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figg. 11

Determining Ground Water Reservoirs in the Milan Alluvial Plain Using a Stratigraphic Well-Log Database

Studio dei sistemi fluviali e fluvioglaciali della pianura milanese tramite una banca dati di stratigrafie di pozzi

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ABSTRACT - In this work the detailed quantitative reconstruction of the textural characteristics of the subsurface sediments of the Milan plain is provided. The core of this study is the organization and codification of the numerous data concerning the water wells, for a total of 7853 wells, 3472 of which have stratigraphic logs. The stratigraphic data have been codified in a database, extracted and elaborated in GOCAD (Geological Object Computer Aided Design). Three-dimensional georeferenced objects were then created, and the percent value of the textural classes (gravel, sand and clay), extracted from the database, was assigned to each stratigraphic level of the wells. The spatial data of the study area, between the topographic surface and the aquifer bottom surface, were elaborated with GIS technologies and than converted into GOCAD format. A 3D calculation grid was built between the two surfaces, consisting of regular cells of 250 m square base and variable thicknesses from 1.8 to 2.3 m, for a total of 207 rows, 267 columns and 96 layers. The percentage of gravel, sand and clay was assigned to each cell located in correspondence to the 3D georeferenced wells. Using the Discrete Smooth Interpolator (DSI), the values have been interpolated in all three-dimensional spaces defined by the 3D grid and the three-dimensional reconstruction of the textural distribution of the subsurface sediments of the Province of Milan realized. The model shows quantitatively the spatial distribution of the superficial aquifers and of the deep aquifers, which commonly are not studied and never quantified in their structure. The reconstruction of the 3D distribution of textural parameters can be considered the starting point of many hydrogeological applications, such as the mode of propagation of pollutants, the fluid flow and fluid transport models and the mass balance evaluation.

KEY WORDS: Database, Stratigraphic Well, 3D Grid, Alluvial Plain, GOCAD

RIASSUNTO - Il lavoro si riferisce alla ricostruzione quantitativa dettagliata delle caratteristiche tessiturali del sottosuolo della pianura milanese. Il punto centrale dello studio è l'organizzazione e la codifica dei numerosi dati stratigrafici dei pozzi per acqua (7853 archiviati), 3472 dei quali hanno il dato stratigrafico codificato. I dati stratigrafici sono stati codificati in un database, estratti ed elaborati in GOCAD (*Geological Object Computer Aided Design*). Oggetti tridimensionali georeferenziati sono quindi stati creati e ad ogni livello stratigrafico dei pozzi è assegnato un valore percentuale delle classi tessiturali, ghiaie, sabbie e argilla, estratto dal *database*. I dati spaziali dell'area di studio (superficie topografica e base degli acquiferi) sono stati elaborati in un GIS e successivamente convertiti in formato GOCAD. Una griglia 3D è stata costruita tra le superfici e ogni cella assume una forma ad esse proporzionale. La griglia di calcolo è stata creata con celle regolari di 250 m di lato e spessori variabili da 1.8 a 2.3 m, per un totale di 207 righe, 267 colonne e 96 strati. Le percentuali di ghiaia, sabbia e argilla sono attribuite a ogni cella situata in corrispondenza di ogni pozzo georeferenziato. Utilizzando il *Discrete Smooth Interpolator* (DSI), i valori sono stati interpolati in tutte le celle tridimensionali definiti dalla griglia 3D, realizzando la ricostruzione tridimensionale della distribuzione tessiturale del sottosuolo della Provincia di Milano. Il modello traduce quantitativamente non solo l'acquifero tradizionale, ma anche gli acquiferi più profondi che non sono comunemente studiati e mai quantificati nella loro struttura. La ricostruzione della distribuzione 3D dei parametri tessiturali può essere considerata il punto di partenza per molte applicazioni idrogeologiche, come il moto di propagazione e distribuzione dei contaminanti, la valutazione di bilancio di massa di un sistema idrogeologico e la applicazione di modelli di flusso e trasporto.

PAROLE CHIAVE: Banca dati, Dati stratigrafici dei pozzi, Griglia tridimensionale, Pianura alluvionale, GOCAD

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1. - INTRODUCTION

The textural and hydrogeological properties of the studied deposits are strictly connected to the sedimentary processes which take place in fluvial and fluvio-glacial systems. The proposed methodology brings together geological knowledge, the codified well data logs stored in a hydrogeological geo-eferenced database, the Geographic Information System (GIS), and 3D calculation software. A detailed subsurface distribution of the hydrogeological parameters has been created using, in particular, the stratigraphic well data that commonly are not considered in a quantitative way nor elaborated to calculate textural distributions.

2. - STUDY AREA

The area studied is located in the Po alluvial plain (fig. 1), which is characterized by a very high density of urban, industrial and agricultural activities. The Milan Province, 1989 km2 wide, contains 189 municipalities, and 71% of the land is used for agricultural purposes. In the province area a total of 7583 wells were identified and located, 3472 of which have a stratigraphic log (fig. 1). The area also has a natural hydrographic network, as well as a man-made one. The former is represented by the Adda and Ticino rivers, the eastern and western boundary of the study area, respectively.

The hydrogeological system consists of fluvial and fluvio-glacial deposits, mostly gravel and sand with discontinuous silt and clay confining layers. Such deposits correspond to the Mindel, Riss and Wurm fluvioglacial deposits and to the ancient floods.

From the hydrogeological point of view, an unconfined shallow aquifer is underlain by deeper confined aquifers (AVANZINI *et alii*, 1995; PROVINCIA DI MILANO & POLITECNICO DI MILANO, 1995; PROVINCIA DI MILANO, 2001).

