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The architecture of alluvial aquifers: an integrated geological-geophysical methodology for multiscale characterization

Una metodologia integrata, geologico-geofisica, per la caratterizzazione multiscala dell'architettura degli acquiferi alluvionali

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ABSTRACT - The aim of this work is the improvement of a methodology for the integration of near-surface geoelectrical data (Vertical Electrical Soundings, VES, and Electrical Resistivity Ground Imaging, ERGI) with geological-geomorphological data, in order to characterize the hydrostratigraphy of alluvial plains at different scales. Data integration is based on the mapping of sedimentary bodies that are defined by their geological boundaries, geometry and facies, and traced laterally from subsurface control points (borehole and well logs) with the aid of the vertical electrostratigraphic sequence.

The methodology was applied to the Quaternary alluvial valley of the Sillaro extinct meandering river (Lodi plain south of Milan between the Adda and Lambro terraced valleys). The local stratigraphy consists of LGM sand-gravel meandering river deposits (palaeo-Sillaro) overlying i) a clay to fine sand aquitard (flood plain, Upper Pleistocene), ii) alternating gravel-sand aquifer bodies formed by braiding to meandering depositional systems (Middle-Upper Pleistocene) and iii) a basal aquiclude of silty-clays (flood-plain, Middle Pleistocene). The methodology yields: i) the geological/geomorphological model, ii) the hydrostratigraphic model describing the low rank hierarchical units (hydrofacies) and their evolutive trends up to the assemblage of high rank hydrostratigraphic systems, iii) the characterization of site-specific parameters which affect electrical resistivity (groundwater conductivity, textures, saturation, cementation), iv) planning of the geoelectrical surveys and data acquisition (VES), v) electrical resistivity calibration, correlation of subsurface electrical resistivity models and multiscale interpretation, vi) improvement of details of the subsurface structure (ERGI) and vii) integration between hydrostratigraphy and electrostratigraphy.

89 VES and 3000 m of ERGI sections were acquired over an area of 30 km^2. For shallow investigations at the detailed scale (0-5 m, unsaturated zone) the integration of data yielded the assemblage of stratigraphic units and their apparent electrical resistivity maps, both representative of coarse-grained point-bar deposits and fine-grained oxbow-lake/overbank deposits. For deeper investigations at the regional scale (>5 m, saturated zone) VES models were correlated by vertical polarity of electrical contrasts and lateral persistence of electrical resistivity. Hence, we identified the "electrostratigraphic units" (EsU) that represent 3-D geophysical bodies defined by their electrical contrast with the adjacent units, internal electrical properties, apparent geometry and lateral extent, forming an electrostratigraphic sequence. The EsUs are directly related to heterogeneous and stratified sedimentary volumes. 2-D ERGI sections permitted to improve the characterization of the near-surface transitions between electrostratigraphic units at metric scale. Integration between geological and geoelectrical data permitted to: i) define scale, hierarchy and vertical-lateral continuity of subsurface electrostratigraphic units in relation to the local hydrostratigraphic units, ii) develop and validate the subsurface hydrostratigraphic models of the valley of palaeo-Sillaro river to a maximum depth of 80 m and iii) propose a multidisciplinary methodology to characterize the hydrostratigraphic settings of alluvial plains at different scales.

KEY WORDS: aquifer, electrical tomography, hydrostratigraphy, Po plain, vertical electrical soundings.

RIASSUNTO - Scopo di questo lavoro è lo sviluppo di una metodologia per l'integrazione dei dati derivanti dall'esplorazione geoelettrica da superficie (*Vertical Electrical Soundings, VES, ed Electrical Resistivity Ground Imaging,* ERGI) con le basi

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di dati stratigrafico-sedimentologici e geomorfologici, per la ricostruzione e caratterizzazione di sistemi e complessi idrostratigrafici di origine alluvionale a scale differenti. L'integrazione dei dati è basata sulla mappatura di corpi sedimentari distinguibili in base ai loro limiti geologici, geometria esterna, organizzazione interna delle facies e tracciabili dai punti di controllo in superficie sulla base delle sequenza elettrostratigrafica verticale.

La metodologia è stata applicata alla valle alluvionale quaternaria del Sillaro, un paleo-fiume a meandri che scorreva tra le valli terrazzate dei fiumi Adda e Lambro, nell'attuale pianura lodigiana a sud di Milano. La stratigrafia locale è costituita da depositi fluviali sabbioso-ghiaiosi di età LGM relativi alla piana a meandri del paleo-Sillaro che ricoprono i) un acquitardo argilloso-sabbioso fine (piana di esondazione; Pleistocene superiore), ii) alternanze di corpi acquiferi ghiaioso-sabbiosi rappresentati da sistemi deposizionali con carattere da *braided* a meandriforme (Pleistocene medio-superiore) e iii) un acquitardo limoso-argilloso basale (piana di esondazione; Pleistocene medio).

La metodologia prevede: i) la definizione del modello geologico/geomorfologico, ii) la definizione del modello idrostratigrafico a partire dalle unità di rango minimo (idrofacies) e loro associazioni verticali fino all'assemblaggio delle unità di rango superiore (sistemi idrostratigrafici), iii) la caratterizzazione dei parametri sito-specifici che influenzano la resistività elettrica dei terreni (conducibilità delle acque sotterranee, tessitura, saturazione, cementazione), iv) la pianificazione delle indagini geoelettriche e l'acquisizione dei dati (VES), v) la calibrazione della resistività elettrica, la correlazione dei modelli di resistività di sottosuolo e l'interpretazione multiscala, vi) il miglioramento del dettaglio delle strutture sepolte e delle loro eterogeneità orizzontali (ERGI) e vii) l'integrazione tra idrostratigrafia ed elettrostratigrafia.

89 VES e 3000 m lineari di sezioni ERGI sono stati acquisiti in un'area di 30 km^2. A bassa profondità e a scala di dettaglio (0-5 m, zona insatura) l'integrazione dei dati ha consentito di caratterizzare le unità stratigrafiche ed il loro assemblaggio in superficie attraverso mappe di resistività apparente rappresentative della distribuzione dei depositi grossolani di *point-bar* e dei depositi a grana fine di esondazione e riempimento passivo di canale. A profondità più elevate e a scala di indagine regionale (>5 m, zona satura) i modelli VES 1-D sono stati correlati sulla base della polarità verticale del contrasto elettrico e sulla persistenza laterale dei valori di resistività elettrica. In questo modo, sono stati identificati come "unità elettrostratigrafiche" (EsU) dei corpi geofisici 3-D definiti in base al contrasto elettrico con le unità adiacenti, dalle proprietà elettriche interne, alla geometria apparente e all'estensione laterale. Le EsU sono direttamente legate ai corpi sedimentari eterogenei e stratificati e la loro successione verticale determina una sequenza elettrostratigrafica VES riconoscibile. Le sezioni 2-D ERGI hanno consentito di migliorare la caratterizzazione delle transizioni latero-verticali tra unità elettrostratigrafiche fino ad una scala di dettaglio metrica.

L'integrazione tra dati geologici e geoelettrici ha consentito di: i) definire scala, gerarchia e continuità latero-verticale delle unità elettrostratigrafiche di sottosuolo in relazione alle locali unità idrostratigrafiche, ii) sviluppare e validare i modelli idrostratigrafici della valle del paleo-Sillaro fino ad una profondità massima di 80 m p.c. e iii) proporre una metodologia multidisciplinare per la caratterizzazione dell'architettura idrostratigrafica delle piane alluvionali a scale differenti.

PAROLE CHIAVE: acquiferi, idrostratigrafia, Pianura Padana, sondaggi elettrici verticali, tomografia elettrica.

1. - INTRODUCTION

1.1. - GEOLOGICAL AND GEOPHYSICAL APPROACHES TO AQUIFER CHARACTERIZATION

The characterization of sedimentary architecture and the achievement of a valid representation of aquifers heterogeneity at different scales (hydrofacies, hydrostratigraphic system/complex; ANDERSON, 1997; MAXEY, 1964) is a key topic to forecast flow and transport processes in the subsurface of alluvial plains. The recognition of aquifer geometries and internal facies organization is still mainly based on direct methods such as continuous recovery boreholes (geognostic logs, water wells), especially in alluvial plains characterised by extensive human activities. The results that can be obtained from these punctual and expensive investigations are often limited to i) the characterisation of textural properties of the sediments, ii) the definition of sedimentary associations and vertical evolutive trends and iii) lithostratigraphic correlations.

Open problems related to the use of such data are represented by: i) the lateral correlation of stratigraphic surfaces, which bound aquifer bodies at the sampling points; ii) the spatial distribution and density of the hard-data, which could affect the subsurface reconstruction; iii) the definition of the hydraulic properties and iv) the lateral and vertical extent and the relative interconnection of the sedimentary bodies.

