickness at increasing depth, according to the equivalence and suppression principles[9].

On the basis of their lateral persistence, these units are subdivided in i) widespread EsUs, identified in several 1-D models and characterized by good lateral continuity in the study area (Tab. 2), and ii) lens-shaped EsUs, identified in a single or a few 1-D models. The lense-shaped EsUs do not conform with the electrostratigraphic framework defined at a regional scale and represent local geoelectrical heterogeneities with small lateral extent. The uppermost EsUs A and B mainly identify the vertical variation of ρ due to near-surface facies/hydrofacies transition within the unsaturated zone. These EsUs are defined respectively as a conductive body (<70 Ωm) and an underlying high-resistive body (170-1500 Ωm), with metric/sub-metric thickness. The deeper EsUs (C, D, E, F, G) characterize the saturated zone below the water table (generally coincident with the base of EsU B). They represent both conductive and resistive bodies characterized by a thickness that increases with depth up to tens of meters. EsUs C to F represent an alternation of conductive and resistive bodies. EsU G (<70 Ωm) is the deepest conductive unit and is identified in few 1-D models corresponding to the VES that reached the maximum exploration depth.

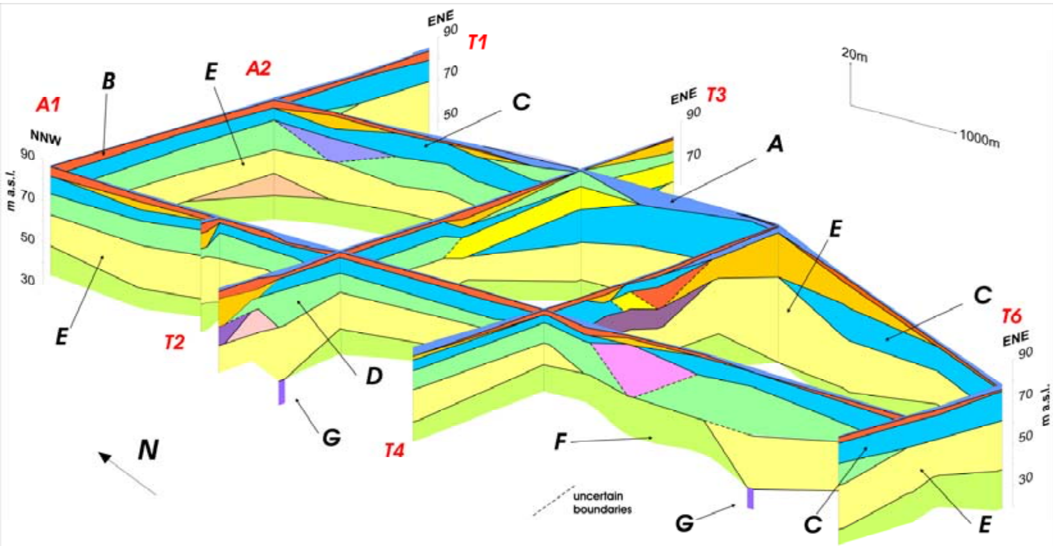

Figure 2: Fence diagrams of NNW-SSE (A1, A2) and WSW-ENE (T1, T2, T3, T4 and T6) VES electrostratigraphic sections (see Fig. 1A for location; black letters refer to the widespread EsUs of Tab. 2).

3.2 Detailed study area

In order to improve the details of the horizontal transitions between the EsUs at the meter-scale, a 2-D ERGI (Electrical Resistivity Ground Imaging[3]) has been planned within a selected area. In particular, ERGI sections have been located to investigate a point-bar complex of the palaeo-Sillaro river, with a regular grid of ERGI sections normal and parallel to the point-bar elongation. Ten sections have been acquired with 48 electrodes using a Wenner-Schlumberger array, electrode spacing from 3 m to 5 m and a roll-along acquisition scheme with an exploration depth of about 40 m b.g.s. The robust inversion of collected data yields 2-D models characterized by areas of approximately uniform electrical properties which are separated from each other by sharp boundaries and which are directly related to the regional electrostratigraphic framework defined through the VES survey (Fig. 3). However, the geoelectrical boundaries between EsUs have no straightforward correspondence in the ERGI sections, because the 2-D resistivity distribution obtained form ERGI is determined for a great number of blocks whose spatial extent depends on the electrode spacing.