3. - METHODOLOGY

The study seeks to provide a detailed quantitative representation of the textural characteristics of the subsoil in the Milan alluvial plain, using an integrated system of database, GIS and 3D model (fig. 2). The focus of the study is the organization and codification of data concerning the water well

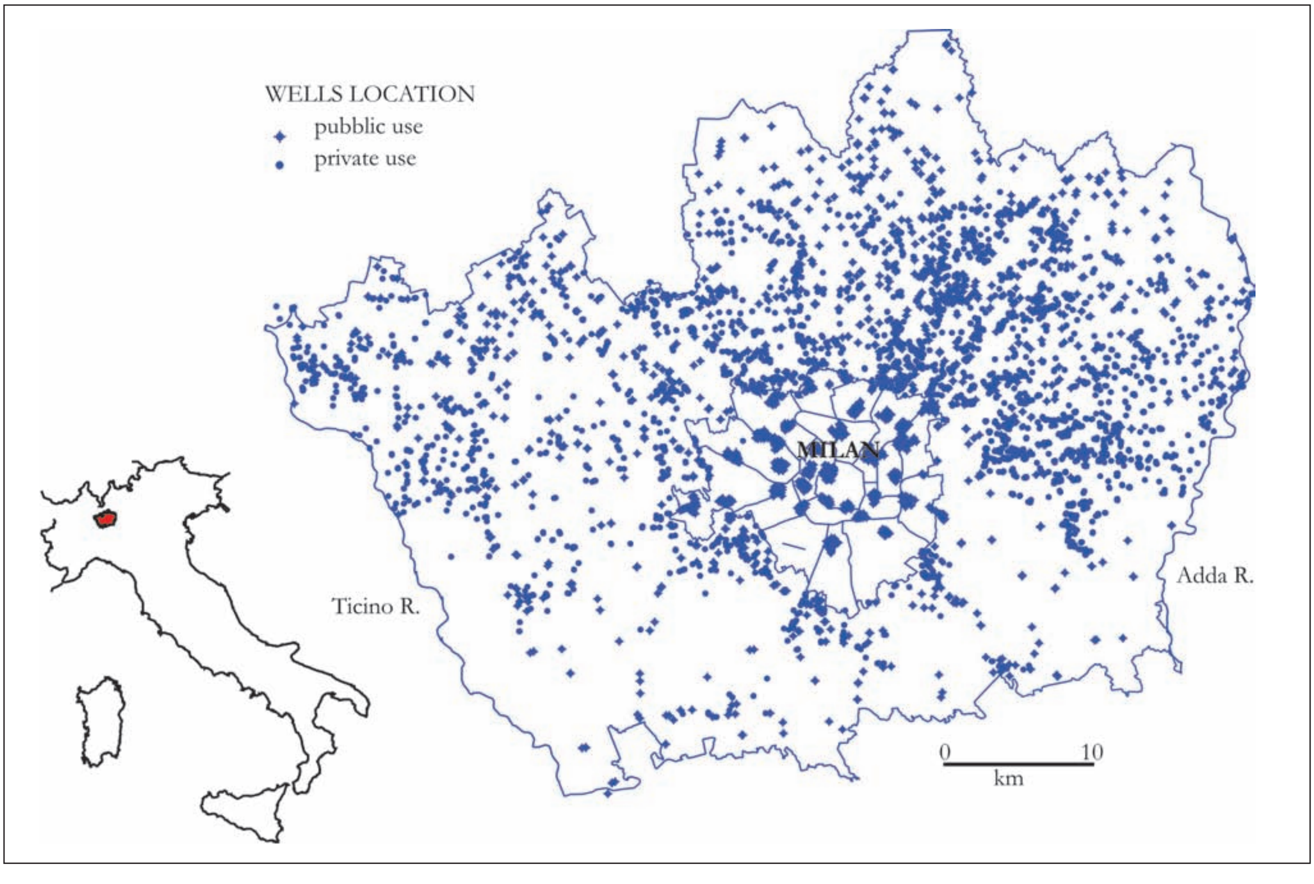

Fig. 1 - Study area: the Province of Milan, located in the northern part of the Po River plain, and surface distribution of the wells.
- *Area studiata: la Provincia di Milano, pianura settentrionale del Fiume Po, con la distribuzione areale dei pozzi.*

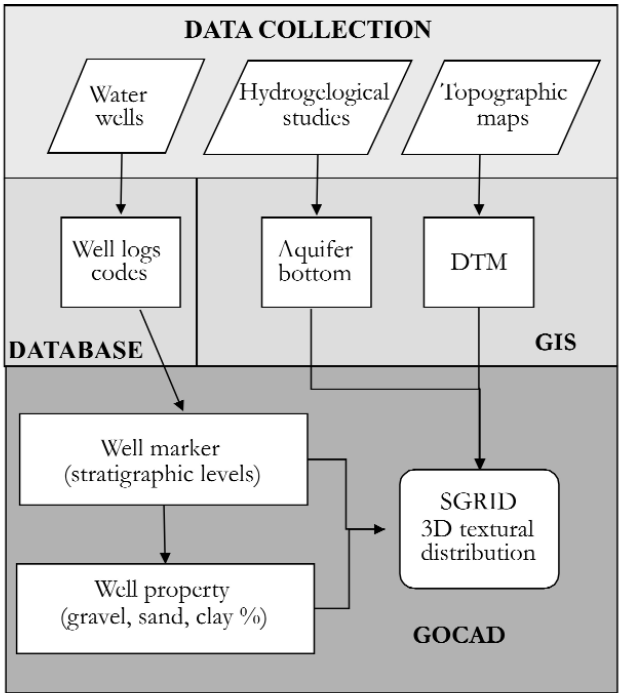

Fig. 2 - Work methodology: integrated use of database, GIS and 3D model (GOCAD).
- *Metodologia di lavoro: uso integrato di database, GIS e modello 3D (GOCAD).*

logs contained in a hydrogeological database. Currently, the data for 7583 wells have been input, 46% of which have stratigraphic logs. All well logs are translated into alphanumeric codes. The codified data have elaborated inside GOCAD (Geological Object Computer Aided Design), an application developed by the National School of Geology (ENSG) of Nancy, France, which makes it possible to build a three-dimensional (3D) calculation grid (GOCAD, 2001). A powerful engine, the Discrete Smooth Interpolator (DSI) of MALLET (1992, 1997), is used to interpolate the data along three directions of properties attributed to single wells of the three textural classes considered (i.e., gravel, sand and clay) throughout the province. The distribution of any other quantitative parameter may also be calculated.

In the methodology proposed (BONOMI *et alii*, 2001, 2002), the properties can be textural (e.g. percent of gravel, sand and clay) or hydrogeological (hydraulic conductivity and porosity). The elaboration may concern any portion of subsoil, bordered by one or more surfaces. In the proposed example, the referenced surfaces are the DTM (Digital Terrain Model) and the base of the deeper aquifers. Using the stratigraphic well data, this methodology (fig. 2) allows us to show and quantify the geometrical 3D relationships, according to the general theories of evolution and deposition of the fluvial and fluvioglacial systems. Furthermore, the methodology enables us to use the data in a homogeneous and suitably statistical manner and to make very useful calculations.