DC resistivity methods such as Vertical Electrical Soundings (VES; DAHLIN, 2001) and Electrical Resistivity Ground Imaging (ERGI; BAINES *et alii*, 2002) yield respectively the 1-D and 2-D electrical resistivity distribution in the ground. In the case of porous aquifers, the bulk electrical resistivity is controlled by the prevailing process of current conduction ("shale" vs. electrolytic conduction) determined by the occurrence of fine-grained sediments and saline groundwaters which enables the current conduction through the porous media as a function of porosity, clay content, sediments textures and pore-fluid salinity. VES technique is a cost-and-time effective exploration tool. It can be employed in many different geological settings and enables to collect a large amount of 1-D electrostratigraphic data on wide areas providing multi-scale imaging of stratified aquifers. VES vertical resolution relies on the well-known equivalence and suppression principles and only major resistivity variations can be identified at increasing depth, as a complex combination of thickness and resistivity contrasts (KELLER & FRISCHKNECHT, 1966; REYNOLDS, 1997; TELFORD *et alii*, 1990).

To improve the spatial resolution of vertical/horizontal transition between silt-clay aquitard /aquiclude and sand-gravel aquifers, ERGI technique yields a large number of resistivity measurements along oriented sections, hundred of meters long (BAINES *et alii*, 2002; BERSEZIO *et alii*, 2007; BOWLING *et alii*, 2007).

When textural/porosity/silt-clay fraction contrasts among beds are present and when the data interpretation is independently constrained with the pore-fluid properties, these features make the DC methods a powerful exploration tool to differentiate litho-textural associations (silt-clay aquitard/aquiclude; sand and gravel aquifers; BAINES *et alii*, 2002; BERSEZIO *et alii*, 2007; BRATUS & SANTARATO, 2009; GOURRY *et alii*, 2003; HICKIN *et alii*, 2009; ZAHLEA *et alii*, 2005).

1.2. - AIM OF THE WORK

This work aims to improve an integrated methodology to merge near-surface geoelectrical data with geological and hydrostratigraphic data, used as constrains for the definition of *geophysical bodies* with specific relationships with the *sedimentary bodies* at different scales. At this purpose, after a correlation between the bulk electrical resistivity of the porous media and the pore-fluid saturation and chemistry, the electrical resistivity is considered as a "proxy" of the sedimentary facies characterized by a litho-textural content and a prevailing process of current conduction ("shale" vs. electrolytic conduction). Assuming that the sedimentary heterogeneity can be described with hierarchical elements at different scales (hydrofacies, hydrostratigraphic system/complex/group; HUGGENBERGER & AIGNER, 1999; MAXEY, 1964; MIALL, 1996) and recalling that the resolution of DC surveys decreases with depth, this integrated approach allows to interpret the resistivity distribution as a function of the hierarchical properties of aquifers, i.e., the vertical trends and proportions of facies with prevailing "shale" or electrolytic conduction.

1.3. - THE CASE STUDY

The integrated methodology was applied to the Lodi Quaternary alluvial plain south of Milan, Italy (fig. 1) which belongs to the Neogene Po plain foredeep basin, bounded to the North, by the frontal thrusts of the Southern Alps and to the South by the external arcs of the Northern Appennines (ENI-REGIONE LOMBARDIA, 2002; PIERI

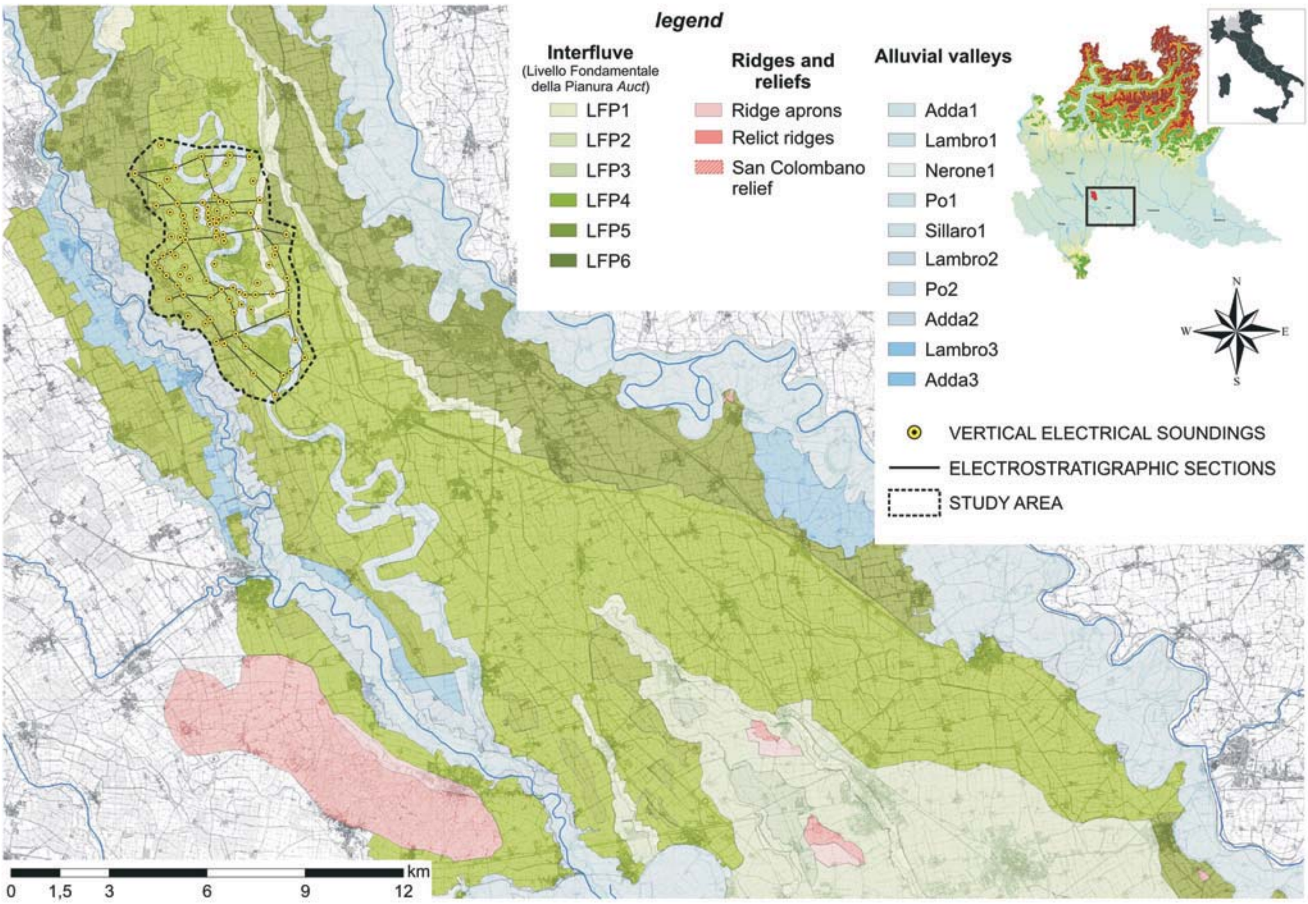

Fig. 1 - Lodi alluvial plain: location of the study area (dashed box; geological map from BAIO *et alii*, 2009).
- *La pianura Lodigiana: ubicazione dell'area in studio (a tratteggio; carta geologica da* BAIO et alii, *2009).*

& GROPPI, 1981). The basin was filled during Pliocene by deep marine sediments and, from Early to Middle Pleistocene, by at least three transgressive-regressive cycles (ENI-REGIONE LOMBARDIA, 2002); the youngest marine-to-transitional deposits are referred to the lower portion of Middle Pleistocene (MUTTONI *et alii*, 2003). From Middle Pleistocene an alluvial succession of Alpine provenance spread over the study area with the deposition of fluvial and glacio-fluvial sand-gravel sediments, whose maximum total thickness reaches some hundreds meters and becomes thin (a few meters) above the tectonic relief of San Colombano Hill (ALFANO & MANCUSO, 1996; BERSEZIO *et alii*, 2004) and Casalpusterlengo, Zorlesco and Chiesiolo buried structures (BERSEZIO *et alii*, this volume) to the South. The study area (fig. 1) is 30 km^2 wide and is located across the relict meandering river belt of the Sillaro palaeo-river of LGM-post and glacial age, entrenched in the local "Livello Fondamentale della Pianura" (i.e., basic plain level, LFP from now on; CASTIGLIONI & PELLEGRINI, 2001) between Adda (to the East) and Lambro (to the West) major river valleys.

1.4. - METHODOLOGY

The adopted methodology aims to efficiently map sedimentary bodies, that are defined by their boundaries, geometry and facies organization. The workflow can be summarized as follows:
i) definition of the geological/geomorphological model on the basis of the surface-subsurface data;
ii) elaboration of the hydrostratigraphic model describing the low rank hierarchical units (hydrofacies) and their evolutive trends (fining/coarsening upwards sequences), up to the assemblage of high rank hydrostratigraphic systems;
iii) characterization of site-specific parameters which affect the electrical resistivity (groundwater conductivity, soil saturation, porous matrix cementation);
iv) planning of the 1-D geoelectrical surveys (VES) and data acquisition;
v) calibration of the electrical resistivity with the hydraulic and litho-textural properties through the definition of the local petrophysical relationship between physical sediments' properties;
vi) correlation of subsurface electrical resistivity models and identification of the electrostratigraphic framework;
vii) improvement of details of the subsurface electrostratigraphic framework with 2-D resistivity imaging (ERGI);
viii) integration between hydrostratigraphy and electrostratigraphy and elaboration of the final model.