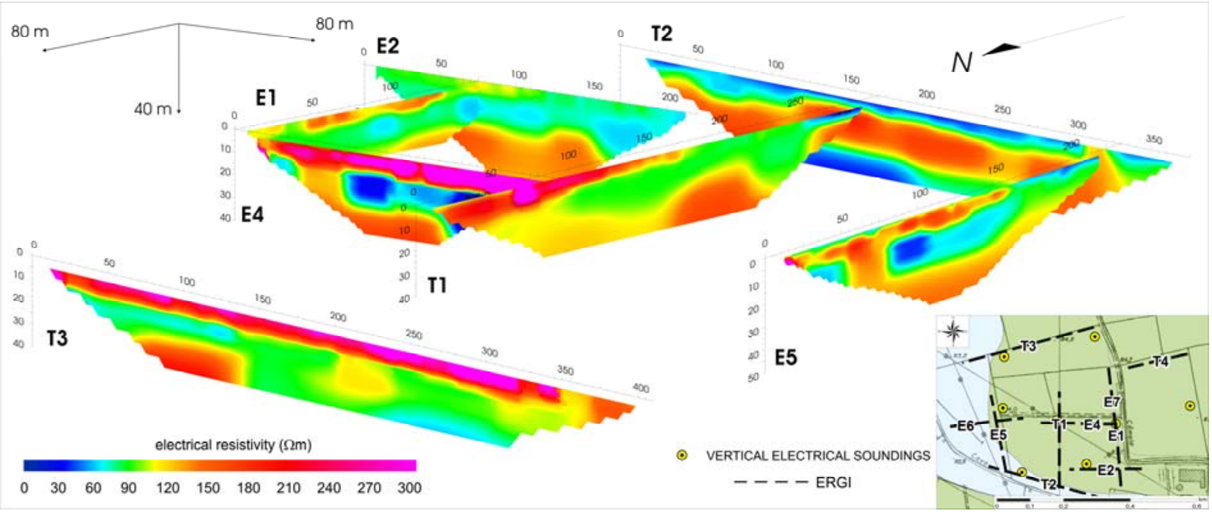

Figure 3: 3-D panel of ERGI models collected in the detailed survey area corresponding to the Sillaro point bar complex (the box in the lower right corner corresponds to the red dashed box in Fig. 1A).

4 HYDROGEOPHYSICAL CHARACTERIZATION

4.1 Local petrophysical relationship between ρ and K

In order to interpret the 1-D ρ distribution obtained from correlation of VES models as a proxy of the sediments' hydrostratigraphic properties, the site-specific physical parameters which affect the electrical resistivity as qualitatively expressed by the Archie's law (groundwater conductivity, saturation and cementation[2]) have been monitored during the field acquisition of geoelectrical data. The average pore-fluid conductivity in the study area (550 μS/cm) is estimated from direct sampling of the surface groundwater at deep excavation points and chemical analyses of groundwater extracted from water wells; the pore fluid saturation is determined in relation to the depth of the local water table (from 0.9 up to 6.3 m b.g.s.); the available subsurface data do not provide evidence of cementation. In a second stage, a calibration of the ρ measurements against K estimates and litho-textural properties is attempted, considering separately the unsaturated and the saturated zone and fixing the average electrical conductivity of local groundwater. In the unsaturated zone, a direct calibration between electrical resistivity and hydrofacies is obtained at VES stations thanks to hand-auger drilling down to 5 m b.g.s. In the saturated zone, an indirect calibration is attempted, comparing the electrostratigraphic framework at increasing depths with the litho-textural associations (i.e. hydrofacies) interpreted from the available stratigraphic logs.

A coarse-to-fine litho-textural ratio (C/F; cut-off ∅=0.30 mm) is used to classify high-permeability gravel-sandy gravel hydrofacies (C/F>10), gravelly sand hydrofacies (1<C/F<10) and low-permeability silt-clay hydrofacies (C/F<1). The variability of C/F is compared with K (m/s) and ρ (Ωm) of hydrofacies, both in the unsaturated and the saturated zone. Then, a local petrophysical relationship between K and ρ (Fig. 4A) is established and enables to identify a fine litho-textural association (C/F<1), with a prevailing "shale" conduction, low ρ and small K, and a coarse association (C/F>1), with a prevailing electrolytic conduction, high ρ and high K. This local petrophysical relationship is used to reclassify shallow (unsaturated zone) and deep (saturated zone) EsUs in terms of the prevailing hydraulic properties of the equivalent volume (permeability classes: low, intermediate or high K: Fig. 4B).