4. - WELL DATABASE

The hydrogeological database used is a custom-built package named TANGRAM (BONOMI *et alii*, 1995). This package can be used to store and display all data regarding water wells: administrative information, well characteristics, stratigraphic logs, water level, and hydrochemical details. All well logs are translated into alphanumeric codes. Specifically, the definition of each stratigraphic level is converted into 8 alphanumeric characters. The code may be divided in two parts: the first (four characters) is related to the predominant texture (e.g., gravely sand); the second (the remaining four characters) defines the secondary texture (e.g., silty clay). In this way, the stratigraphic well data, which are often considered a simple description of the well logs, may be codified and subsequently quantified and processed.

For the hydrogeological characterization of the subsurface, it is necessary for all wells to have been measured; the wells have been projected onto the DTM of Milan Province, and an elevation value has been assigned. The database contains data on 7583 wells, 5576 of which are georeferenced and 3472 of which have stratigraphic logs. Among these, 1637 wells reach a depth of 100 m, while only 98 wells exceed 200 m. In the codified stratigraphic logs a weight has been attributed to the digits of the texture code, based on a preset depth interval divided into segments of two meters depth. This constitutes the starting point for the subsequent three-dimensional calculations.

5. - UNCONFINED AND CONFINED AQUIFERS

The unconfined and confined aquifers of the Milan area of the Po River plain, have a vertical extension within a range of 80 to 200 m. The upper surface of the investigate sedimentary body is defined by the topographic surface (MARCHETTI, 1992). The lower surface represents the physical lower limit of the deep aquifer only in the northern part of the area where the wells (for a total number of 228) are deeper. On the contrary, from the city of Milan to the south, the wells are less deep, and they reach the base of the deeper aquifer in a limited number of cases. A surface related to the maximum average depths reached by the wells for the exploitation of ground water in the Milan

Province has therefore been identified; in the subsequent three-dimensional calculations, this new surface allows for a hydrogeological characterization of the portion of the subsurface in which ground water withdrawal takes place.

Surfaces and wells are translated into GOCAD 3D virtual objects. They contain location information (well column) and property information (well logs or well curves). Any depth marker or interval of significance in a well can also be included in GOCAD wells in the form of well markers or well zones. Each marker corresponds to the bottom of the stratigraphic level in the well column. They differ in name and in color. The name is linked to the alphanumeric code stored in the database, and the same color corresponds to the same code.

6. - THREE-DIMENSIONAL CALCULATIONS

In order to create a three-dimensional hydrogeological model of the study area, a GOCAD-object SGrid has been prepared and all available textural information implemented. SGrid is a three-dimensional stratified grid modeled by surfaces (in this case, DTM and a deep aquifer bottom) in which the properties can be directly attributed. The SGrid developed contains 96 layers, each comprised of 207 rows and 267 columns, for a total of 5.361.093 cells with constant dimensions (250 x 250 m). The height of the cells fluctuates around a mean value of 2 m because of the proportional deformation from the top to the bottom of the SGrid. This technique provides for a better adaptation of the SGrid geometries to the two surfaces. The properties extracted from the database for every 2 m of depth are then attributed to the nodes of the grid in correspondence with the wells. Then the DSI processes the whole volume of the property distributions.

The first result of the model analysis is the general visualization and parameterization of the three considered textural classes in the subsurface throughout the province. Different ways of visualizing gravel, sands and clay in the territory of the Milan Province lead to some significant conclusions regarding its hydrogeological structure, which can then be compared with the wealth of hydrogeological knowledge available in this area.

A first step might be a visualization of the characteristics of the shallowest layer (fig. 3). With regard to the coarse sediment distribution, figure 3A shows the presence of numerous bodies that contain roughly 80% gravel. From the hydrogeological point of view, this area coincides with the recharge areas characterized by the presence of Wurmian and recent fluvioglacial deposits.

From north to south, these bodies undergo a drastic reduction in accordance with the decrease in the energy of the transport agents of the fluvioglacial sediments (BERETTA *et alii*, 1985; CAVALLIN *et alii*, 1983). At the same time, the sands (fig. 3B), which are present in the northern-eastern area as isolated bodies and in the northern-western area at an average of just above 20%, increase progressively towards the south, both in percent terms and as an extension of the individual bodies, replacing the coarse deposits.

Conversely, with regard to the distribution of the fine-grained textures (fig. 3C), the outcrop of clayey fluvioglacial terraces is well represented in the central-northern and western-northern areas. On the other hand, it is also evident that

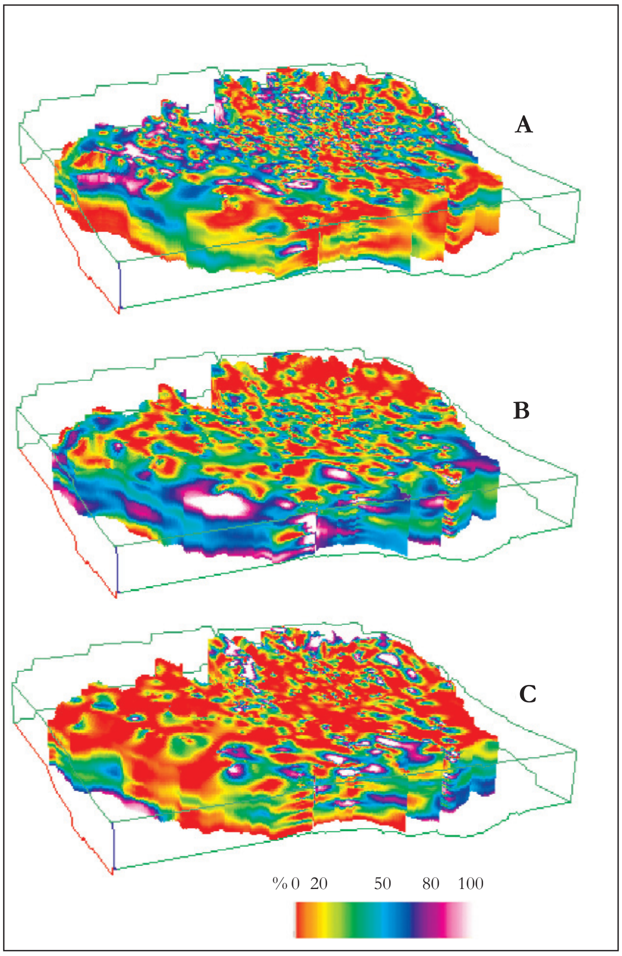

Fig. 3 - Three-dimensional percent distribution of gravel (A), sand (B) and clay (C).
- *Distribuzione tridimensionale della percentuale di ghiaia (A), sabbia (B) e argilla (C).*