2. - CONCEPTUAL MODEL OF THE PALAEO-SILLARO VALLEY

Geological mapping, interpretation and correlation of subsurface data yielded a preliminary conceptual model including several components: geometry (area, shape and thickness of the sedimentary bodies), sedimentology (textures and sediment composition, facies associations, lateral and vertical evolutive trends), stratigraphy (hierarchy, stacking patterns and age of the stratigraphic units) and hydrostratigraphy (estimates of porosity and permeability, relationship with pore-fluids).

2.1. - STRATIGRAPHIC FRAMEWORK

According to BERSEZIO *et alii* (2004) five depositional units of Middle Pleistocene-Holocene age form the subsurface of the Lodi plain, down to 100 m below the ground surface (fig. 2, box C).

Their deposition was controlled by the Middle to Upper Pleistocene climatic-tectonic cycles during the glaciations and the last tectonic pulses at the front of the Apennine thrusts (San Colombano, Casalpusterlengo, Zorlesco and Chiesiolo buried structures; BERSEZIO *et alii*, this volume; BINI, 1997b; ENI-REGIONE LOMBARDIA, 2002).

The lowermost subsurface unit (Unit 1; Middle-Upper Pleistocene) has no relationship with the ground surface in the study area. The topmost portion of the overlaying Unit 2 (Upper Pleistocene) and Unit 3 (LGM – Post-glacial) form the present-day topographic surface, the geomorphological LFP *Auct.* in the Lodi plain. It shows an average SSE dip of about 0.15% and is cut by the terrace scarps of the Lambro and Adda valley systems (fig. 2, box A). In the study area Unit 3 corresponds to the depositional system of the palaeo-Sillaro meandering river belt that is confined within a terraced valley with an average width of 3 km. The meandering trace of the abandoned river is well preserved, showing a mean radius of curvature of about 1 km (BERSEZIO, 1986; VEGGIANI, 1982). To the North the terrace scarps expose the top of Unit 2, attributed to the Upper Pleistocene glacio-fluvial Besnate Allogroup (BERSEZIO *et alii*, 2004; BINI, 1997a, 1997b; DA ROLD, 1990). The Lambro valley Post-glacial depositional systems are Units 4 and 5 (fig. 2, box A and C) that will not be dealt with.

2.2. - STRATIGRAPHIC MODEL

The stratigraphic model was elaborated by traditional correlation of the available data through litho-textural classification of sediments after MIALL's (1996) classification, modified to specify

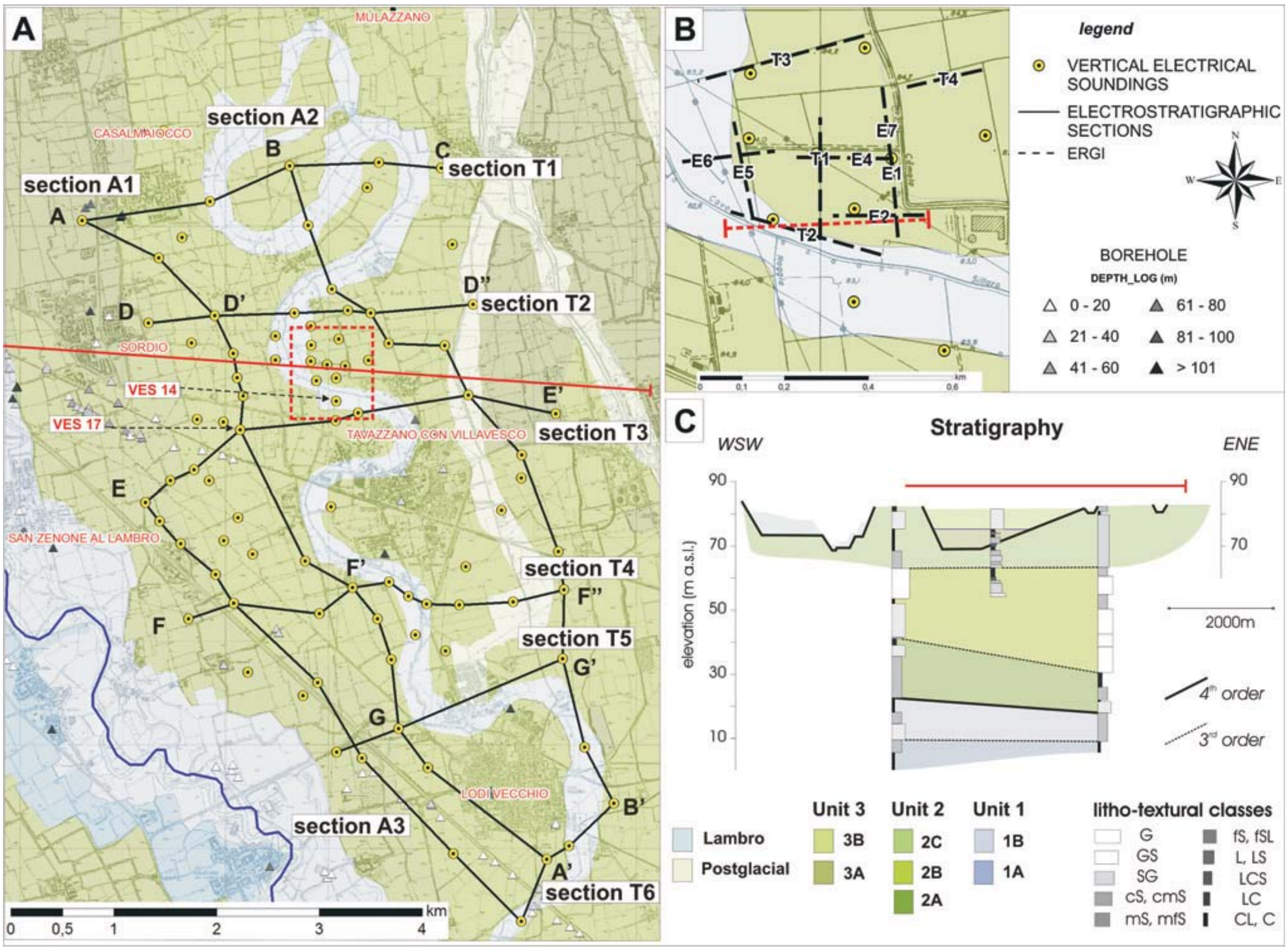

Fig. 2 - Geological map (box A; from Baio *et alii*, 2009) of the Lodi plain showing the location of the subsurface data points, of the VES, of the area covered with a detailed ERGI survey (dashed box; the location of the ERGI profiles is shown in box B) and of the traces of the hydrostratigraphic (fig. 3) and electrostratigraphic (fig. 5, 7 and 9) sections. Simplified geological section across the palaeo-Sillaro valley (red continuous line in box A) is shown in box C.

- *Carta geologica (A; da* Baio et alii, *2009) della pianura lodigiana, che illustra la posizione dei dati di sottosuolo, dei VES, dell'area coperta con il rilievo ERGI di dettaglio (rappresentata con il quadrilatero a tratteggio rosso in A; l'ubicazione dei profili ERGI è riportata nell'inserto B) e le tracce delle sezioni idrostratigrafiche (fig. 3) ed elettrostratigrafiche (fig. 5, 7 and 9). Una sezione geologica semplificata attraverso la valle del paleo-Sillaro (linea rossa continua nell'inserto A) è mostrata nell'inserto C.*

the grain size association of the sedimentary facies.

The hierarchy of the sedimentary discontinuities was determined after the identification of the sharp boundaries between gravel-sand beds above fine grained sediments.

Four informal hierarchical orders were defined, starting from the minimum rank sequences, or genetic units (minimum fining-upwards, stationary or coarsening upwards vertical trends). The stack of these lowest rank units originates the stratigraphic hierarchy of depositional elements, stratigraphic sub-units and stratigraphic units shown in table 1.

The hierarchical classification enabled to identify three highest-rank stratigraphic units, bounded by 4th order stratigraphic surfaces that are formed by stacked sub-units bounded by 3rd order stratigraphic surfaces (fig. 2, box C). The 4th order units correspond, from the bottom to the top, to the Unit 1, 2 and 3 described by Bersezio *et alii*, (2004). Unit 1 (Middle Pleistocene, maximum detectable thickness 25 m) consists of sand, silt and clay facies, arranged in fining upwards sequences, tens of meters thick. It is bounded at the top by a planar erosional surface, at an elevation between 30 m and 40 m above sea level. Two sub-units (1A, 1B) are bounded by 3rd order surfaces. Sub-unit 1A is characterized by organic-rich silt-clay, fining upwards sequences; sub-unit 1B consists of sand-silt fining upwards sequences, up to 15 m thick. Unit 2 (Middle-Late Pleistocene, maximum detectable thickness 45 m) is formed by stacked gravel and sand depositional elements, with rare fine grained layers. It is bounded at the top by the present-day topography in the northern area and by the concave erosional surface at the base of the uppermost Unit 3, to the south. From its base and upwards, Unit 2 is formed by three sub-units (2A, 2B, 2C) bounded by 3rd order surfaces. Sub-unit 2A consists mainly of sands and gravelly-sands, up to 10 m thick, and subordinated fine grained layers. Sub-unit 2B is the coarsest sedimentary body, characterized by gravel and sandy-gravel fining-upwards sequences, up to 25 m thick. Sub-unit 2C is a sand and silty-clay facies association, forming two fining-upwards sequences; its total thickness ranges from 5 m, due to the top truncation, and 25 m.