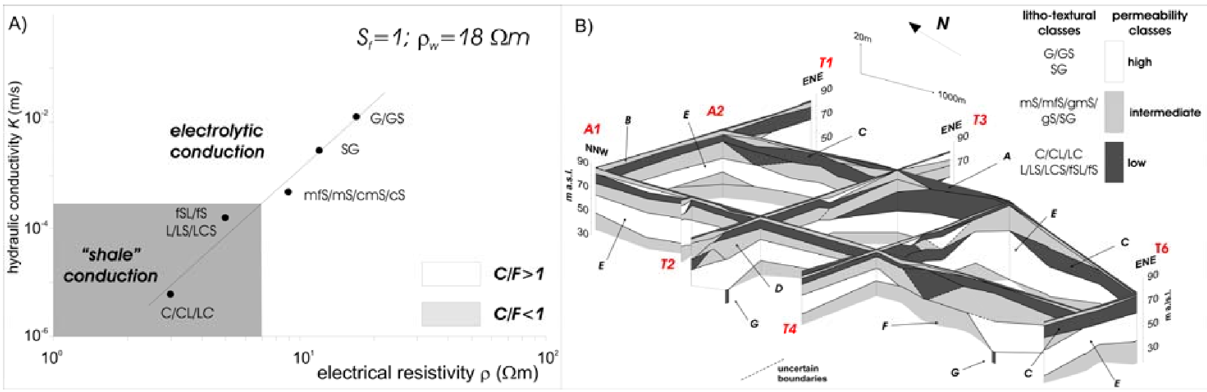

Figure 4: *A*) local petrophysical relationship between hydraulic conductivity estimates and electrical resistivity, for fixed values of fluid saturation (S_f) and mean groundwater electrical resistivity (ρ_W); *B*) VES electrostratigraphic sections (same as Fig. 2) interpreted in terms of the dominant hydraulic properties.

EsU	Range of ρ (Ωm)	Estimated K range (m/s)	Thickness range (m)	Depth range(m b.g.s.)
A	<70	$< 3.0\cdot10^{-4}$	0.5-9	0-10
B	170-1500	$2.8\cdot10^{-4}$ - $1.9\cdot10^{-3}$	0.5-5	0.5-6
C	20-70	$1.6\cdot10^{-6}$ - $3.0\cdot10^{-4}$	5-10	5-15
D	70-100	$3.0\cdot10^{-4}$ - $1.3\cdot10^{-3}$	10-15	15-25
E	110-200	$1.9\cdot10^{-3}$ - $2.3\cdot10^{-2}$	10-25	25-45
F	70-90	$3.0\cdot10^{-4}$ - $8.4\cdot10^{-4}$	10-30	25-60
G	<70	$< 3.0\cdot10^{-4}$	-	>60-70

Table 2: VES electrostratigraphic model for the palaeo-Sillaro valley based on the widespread EsUs.

4.2 Integration between hydrostratigraphy and electrostratigraphy

The integration between the electrostratigraphic and the hydrostratigraphic models permits to validate and partially revise the hydrostratigraphic framework in the alluvial valley of palaeo-Sillaro river, in terms of vertical hydrostratigraphic successions, average hydrodynamic properties and distribution of lateral heterogeneities. According to the equivalence and suppression principles[9], which limit the interpretation of DC measurements at increasing exploration depth, shallow EsUs (in the unsaturated zone) coincide with hydrofacies whereas deep EsUs (in the saturated zone) can be interpreted as the geoelectrical images of the connectivity of the sedimentary bodies that are characterized by peculiar facies (i.e. litho-textural), hydraulic and electrical properties at a physical scale comparable with the hierarchical scale of hydrostratigraphic systems.