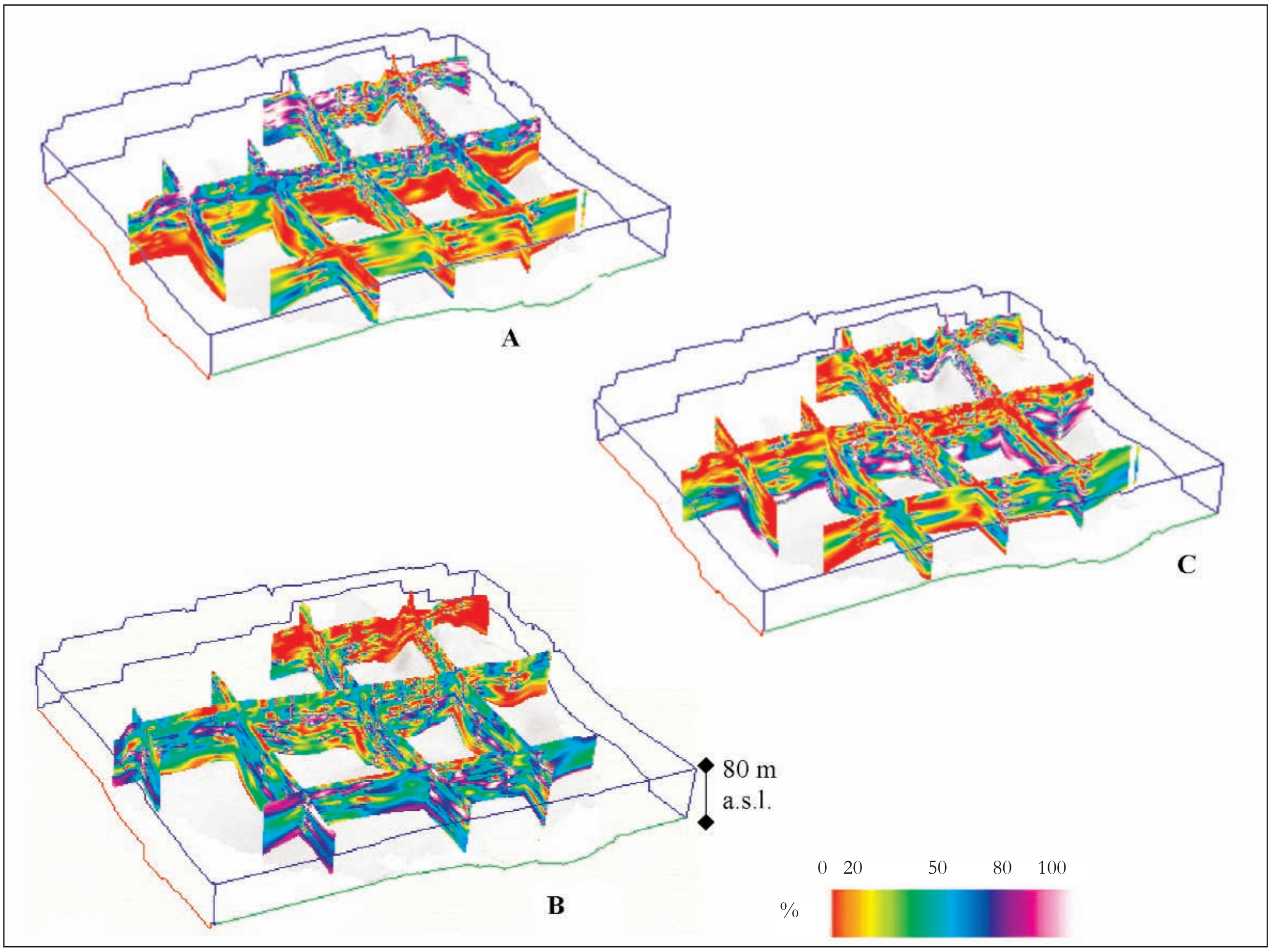

Fig. 4 - North-South and East-West sections inside the SGrid, of gravel (A), sand (B) and clay (C).
- Sezioni Nord-Sud e Est-Ovest all'interno dell'SGrid, di ghiaia (A), sabbia (B) e argilla (C).

in correspondence with the most important rivers, especially the Adda and Ticino on the eastern and western boundaries, respectively, clays are nearly absent, at least in the uppermost portion of the subsurface. The fine-grained deposits become particularly significant in the southern zone of the province, where it is possible to observe extended clay lenses on surface and in the subsurface.

6.1. - Key Sections

An analysis of the percent distribution of the coarse, medium and fine-grained components inside the SGrid can also be made through a detailed observation of individual sections (fig. 4, 5). The sections have been chosen with a discrete distribution for pointing out and verifying the hydrogeological structure of the Province of Milan as a function of its geological evolution (Marchetti, 2001).

One of the most interesting aspects that can be emphasized is the possibility to follow the trend of the gravel-sandy lithozone throughout the whole area and the trend of the clayey-sandy lithozone al least in the northern area, where it is intercepted by the existing wells. Gravels, at rates of more than 60%, prevalently constitute the hydrological structure of the northern-western area, while sands become considerable and substitute nearly all gravel toward the south. This aspect is particularly evident in the western limits, where the Ticino River deposits are, and is less evident on the eastern side, close to the Adda River.

Conversely, with regard to the fine-grained sediments, a progressive deepening of the clayey lithozone from north to south is evident as a typical characteristic of the subsoil of the province in concomitance with the growth of the thickness of permeable deposits, which become more and more sandy. Finally, it must be underlined that the cross-sections in figure 4 enable us to appreciate the development of the bodies, even in 3D, contemporaneously. By cutting the SGrid with horizontal