Unit 3 (Latest Pleistocene, LGM – Post-glacial, maximum thickness 15 m) is characterized by sand-gravel and silt-clay facies. It was formed by the palaeo-Sillaro meandering depositional system. Unit 3 is bounded at the top by the present-day topography. The 4th order basal erosional unconformity truncates Unit 2 down to the base of sub-unit 2C, laying between 70 m and 75 m above sea level. This buried erosional surface is connected with the emerging terrace scarps which bound the palaeo-Sillaro valley. Unit 3 includes two sub-units (from the base to the top: 3A and 3B), which define two sand-gravel fining upwards sequences.

2.3. - HYDROSTRATIGRAPHY

The stratigraphic model provides the base for hydrostratigraphy from the low rank units (hydrofacies) up to their assemblage into aquifer/aquitard systems and complexes. The hierarchy of stratigraphic and hydrostratigraphic units is presented in tab. 1, the elements for hydrofacies characterization are presented in tab. 2. The facies association was at first described by litho-textural classes; then porosity and hydraulic conductivity were estimated and compared with bibliographic data (BERSEZIO *et alii*, 1999; JUSSEL *et alii*, 1994; KLINGBEIL *et alii*, 1999) and with the results of laboratory tests upon analogue sedimentary facies exposed in the study area (DELL'ARCIPRETE *et alii*, 2008). The resulting hydrofacies scheme (in the sense of ANDERSON, 1997) was simplified in a threefold classification of broad and semi-quantitative permeability classes (tab. 2) to facilitate comparisons with the electrical properties resulting from VES and ERGI surveys.

Hydrofacies were assembled into hydrostratigraphic systems (sensu MAXEY, 1964; DOMENICO & SCHWARTZ, 1990): sand/gravel aquifer systems (high to intermediate permeability hydrofacies) and aquitard/aquiclude systems (low permeability hydrofacies), associated with rare intermediate permeability hydrofacies on the base of the spatial distribution and relative interconnection of, respectively, sand-gravel and silt-clay bodies as portrayed by the hydrostratigraphic sections across the palaeo-Sillaro valley (fig. 3).

Two aquifer systems (S2-S4) were identified,

Tab. 1 - *Stratigraphy and hydrostratigraphy in the palaeo-Sillaro valley.*
- Stratigrafia e idrostratigrafia della valle del paleo-Sillaro.

Stratigraphic units (age)	Stratigraphic sub-units	Depositional elements	Minimum genetic units	Thickness (m)	Hydrostratigraphic units	
Unit 3 (Latest Pleistocene, LGM + Postglacial)	3B	sand, gravelly sand fining upward sequence	· silt to clay fining upwards sequences	3 - 8	aquifer system S4	complex C2
			· clayey silt lenses			
	3A	sand, gravelly sand fining upward sequence	· gravelly sand to silt and clay fining upwards sequences	5 - 10		
			· clayey silt lenses			
Unit 2 (Middle-Late Pleistocene)	2C	sand to silt-clay fining upward sequence	· sand to silt fining upwards sequences	5 - 20	aquitard system S3	
			· organic-rich clayey silt lenses			
	2B	gravel, sandy gravel bodies	· non-cyclical gravel bodies	15 - 25	aquifer system S2	complex C1
			· gravel to sand fining upwards sequences			
			· clayey silt lenses			
	2A	gravel bodies, sand, gravelly sand fining upward sequence	· gravel to sand fining upwards sequences	5 - 15		
			· clayey silt lenses			
Unit 1 (Middle Pleistocene)	1B	sand to silt-clay fining upward sequence	· sand to silt and clay fining upwards sequences	10 - 15		
			· clayey silt lenses			
	1A	silt-clay fining upward sequence	· clayey silt lenses	10 - 15	aquitard system S1	

Tab. 2 - *Hydrofacies characterization (textural classes, permeability classes and thickness range of minimum rank hydrofacies units, corresponding to stratigraphic depositional elements and genetic units; see table 1).*
- Caratterizzazione delle idrofacies (classi tessiturali e di permeabilità e spessori caratteristici delle idrofacies di rango minimo corrispondenti ad elementi stratigrafici deposizionali e unità genetiche; si confronti con tabella 1).

Textural Classes	Hydrofacies					
	Porosity		Hydraulic conductivity estimates K (m/s)			Thickness range (m)
	BERSEZIO *et alii*, 1999 JUSSEL *et alii*, 1994 KLINGBEIL *et alii*, 1999	DELL'ARCIPRETE *et alii*, 2008	BERSEZIO *et alii*, 1999 JUSSEL *et alii*, 1994 KLINGBEIL *et alii*, 1999	DELL'ARCIPRETE *et alii*, 2008	Permeability classes	
G	0.4	0.43	2.5×10^{-1} - 1.0×10^{-2}	3.2×10^{-2}	high	0-15
GS	-	0.4	-	4.6×10^{-3}		0-15
SG	0.2-0.3	0.42	1.0×10^{-2} - 1.0×10^{-4}	1.3×10^{-3}		0-10
cS/cmS	0.4	0.43	5×10^{-3} - 1.7×10^{-5}	5.2×10^{-4}	intermediate	0-8
mS/mfS		0.44		4.2×10^{-4}		0-8
fS/fSL	-	0.45	5×10^{-3} - 1.7×10^{-5}	1.6×10^{-4}	low	0-15
L/LS	-	-	-	-		0-10
LAS	-	0.5	-	-		0-10
LC	-	-	-	6.0×10^{-6}		0-10
CL/C	-	-	-	-		0-15

separated by an aquitard system (S3) and bounded at the base by a widespread basal aquitard (S1).

These units form two aquifer complexes (C1-C2) that presumably correlate in some way with the Aquifer Groups A and B and with the topmost portion of Group C of ENI-REGIONE LOMBARDIA (2002). The phreatic aquifer system S4 hosts the local water table. The aquitard S3 corresponds to the fine sand to silt-clay succession of the Upper Pleistocene flood plain (sub-unit 2C). In the northern sector of the study area, the separation between aquifer S2 and S4 is limited due to the presence of the palaeo-Sillaro depositional system which truncates the aquitard system S3. Aquifer S2 overlies a basal aquiclude of silty-clays formed by the Middle Pleistocene transitional-to-marine succession (sub-unit 1A) which hosts the salt-fresh water interface (ENI- REGIONE LOMBARDIA, 2002).

3. - ELECTROSTRATIGRAPHY

The assemblage of stratigraphic units and their physical properties (thickness, lateral extent, geome-

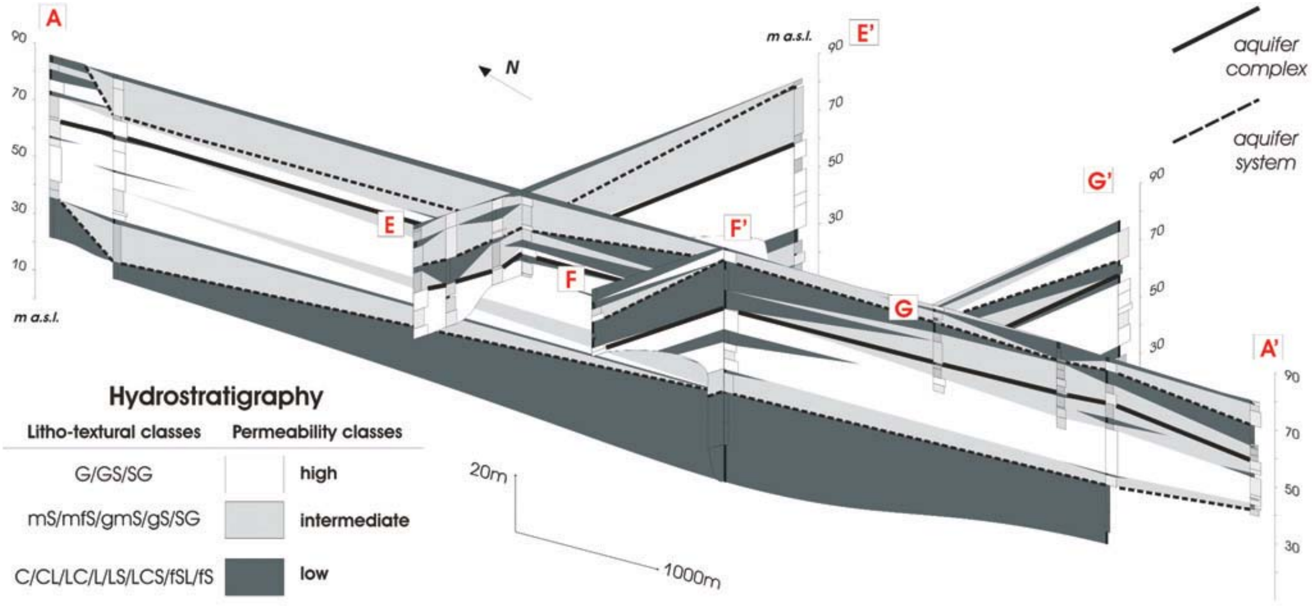

Fig. 3 - 3-D fence diagram of NNW-SSE and WSW-ENE hydrostratigraphic sections across the palaeo-Sillaro valley (see figure 2 for location and lithotextural codes).
- *Correlazione a siepe delle sezioni idrostratigrafiche attraverso la valle del paleo-Sillaro (l'ubicazione e i codici litologici e tessiturali sono riportati in figura 2).*

Tab. 3 - *Characteristics of survey areas and of geophysical prospecting.*
- Caratteristiche delle aree di studio e delle prospezioni geoelettriche effettuate.