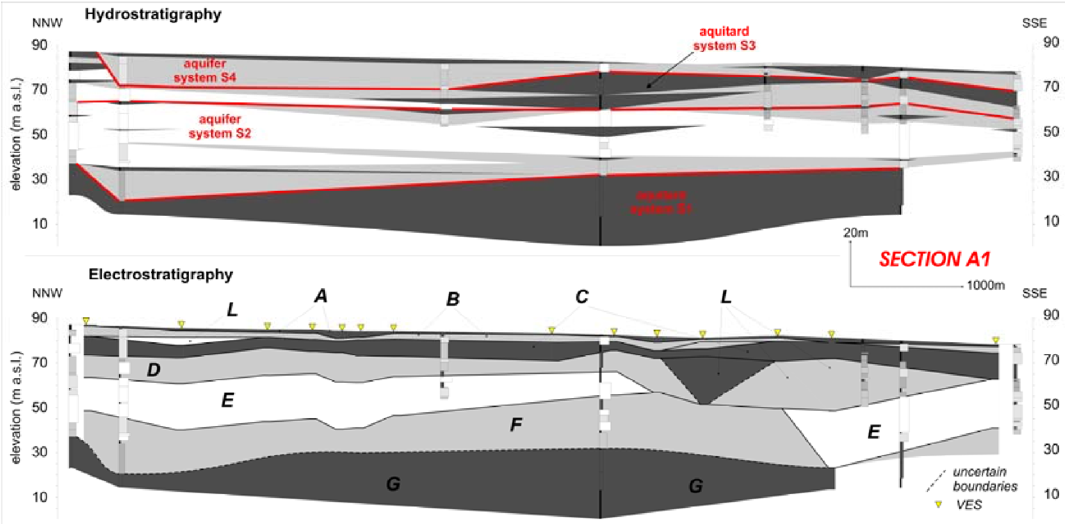

Figure 5: integration of hydrostratigraphy and electrostratigraphic model along Section A1 (see Fig. 1 for location and Fig. 4B for permeability classes; the letter L refers to the lens-shaped EsUs).

From NNW to SSE (Fig. 5), the electrostratigraphy confirms the presence of coarse-grained resistive sheet-bodies (sand-to-gravel, gravel) with ρ ranging in the uppermost part from 110 to 200 Ωm (Unit E; estimated K from $1.9 \cdot 10^{-3}$ m/s to $2.3 \cdot 10^{-2}$ m/s) and, in the lowermost part, from 70 to 90 Ωm (Unit F; estimated K from $3.0 \cdot 10^{-4}$ m/s to $8.4 \cdot 10^{-4}$ m/s). They form the aquifer system S2 at the top of the older sandy-clay meandering river belt of Middle Pleistocene age (sub-unit 1A) characterized by ρ<70 Ωm and estimated $K<3.0 \cdot 10^{-4}$ m/s (Unit G), corresponding to the aquitard system S1. The subsequent backstepping to north of the depositional system during the Upper Pleistocene, and the development of a sandy meandering system with a clay-rich flood plain over the entire study area is represented by sub-unit 2C plausibly corresponding to EsUs C (20 Ωm<ρ<70 Ωm; $1.6 \cdot 10^{-6}$ m/s<K<$3.0 \cdot 10^{-4}$ m/s) and D (70 Ωm<ρ<100 Ωm; $3.0 \cdot 10^{-4}$ m/s<K<$1.3 \cdot 10^{-3}$ m/s), that represent the aquitard system S3. The integration of hydrostratigraphy with electrostratigraphy ameliorates the interpretation of the lateral terminations of the coarse grained part of the aquifer system S2.

5 CONCLUSIONS

The integration between hydrostratigraphy and electrostratigraphy allows to develop and cross-validate the subsurface hydrostratigraphic models of the Sillaro palaeo-valley. In the near-surface, EsUs represent vertical resistivity variations related to the litho-textural contrasts at the scale of the hydrofacies[1], as a function of the proportion between fine and coarse textures within each sedimentary facies (C/F ratio). At greater depths, matching the hydrostratigraphic systems scale[7,10], an heterogeneous and hierarchically organised medium, for which the litho-textural contrasts between different facies produce resistivity variations, behaves as an equivalent assemblage corresponding to an EsU. A reliable representation of the connectivity of the sedimentary bodies can be obtained by the identification of the regional electrostratigraphic sequence through the correlation of 1-D VES models. This procedure provides a tool to map local heterogeneities, i.e., EsUs that do not conform with the regional electrostratigraphic sequence. An improved mapping of the horizontal transitions (up to a metric scale) between EsUs can be obtained with the 2-D ERGI models. This integrated multidisciplinary approach gives the chance to reduce the disparity between the lateral and the vertical resolution of the hydrostratigraphic reconstruction, traditionally based on point data and allows to obtain a better conceptualization for the mathematical modelling of flow and transport processes in the hierarchically stratified porous media.

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