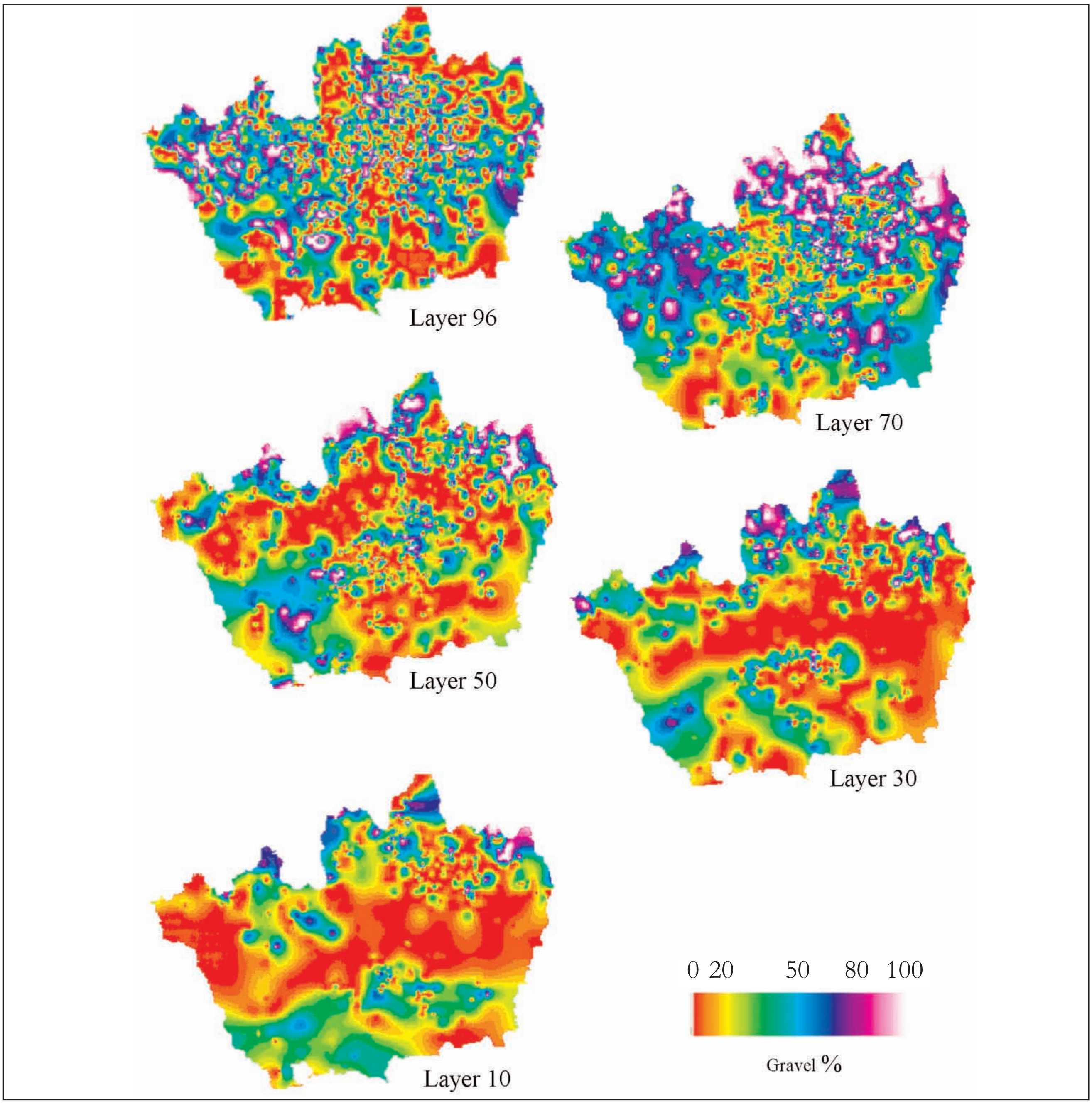

Fig. 5 - Gravel distribution in layers at different depths numbered from the base of the model to the ground surface. Layer 96 is at the topographic surface (from about 250 m to 80 m s.l.); layer 10 is one of the deepest ones (from about 100 m to -50 m s.l.).
- Distribuzione della ghiaia a varie profondità, con numerazione degli strati a partire dalla base del modello. Lo strato 96 è posto alla superficie topografica (da circa 250 m l.m. a 80 m l.m.); lo strato 10 è uno dei più profondi (da circa 100 m a -50 m l.m).

planes at different depths, some horizontal sections have been shown in figure 5, by gravel class. This representation shows the vertical detailed development of the principal bodies existing within the modeled subsoil and verifies the modification of the distribution of the gravels percentage in depth.

6.2. - East-West Sections

Many cross-sections, which extend to the entire province, were therefore chosen and analyzed by comparing them with the sections published in related literature. This representation is certainly very significant because it allows having a detailed textural distribution of the lithozone in the area both vertically and laterally. Furthermore it allows to highlight possible paleochannels both of the aquifers and of the argillaceous intervals. The traces of the sections described below are shown in figure 6.

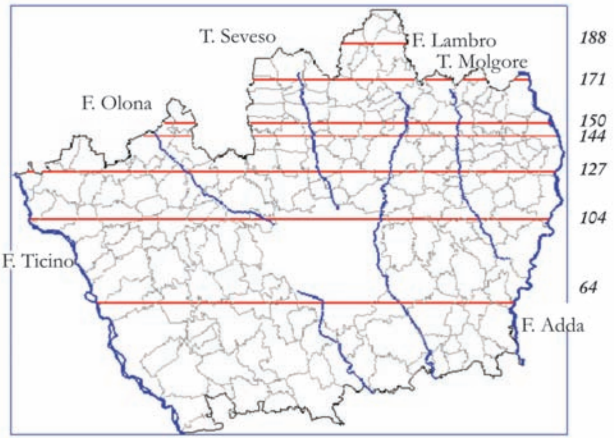

Fig. 6 - Location of the East-West and North-South sections discussed in the text. In blue, surface hydrography; in black, municipalities.
- *Ubicazione delle sezioni Est-Ovest e Nord-Sud discusse nel lavoro. In blu, gli elementi idrografici; in nero, i limiti amministrativi.*

6.2.1. - *Section 188:*
Giussano - Besana Brianza

This short cross-section (fig. 7) is particularly significant as it confirms the presence of a single superficial aquifer with a basal confining layer of clay and bedrock in the northern part of the examined area. This aquifer, located on the western side of the Lambro River and constituted by coarse material about 120 meters thick, is known as paleochannel of the Lambro River, that is an ancient valley of the same river with its fluvial deposits. This structure can be followed for several kilometers towards the south, first running parallel to the river and then slightly departing towards the west.

6.2.2. - *Section 150:*
Rescaldina - Trezzo sull'Adda

This section (fig. 8) shows a detailed reconstruction, in the central and northern sectors of the province, of the different hydrogeological structures existing on the eastern and western side of the Lambro River. While west of the Lambro River one can observe a quite consistent thickness of the aquifer (in the average about 70 m), on the eastern side it is evident that there is a reduction of the thickness up to about 30 m, with a consequent reduction of transmissivity. In this sector, most of the public wells withdrawal is from deep aquifers characterized by medium to fine-grained sediments.