Width	Area (km^2)	DC survey type	Horizontal resolution	Vertical resolution		Exploration depth
				Near surface	*Depth*	
Regional study area	30	89 VES (half spacingmax=300 m)	hundred of meters	dm to m	m to tens of M	50-70 meters below ground level
Detailed study area	<1	10 ERGI (48 electrodes; 5 m spacing)	meters	meters	m to tens of M	40 meters below ground level

try, litho-textural associations, hydrofacies) were used as the conceptual framework for the definition of two survey areas of different horizontal width (regional study area and detailed study area; fig. 2; tab. 3).

In order to interpret the electrical resistivity distribution in terms of litho-textural properties, the site-specific physical parameters which affect the electrical resistivity as qualitatively expressed by the Archie's law (groundwater conductivity, saturation and cementation; ARCHIE, 1942; KELLER & FRISCHKNECHT, 1966; REYNOLDS, 1997; TELFORD *et alii*, 1990) were monitored during the field acquisition of geoelectrical data. The characterization of these parameters can be summarized as follows:

- the average pore-fluid conductivity in the study area is 550 μS/cm, corresponding to an average electrical resistivity of 18 Ωm. This value was estimated by i) direct sampling of the surface groundwater at deep excavation points and analysis with a portable conductivity meter and ii) bibliographic data (SISTEMA INFORMATIVO FALDA SIF, PROVINCIA DI MILANO) relative to chemical analyses of groundwater extracted from water wells;
- the pore fluid saturation was determined in relation to the depth of the water table, which is shallow (from 0.9 m to 2.5 m below ground level) in correspondence to the present-day, topographically depressed, Sillaro underfit stream and deeper (between 4.1 m and 6.3 m b.g.l.) in correspondence to the top of older terraces within the palaeo-Sillaro valley;
- on the base of the available subsurface data (geognostic boreholes, water-well stratigraphy) no evidence of cementation was detected in the investigated stratigraphic succession.

3.1. - REGIONAL STUDY AREA

The regional survey consisted of 89 VES collected with Schlumberger array. The average exploration depth is about 70 m b. g. l., over a 30 km^2 wide area (tab. 3) where Unit 3 is outcropping, but for a limited extent in the northern sector, where Unit 2 is found (fig. 2, box A and C). Each VES sounding was carried out with half-spacing of the current dipole varying between 1 m and 300 m (the half-spacing of the potentiometric dipole varied from 0.5 m to 50 m) and a maximum of 17 apparent electrical resistivity measurements for each sounding. Some VES were acquired as close as possible to the position of subsurface data (namely, water wells) in order to calibrate the results. The distance between soundings ranges from 200 m to 1000 m, for an areal density from 2 VES/km^2 up to 12 VES/km^2; this choice was aimed at obtaining 1-D resistivity models at an horizontal scale comparable with the size of the depositional elements (tab. 1).

3.1.1. - *Data processing*

The elaboration of 1-D models was performed by: 1) fixing the number of resistive and conductive layers that comprise the electrostratigraphic sequence on the basis of the minimum, maximum and inflexion points of the apparent resistivity curves (KELLER & FRISCHKNECHT, 1966); 2) cali-

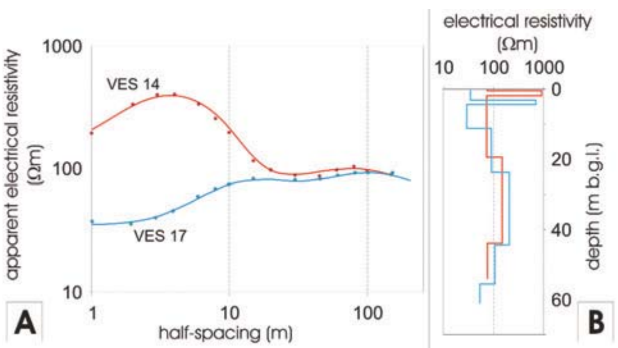

Fig. 4 - Example of the best-fitted apparent electrical resistivity curves (box A; dots represent field data) and the corresponding 1-D inverse models (box B) obtained for two VES collected respectively within (VES 14, red curve: RMS 4.8%) and outside (VES 17, blue curve: RMS 2.4%) the present-day Sillaro underfit stream (VES ubication is shown in fig. 2, box A).

- *Esempio di curve di resistività elettrica apparente simulate (riquadro A: i punti rappresentano le misure acquisite) con i corrispondenti modelli inversi 1-D (riquadro B) per due VES posizionati rispettivamente all'interno (VES 14, curva rossa:* RMS 4.8%*) e all'esterno (VES 17, curva blu:* RMS 2.4%*) del paleo-alveo del Sillaro.*

brating 1-D models of electrical resistivity with the RES1D software (LOKE, 2001). The inverse procedure required a maximum of 5 iterations and the models with a high RMS error were re-processed with an increasing number of layers in order to decrease the RMS error. Finally the number of electrolayers ranges from 3 to 7, for a maximum investigation depth of 70 m b. g. l. (fig. 4). Most of the models are well fitted; 11 models only show relative RMS error greater than 3%.

3.1.2. - *Electrostratigraphic interpretation*

Correlation of VES 1-D models was based on two criteria: 1) the discontinuities between electrolayers were characterized on the base of the vertical polarity of the resistivity contrast (vertical stacking of resistive above conductive layer or vice versa) determining the local vertical electrostratigraphic sequence; 2) the polarity of resistivity contrasts between electrolayers was 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 allowed to recognize the *geoelectrical bodies* in the subsurface that could be traced through the investigated volume by the horizontal variation of the vertical electrostratigraphic sequence identified in VES models and are characterized by an increasing thickness at increasing depth, according to the equivalence and suppression principles (KELLER & FRISCHKNECHT, 1966).

They represent 3-D bodies showing i) a clear resistivity contrast with the adjacent bodies, ii) peculiar internal electrical properties and iii) a typical apparent geometry and vertical/horizontal extent. Considering the analogy with the definition of "lithostratigraphic units" (NASC, 1983; NASC, 2005), each geoelectrical body was informally defined "electrostratigraphic unit" (EsU). Differently from a lithostratigraphic unit, an EsU can be defined only by the resistivity contrasts, that can be traced over significant distances preserving the same vertical polarity.

Nine electrostratigraphic correlation sections were elaborated (fig. 2, box A), with a kilometric horizontal extent and longitudinal and transverse orientation with respect to the main drainage axis (NNW-SSE) of the palaeo-Sillaro valley. These sections were mounted on a 3-D panel (fig. 5, box A) to check their coherence at the intersection points and to build up the electrostratigraphic framework of the investigated volume.

On the base of their lateral persistence, the EsUs were subdivided in (tab. 4):

- widespread units, that could be identified in several 1-D models and characterized by good lateral continuity in the study area;
- lens-shaped units, identified in a single or a few 1-D models.

The widespread EsUs were used to define the electrostratigraphic model of the study area at a regional scale and they were coded, from top to bottom, respectively with the letters from A to G (tab. 4).

The uppermost EsUs A and B (fig. 5, 7 and 9) mainly identify the vertical variation of electrical resistivity due to the near-surface facies/hydrofacies transition within the unsatured 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 (unit C, D, E, F; fig. 5, 7 and 9) characterize the saturated zone below the water table (generally coincident with the base of EsU B; fig. 7, box 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 (fig. 5; fig. 9); for this reason, its identification is quite uncertain. The lense-shaped EsUs (unit L; fig. 5 and 7) do not conform with the electrostratigraphic framework defined at a regional scale and represent local features with small lateral extent. Therefore their geometry remains more uncertain and in some cases different equivalent correlations could be proposed.

3.2. - DETAILED SURVEY AREA

In order to improve the details of the horizontal transitions between the electrostratigraphic

Tab. 4 - *VES electrostratigraphic model for the palaeo-Sillaro valley (regional study area) based on the widespread EsUs.*
- Modello elettrostratigrafico VES della valle del paleo-Sillaro (area di studio a scala regionale).

EsU	Electrical resistivity ρ range (Ωm)	Thickness range (m)	Depth range (m b.g.l.)
A	< 70	0.5 - 9	0 - 10
B	170 - 1500	0.5 - 5	0.5 - 6
C	20 - 70	5 - 10	5 - 15
D	70 - 100	10 - 15	15 - 25
E	110 - 200	10 - 25	25 - 45
F	70 - 90	10 - 30	25 - 60
G	< 70	-	> 60 -70

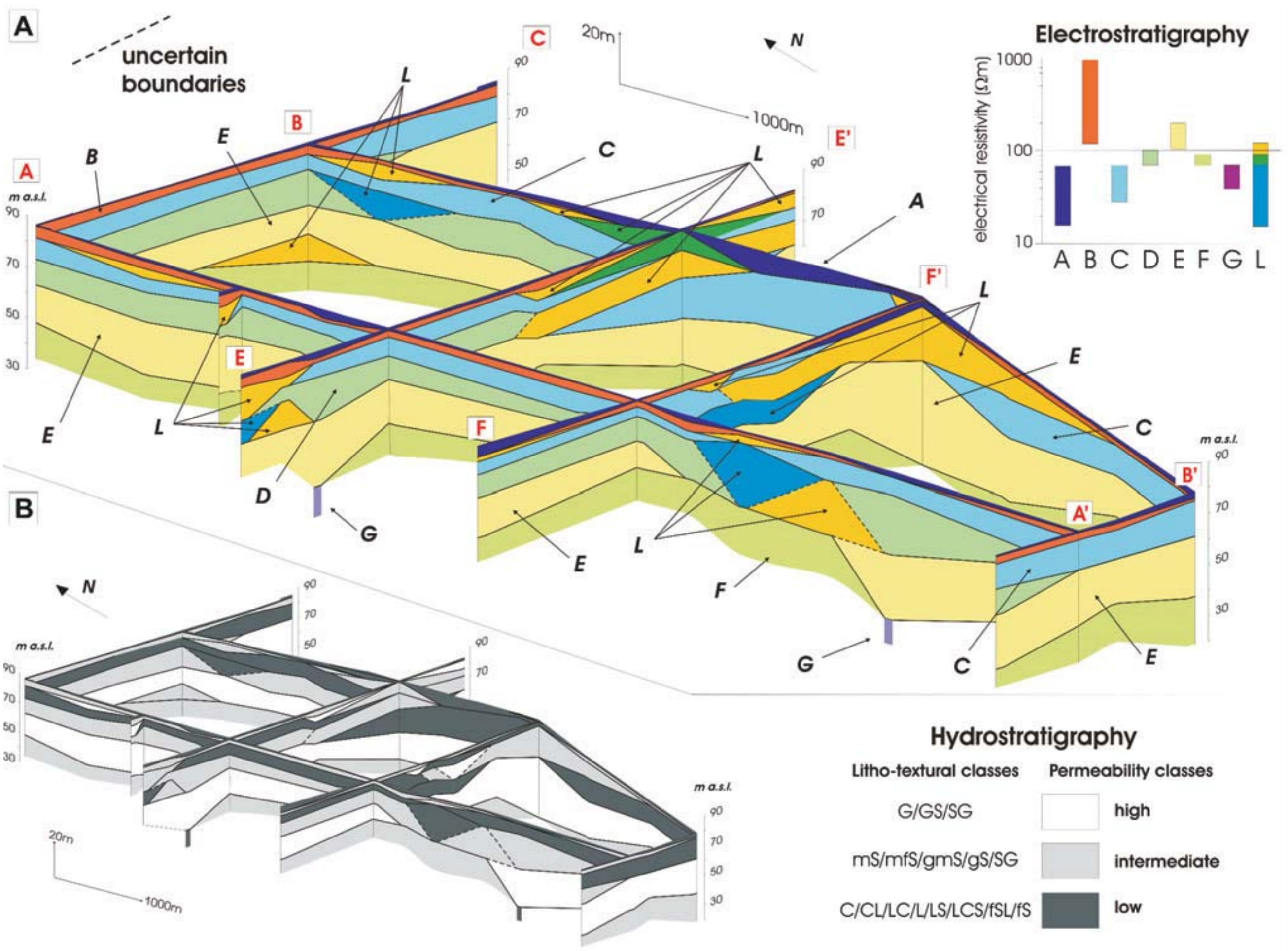

Fig. 5 - Fence diagrams of NNW-SSE (A1, A2) and WSW-ENE (T1, T2, T3, T4 and T6) VES electrostratigraphic sections (box A; see figure 2, box A for location) and plot of EsUs' electrical resistivity (upper right corner; units from A to F refers to EsUs described in table 4, units L refers to the lense-shaped EsUs). In the lower plot (box B): 3-D panel of electrostratigraphic sections (same as box A) interpreted in terms of the dominant hydraulic properties at the regional scale across the palaeo-Sillaro valley.

- Correlazione a siepe delle sezioni elettrostratigrafiche (riquadro A: ubicazione in figura 2, riquadro A) ottenute dai VES e resistività elettrica delle EsUs (riquadro in alto a sinistra destra; le unità da A a G si riferiscono alle EsUs descritte in tabella 4; le unità L rappresentano EsUs lenticolari). Riquadro in basso (B): pannello di correlazione 3-D tra le sezioni elettrostratigrafiche nella valle del paleo-Sillaro, interpretate in funzione delle proprietà idrodinamiche alla scala regionale.

units at the metre-scale, a 2-D ERGI survey was planned within a selected area (fig. 2, box A). In particular, ERGI profiles were located to investigate a point-bar complex of the palaeo-Sillaro river (Unit 3), with a grid normal and parallel to the point-bar elongation (fig. 2, box B). Ten sections were acquired with 48 electrodes using a Wenner-Schlumberger array, electrode spacings from 3 m to 5 m and a roll-along acquisition scheme for a maximum length of the array of 410 m. The maximum number of apparent electrical resistivity measurements for a single section was 1220.

3.2.1. - *Data processing*

For each ERGI section a preliminary datum removal of bad measurements (less then 10% of the total), mainly due to poor coupling between electrode and ground, was performed. Inversion of field apparent resistivity data was performed with the RES2DINV software (LOKE & BARKER, 1995).

The final 2-D resistivity models were obtained after a maximum of 8 iterations, using the L1-norm optimization method, which is quite robust and reduces the effect of outliers in the field data sets (FARQUHARSON & OLDENBURG, 1998). Relative RMS error ranges from a minimum of 1.2% to a maximum of 13.4%, with an estimated maximum depth of investigation of 40 m below the acquisition surface.

3.2.2. - *Electrostratigraphic interpretation*

The robust inversion yielded 2-D models characterized by areas of approximately uniform electrical properties which are separated from each other by sharp boundaries (LOKE *et alii*, 2003) and directly related to the regional electrostratigraphic framework defined through the VES survey. These areas represent the analogue of the EsUs defined through the correlation of the VES electrostratigraphic sections. The ERGI sections were fixed on a 3-D panel (fig. 6, box A) to verify the internal coherence of the subsurface electrical resistivity at the intersections. 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. The correspondence between these regions and EsUs was explored by comparing 2-D sections with the nearest VES electrostratigraphic section.

In figure 6 (box B) the correspondences between the uppermost conductive regions (0-15 m b.g.l.; 30-40 Ωm) with the EsUs C and D and between the lowermost resistive regions (> 15 m b.g.l.; 130-160 Ωm) with the resistive EsU E are shown at a metric horizontal scale. Due to the large electrode spacing, ERGI survey cannot yield accurate reconstructions for the near-surface unsaturated zone.

4. - INTEGRATION OF HYDROSTRATIGRAPHIC AND ELECTROSTRATIGRAPHIC MODELS

In order to integrate the hydrostratigraphy with the electrostratigraphic model of the palaeo-Sillaro valley, a calibration between the electrical resistivity measurements and the hydraulic and litho-textural estimates was attempted, considering separately the unsaturated and the saturated zone and fixing the average electrical conductivity of local groundwater in the Lodi plain (18 Ωm). In the unsaturated zone (<5 m b.g.l.), a direct calibration between electrical resistivity and hydrofacies was obtained at VES stations thanks to hand-auger drilling down to 5 m b.g.l.: the depth of the boundaries between near-surface EsUs was compared with the depth of hydrofacies transitions and with the local groundwater level (fig. 7, box B). In the saturated zone (>5 m b.g.l.), an indirect calibration was attempted, comparing the electrostratigraphic framework at increasing depths with the vertical litho-textural associations (i.e. hydrofacies) interpreted from the available stratigraphic logs (fig. 7, box C). In order to