The extension of this structure is relevant in the northeastern part of the province as a consequence of tectonic phenomena, which cause the rising of the clayey marine substrate (Villafranchian clay) and the consequent reduction of fluvioglacial sediment thickness in the entire eastern sector. With regard to the deep permeable levels contained in the Villafranchian clay, it is possible to observe the irregularity and the limited extension of the sand lenses, and less frequently of the gravel lenses.

6.2.3. - *Section 144:*
Legnano - Trezzo d'Adda

Compared with the previous section, this one (fig. 9), located immediately to the south, confirms the previous structure as a progressive reduction of this superficial gravel lithozone from

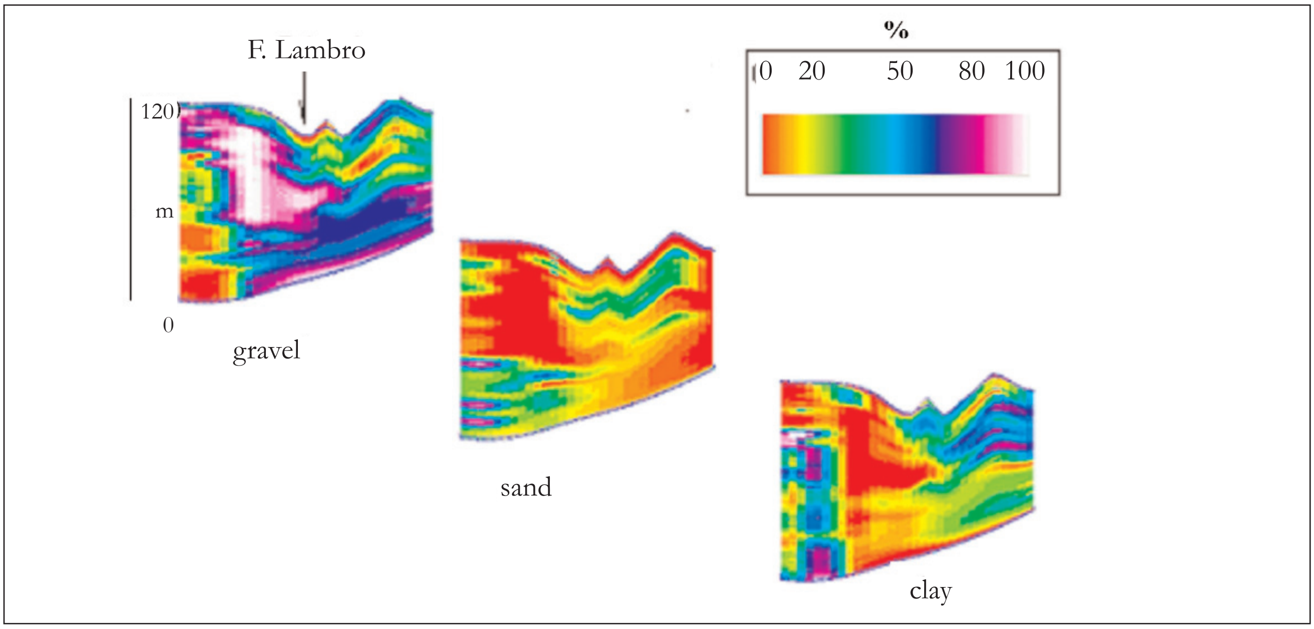

Fig. 7 - East-West section 188: Giussano - Besana Brianza (location in fig. 6).
- *Sezione Est-Ovest 188: Giussano - Besana Brianza (traccia in fig. 6).*