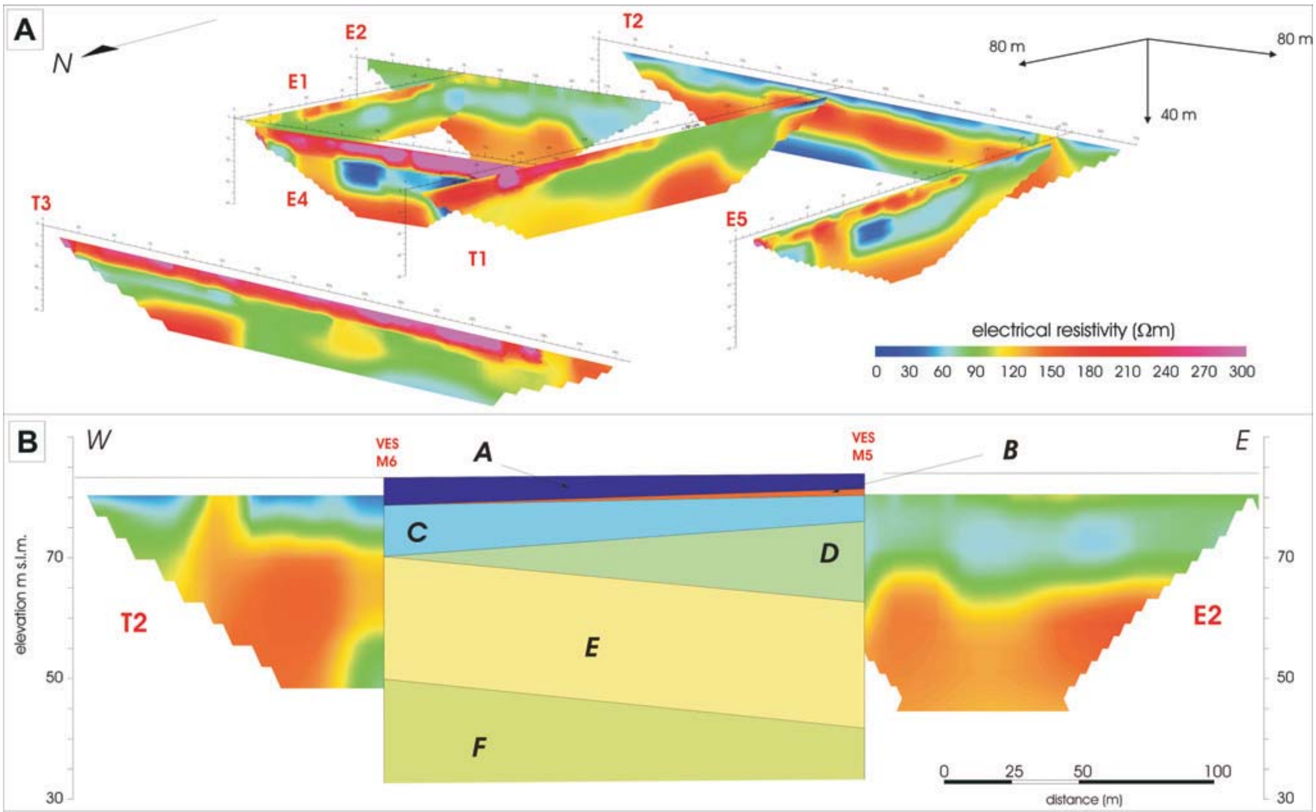

Fig. 6 - 3-D panel of 2-D ERGI models collected in the detailed survey area corresponding to the abandoned Sillaro point bar complex (box A; for location see figure 2, box A and B). The section in the lower plot (box B) corresponds to red dashed line in figure 2 (box B) and compares the electrical resistivity distribution determined from 2-D ERGI high resolution survey (T2, E2) and 1-D VES electrostratigraphic correlation at regional scale.

- Pannello di correlazione tra i modelli ERGI rilevati nell'area di dettaglio in corrispondenza del complesso di barra di meandro del paleo-Sillaro (l'ubicazione è riportata in figura 2, riquadro A e B). La sezione in basso (riquadro B), corrispondente alla linea rossa a tratteggio in figura 2, riquadro B, presenta il confronto tra i rilievo ERGI T2, E) e la corrispettiva sezione di correlazione elettrostratigrafica basata sui modelli 1-D VES.

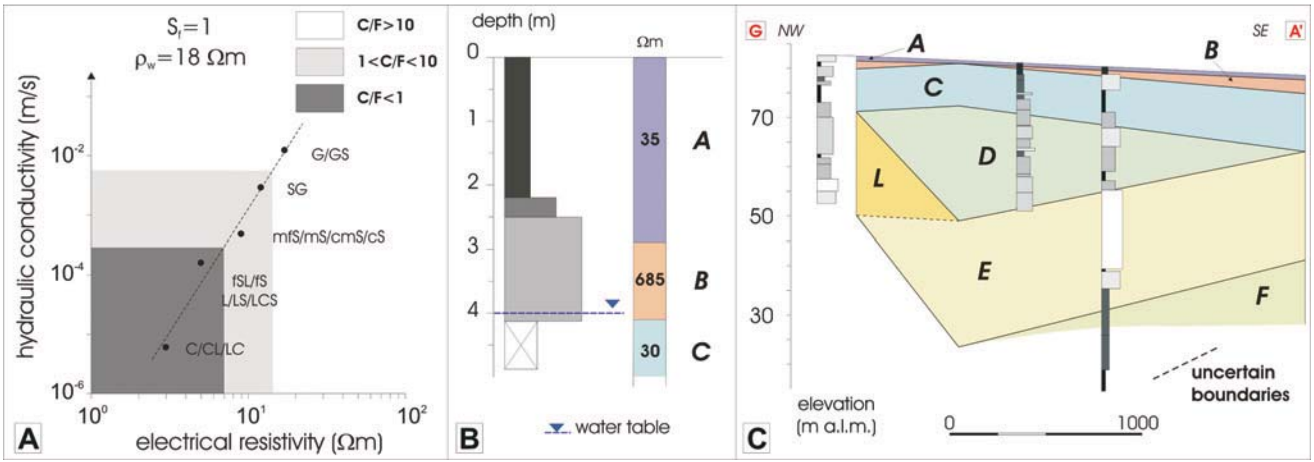

Fig. 7 - Local petrophysical relationship between hydraulic conductivity estimates, electrical resistivity, fluid saturation (S_f) and mean groundwater electrical resistivity (Ωm) (box A); the black dots represent the values of electrical resistivity calibrated for different hydrofacies. Direct calibration (box B) between 1-D electrical resistivity and hydrofacies at VES stations in the unsaturated zone (dashed line represents water table; see fig. 2, box C for lithotextural codes). Indirect calibration between electrostratigraphic framework and hydrofacies associations (box C) based on stratigraphic boreholes along electrostratigraphic section A1 (ubication is shown in figure 2, box A).

- Correlazione petrofisica locale (riquadro A) tra stime di conducibilità idraulica, resistività elettrica, saturazione (Sf) e resistività media della acque sotterranee (Ωm); i punti neri indicano i valori di resistività elettrica calibrati per le diverse idrofacies. Calibrazione diretta tra VES e idrofacies (riquadro B) ai punti di rilievo geoelettrico nella zona insatura (la linea a tratteggio rappresenta la tavola d'acqua; i codici tessiturali sono riportati in figura 2, riquadro C). Calibrazione indiretta tra elettrostratigrafia ed associazione di idrofacies (C) lungo la sezione elettrostratigrafica A1 (ubicazione in fig. 2, riquadro A).

interpret the electrical resistivity as a "proxy" of the hydrostratigraphic properties, the coarse-to-fine litho-textural ratio (C/F, adimensional; cut-off ∅=0.3 mm) was calculated for 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 threefold classification based on the C/F ratio mimics the broad classification of hydrofacies permeability adopted in tab. 2. The variability range of the C/F ratio was compared to the hydraulic conductivity *K* (m/s) and the electrical resistivity ρ (Ωm) of hydrofacies, both in the unsaturated and in the saturated zone. A local petrophysical relationship between hydraulic and electrical conductivity was established (fig. 7, box A) to reclassify the electrical resistivity at near-surface and at increasing depth in term of the prevailing hydraulic properties (low-intermediate-high permeability) of the equivalent volume (fig. 5, box B).

4.1. - Near-surface reconstruction

In order to characterize at the detailed scale (shallow depth, 0-5 m, unsaturated zone) the stratigraphic Units 3 and 2, a map of apparent electrical resistivity has been obtained by interpolating data for half spacing of 4 m with an inverse distance method (fig. 8). According to the local near-surface geological and geomorphological model (sand-gravel to silt-clay fining-upwards point-bar sequence, terrace scarps, slopes) and the electrostratigraphic model (tab. 4), regions of low and high apparent resistivity can be interpreted as characterized by respectively high and low thick-

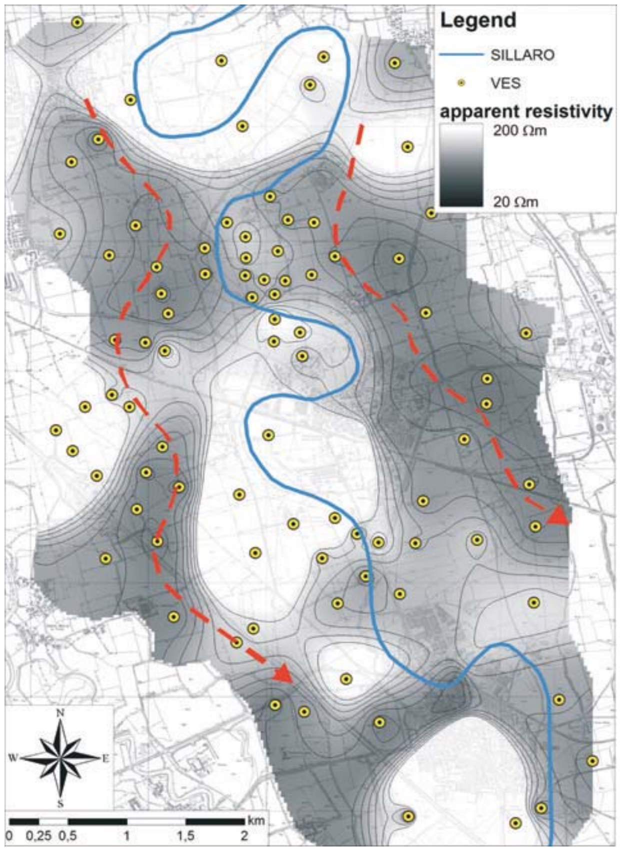

Fig. 8 - Apparent resistivity map (half-spacing 4 m; contours 20 Ωm) of the palaeo-Sillaro valley. The dashed lines along the west and east borders of the paleo-Sillaro meandering abandoned trace (continuous line) represent two inferred extinct fluvial traces of the palaeo-Sillaro river that could be observed by the integration of apparent electrical resistivity of near-surface sediments and geomorphological survey.