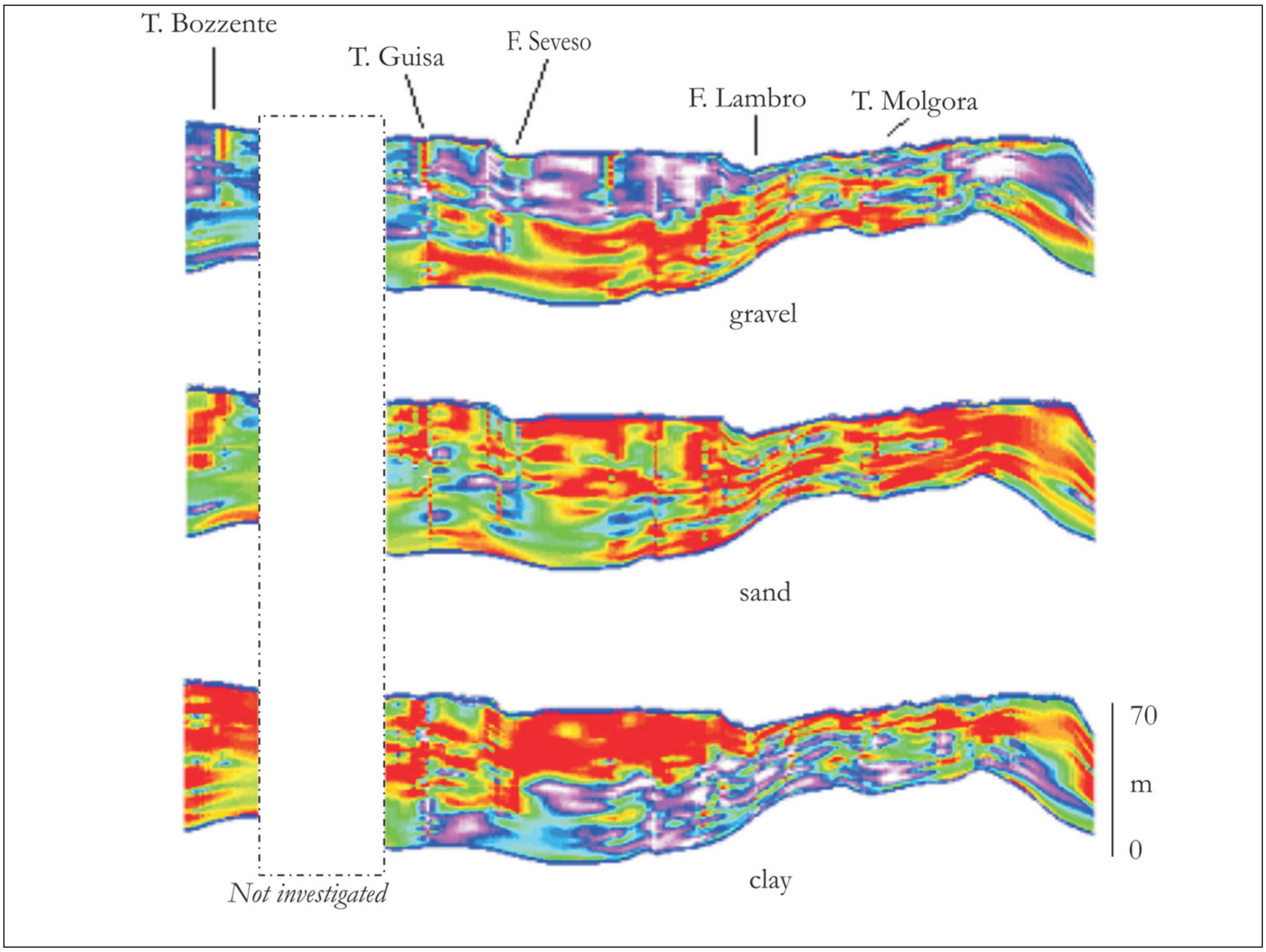

Fig. 8 - East-West Section 150: Rescaldina - Trezzo sull'Adda. Percent distribution of gravel, sand and clay (location in fig. 6; color legend in fig. 7).
- *Sezione Est-Ovest 150: Rescaldina - Trezzo sull'Adda. Distribuzione percentuale di ghiaia, sabbia e argilla (traccia in fig. 6; legenda colori in fig. 7).*

west towards east and a clear prevalence of gravels in the first aquifer, which is typical of the area to the north. In detail, the top of the clayey lithozone can be located at a depth of 80 m in the central area, where the structure of the paleochannel of the Lambro River is evident, and at 30 m in the eastern area. A new deepening is evident near the Adda River.

On the western side of the paleochannel of the Lambro River, the existing reduction of transmissivity of the first aquifer, as a consequence of a reduction of both the thickness and the texture, is quite visible; while on the western limit, the thickness increases up to more than 110 m.

6.2.4. - *Section 104:*
Turbigo - Cassano d'Adda

This section (fig. 10) is located in the intermediate portion of the province which is characterized by a relevant thickness of the superficial aquifer, the bottom of which is 90 m deep in the central part (in correspondence of Milan), and in other places even exceeding 100 m. It also shows a contemporary increase in the frequency and extension of sand levels. This hydrogeological structure indicates a high exploitation potential (BARNABA, 1998). Even in the eastern area, the potentiality of the aquifer grows as a consequence of more developed permeable structures.

6.3. - NORTH-SOUTH SECTIONS

The north-south sections show a gradual southward increase of the thickness and frequency of the fluvioglacial sediments as a consequence of the deepening of marine sediments. This implies an increase in transmissivity from the northern to the middle part of the province.

At the same time, especially in the southern part, e decrease of the sediment grain-size is evident; this implies a gradual replacement of gravels with sands and clays and the confinement of the aquifers.

6.3.1. - *Section 64: Rescaldina - Ozzero*

The cross-section of figure 11A, concerning the eastern areas of the province, shows the presence of the coarse-grained Olona River deposits in the northern and central areas, which constitute about 90-100 m of coarse alluvium with rare sandy levels. The southern portion of the section is dominated by sandy sediments that were likely deposited by the Ticino River.

6.3.2. - *Section 168: Briosco – Locate Triulzi*

The section in figure 11B allows the identification of the principal hydrogeological characteristics of the central sector of the province, from the upper to the intermediate alluvial plain. In the upper plane, the gravel-sandy deposits of the Lambro River dominate, with an almost constant thickness of about 80 m. In the south direction, the progressive increase of the sandy sediments thickness, up to about 110 m, is evident.

7. - CONCLUSIONS

A methodology for converting the well stratigraphic data into alphanumeric codes is proposed using an integrated application of database, GIS and 3D models. The codes allow to quantify and then process the stratigraphic data. The use of a very large number of strati-graphic data over wide areas provide useful sedimentological reconstructions. The codified stratigraphic logs are extracted from the database on a preset depth interval divided into segments. This study considered stratigraphic data for 3472 wells, stored and codified into a database and then imported into GOCAD as percentages of gravel, sand and clay at 2 m depth intervals.

The GOCAD software provided three-dimensional interpolations over the entire territory of the Province of Milan, a reconstruction that is no longer merely executed along sections, but with respect to a whole sediment volume. From a hydrogeological point of view, the 3D representations significantly improve the knowledge of the basic parameters used for the flow models both in terms of pollutants propagation and of ground water flow.