- Mappa di resistività apparente (semi-spaziatura elettrodica pari a 4 m; equidistanza 20 Ωm). Le linee tratteggiate lungo i bordi orientale ed occidentale della traccia meandriforme del paleo-Sillaro (linea continua) rappresentano due possibili decorsi fluviali abbandonati, rilevabili attraverso l'integrazione della resistività elettrica apparente dei sedimenti superficiali e del rilievo geomorfologico.

nesses of the conductive part of the fining upwards sequences (EsU A, fine litho-textural association, low permeability hydrofacies; tab. 2).

Therefore, the apparent resistivity map yields some useful information about the near-surface horizontal transition between the unsaturated coarse-grained point-bar deposits (EsU B, coarse litho-textural association, high permeability hydrofacies; tab. 2) and the fine-grained oxbow-lake/overbank deposits at regional scale in the unsaturated zone. Within the palaeo-Sillaro valley, two low resistivity areas (<70 Ωm) were identified to the East and to the West of the meandering trace of the present-day Sillaro underfit stream (fig. 8). These areas could interpreted as two possible extinct fluvial traces of the palaeo-Sillaro river, in which the topographical depression associated to the avulsed fluvial channel were filled by a pluri-metric thickness of fine-grained sediments. Notice that this interpretation could not be obtained by the simple geomorphological analysis of terrace scarps and slopes, but results from combination of geological and geophysical data. Hence, the map adds substantial information to the near-surface reconstruction.

4.2. - Subsurface reconstruction

The integration between the electrostratigraphic and the hydrostratigraphic models by the means of the local petrophysical relationship (fig. 7, box A) permits to validate and 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 which limit the interpretation of DC measurements, 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 the hydrostratigraphic systems.

From North to South in a depth range of 25-60 m b.g.l, the electrostratigraphic sections shown in figure 9 confirm the presence of coarse-grained resistive sheet-bodies (sand-to-gravel, gravel) with electrical resistivity ranging in the uppermost part from 110 to 200 Ωm and estimated hydraulic conductivity ranging from $1.9 \cdot 10^{-3}$ to $2.3 \cdot 10^{-2}$ m/s (Unit E) and, in the lowermost part, from 70 to 90 Ωm (Unit F; K from $3.0 \cdot 10^{-4}$ m/s to $8.4 \cdot 10^{-4}$ m/s). These bodies describe a coarsening upwards sequence that can be interpreted as a stage of progradation of the southernmost termination of a glacio-fluvial braiding fan of alpine origin (sub-units 1B, 2A e 2B) of Middle-Upper Pleistocene age (Bersezio *et alii*, 2004). They form the aquifer system S2 at the top of an older sandy-clay meandering river belt of Middle Pleistocene age (sub-unit 1A) characterized by electrical resistivity less than 70 Ωm and estimated K less then $3.0 \cdot 10^{-4}$ m/s (Unit G in fig. 9), corresponding to the aquitard system S1 at the base of the lowermost hydrostratigraphic complex C1. The subsequent backstepping to north of the depositional system during the Upper Plei-

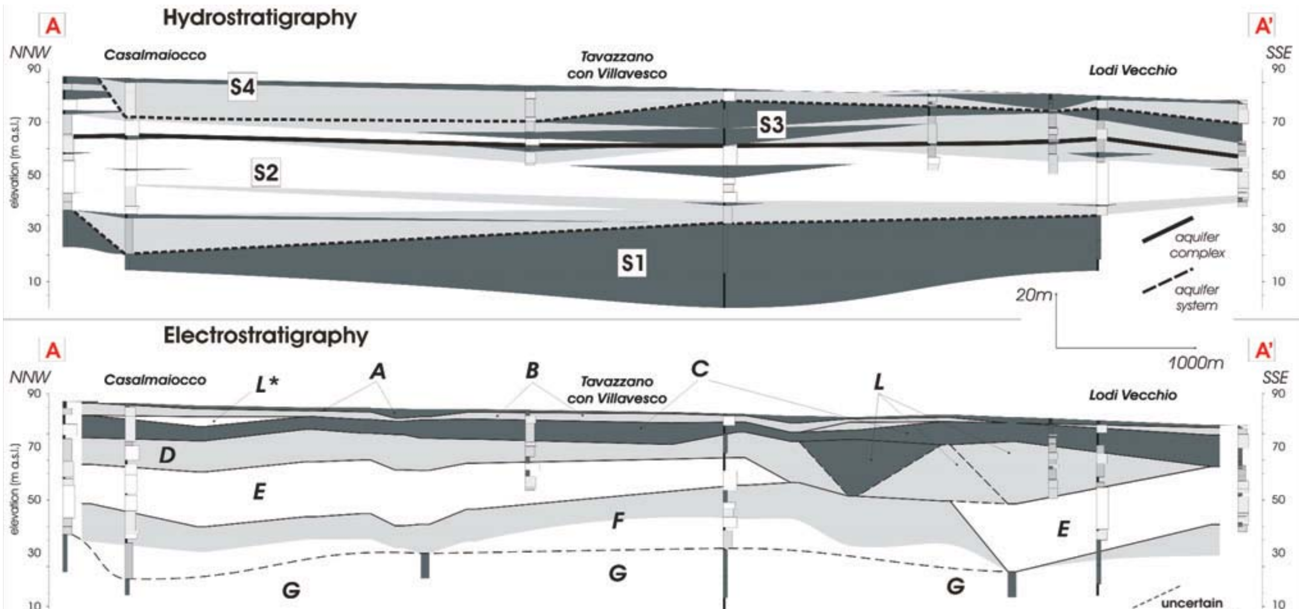

Fig. 9 - Integration of hydrostratigraphy and electrostratigraphy along section A1 (see fig. 2, box A for location and fig 3 and fig. 5 for permeability classes). - *Integrazione delle ricostruzioni idrostratigrafica ed elettrostratigrafica lungo la sezione A1 (fig. 2, riquadro A, per l'ubicazione e fig. 3 e fig. 5 per le classi di permeabilità).*

stocene, 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; $1.6\cdot10^{-6}$ m/s<K<$3.0\cdot10^{-4}$ m/s) and D (70 Ωm<ρ<100 Ωm; $3.0\cdot10^{-4}$ m/s<K<$1.3\cdot10^{-3}$ m/s), that represent the aquitard system S3 at the base the uppermost hydrostratigraphic complex C2. The sharp boundaries between gravel-sand resistive beds of Unit 3, corresponding to aquifer system S4, do not show clear evidences because the high resistivity contrast between near-surface coarse-grained unsaturated sediments (up to 1500 Ωm) and the underlying saturated sediments locally masks the presence of a resistive unit interposed between Units B and D (Unit L* in fig. 9). In the area of Tavazzano con Villavesco and Lodi Vecchio, the integration of hydrostratigraphy with electrostratigraph ameliorated the interpretation of the lateral terminations of the coarse grained part of the aquifer system S2 (fig. 9).

5. - CONCLUSION

The integration between hydrostratigraphy and electrostratigraphy allowed to develop and cross-validate the subsurface hydrostratigraphic models of the Sillaro palaeo-valley to a maximum depth of 80 m. The evaluation of the hydrostratigraphic significance of electrostratigraphic units was put in relation to the well-known equivalence and suppression principles (KELLER & FRISCHKNECHT, 1966) which limits the interpretation at increasing depth of electrical resistivity estimated from the ground surface with the VES soundings. In the near-surface, EsUs represent vertical resistivity variations related to the litho-textural contrasts at the scale of the hydrofacies (ANDERSON, 1997), as a function of the proportion between fine and coarse textures within the each sedimentary facies (C/F ratio). Through the geostatistical interpolation of the near-surface apparent electrical resistivity, representative maps of the near-surface horizontal transitions between the coarse-grained point-bar deposits (Coarse litho-textural association) and the fine-grained oxbow-lake/overbank deposits (Fine litho-textural association) can be obtained. At increasing depth, EsUs represent vertical resistivity variations related to the litho-textural contrasts within an heterogeneous and hierarchically stratified medium at the hydrostratigraphic systems scale (MAXEY, 1964).

A reliable representation of sedimentary heterogeneities can be obtained by the identification of the regional electrostratigraphic sequence through correlation of 1-D VES models with two criteria (polarity of contrasts and uniformity of values of electrical resistivity). These criteria provide a tool to put in evidence 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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