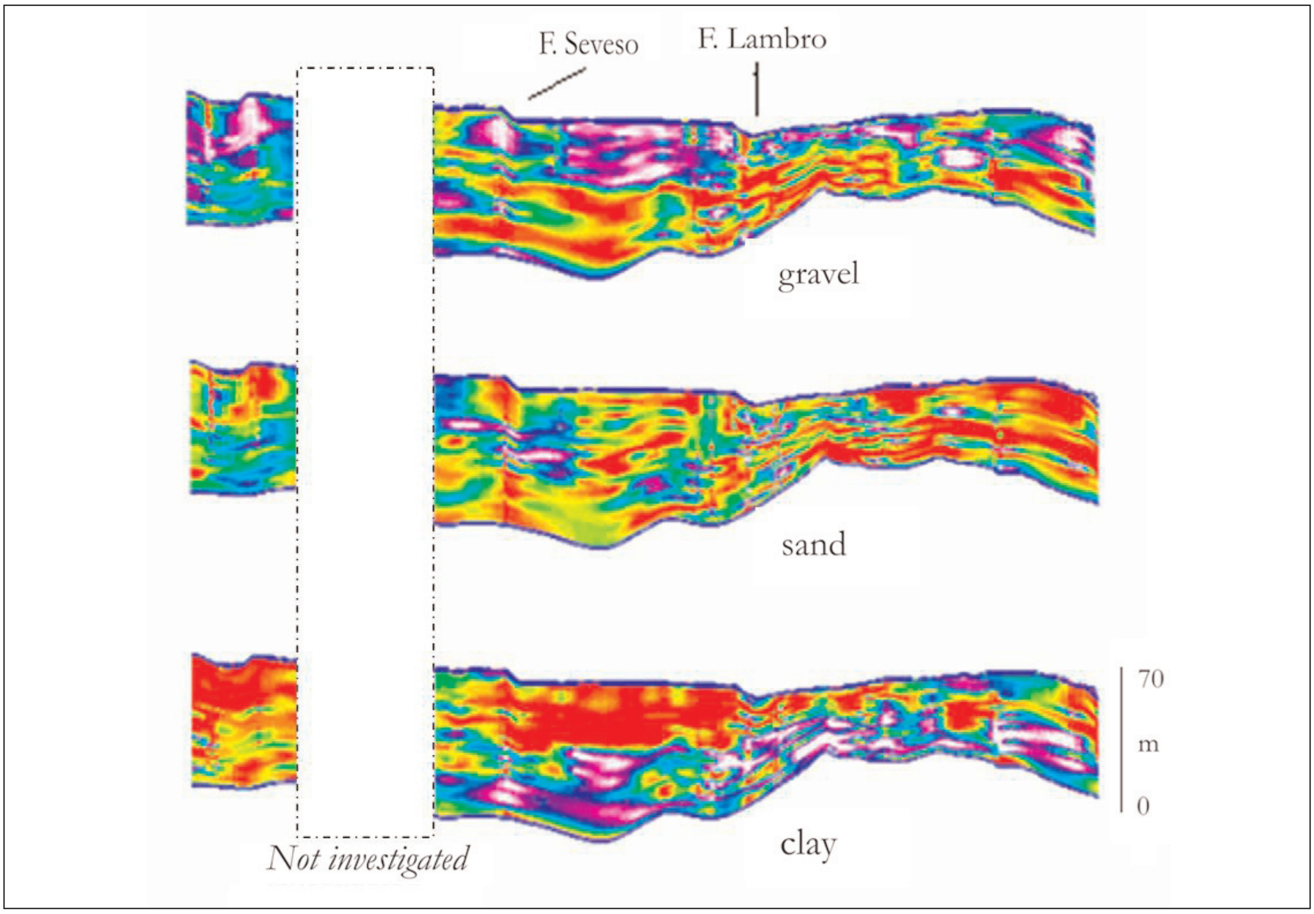

Fig. 9 - East-West Section 144: Legnano - Trezzo d'Adda. Percent distribution of gravel, sand and clay (location in fig. 6; color legend in fig. 7).
- Sezione Est-Ovest 144: Legnano - Trezzo d'Adda. Distribuzione percentuale di ghiaia, sabbia e argilla (traccia in fig. 6; legenda colori in fig. 7).

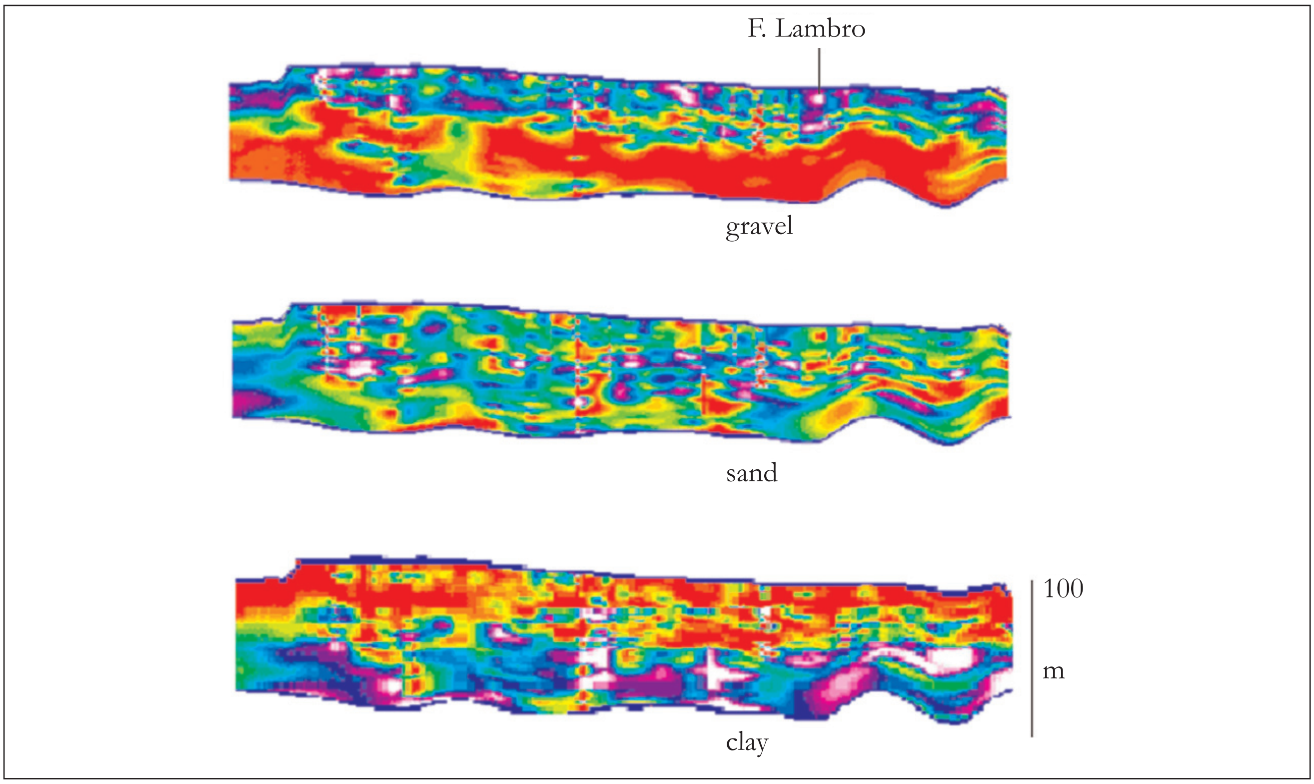

Fig. 10 - East-West Section 104: Turbigo - Cassano d'Adda. Percent distribution of gravel, sand and clay (location in fig. 6; color legend in fig. 7).
- Sezione Est-Ovest 104: Turbigo - Cassano d'Adda. Distribuzione percentuale di ghiaia, sabbia e argilla (traccia in fig. 6; legenda colori in fig. 7).

Fig. 11 - North-South Section 64: Rescaldina - Ozzero (A), North-South Section 168: Briosco - Locate Triulzi (B). Percent distribution of gravel, sand and clay (locations in fig. 6; color legend in fig. 7).
- Sezione Nord-Sud 64: Rescaldina - Ozzero (A), sezione Nord-Sud 168: Briosco - Locate Triulzi. Distribuzione percentuale di ghiaia, sabbia e argilla (tracce in fig. 6; legenda colo ri in fig. 7).

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