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Relations between stratigraphy, groundwater flow and hydrogeochemistry in Poirino Plateau and Roero areas of the Tertiary Piedmont Basin, Italy

Rapporti tra assetto stratigrafico, idrogeologia e idrogeochimica nel settore compreso tra l'Altopiano di Poirino e il Roero (Bacino Terziario Piemontese, Italia)

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ABSTRACT - The study concerns the hydrogeologic setting of a vast portion of land, of about 1000 km^2, between the *Poirino* Plateau, the thalweg of the *Tanaro* River and the hills between the towns of *Bra* and *Asti*.

The stratigraphic framework of the Messinian-to-Pleistocene succession of this area has recently been redefined on the basis of a multidisciplinary study carried out on the entire western Tertiary Piedmont Basin (TPB). This study, performed by a group of researchers from ENI, the *Politecnico di Torino* and the University of Turin, was based on the analysis and interpretation of biostratigraphic, sedimentologic, structural data from both outcrops and subsurface (ENI deep wells and seismic sections). The main result of the stratigraphic analysis of the Messinian to Pleistocene succession of the western TPB was the recognition of three main tectono-stratigraphic units or allogroups, bounded at base and top by major tectonically-induced unconformities. These allogroups have been named: Late Messinian Allogroup (LM), Early Pliocene Allogroup (EP) and Late Pliocene Allogroup (LP). Each of these allogroups is made up of informal lithostratigraphic units characterised by relative lithologic homogeneity and referable to one or to a set of marine or continental genetically related depositional environments (e.g. fluvial, deltaic, shelfal, slope, basinal depositional systems).

In this work, the correlation between the outcrop and subsurface data has made it possible to define a detailed hydrostratigraphic scheme of the entire area under examination. In fact, the informal lithostratigraphic units recognised in the multidisciplinary study have been correlated to their respective hydrogeologic units (aquifer analogues), referred to with their same nomenclature. The hydrogeologic units consist of different sedimentary facies. Hydraulic conductivity values have been assigned to the recognized sedimentary facies on the basis of direct measurements or of bibliographic data. Then different aquifer systems have been identified on the basis of the geometry of the aquifer, semi-permeable (aquitards) and impermeable (aquicludes) layers, of the type and geometry of their contacts, and of the hydrodynamical and hydrogeochemical data.

The main aquifer system is located in the basal part of the Villafranchiano B Hydrogeologic Unit and in the permeable sand layers of the *Sabbie d'Asti B* Hydrogeologic Unit. In the southwestern sector the piezometry of this aquifer system is strongly influenced by the geometry of the unconformity that separates the EP Allogroup from the underlying LM Allogroup and, in the remaining sector, by the geometry of the synclinal structure that involves the *Sabbie d'Asti B* and the *Argille Azzurre B*. This piezometry indicates groundwater flows from the *Poirino* Plateau and *Bra* Hills towards the *Versa* Valley (close to *Asti*) where, in the past, there was an important spring which was tapped for drinking water purposes. At present several wells are in operation and are over-exploiting the aquifer under examination causing a large depression cone. The aquifer system is confined and, below the Eastern Escarpment, is generally artesian. The chemistry of these waters is substantially homogeneous with bicarbonate-

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calcic and bicarbonate-calcic-magnesium facies with decidedly low nitrate contents and iron and manganese levels which are often above the maximum admissible concentrations established by the Italian Law.

A second aquifer system, which at present is not very important but in the past was the only water resource available for the local population, is found in the hilly sector north of the *Tanaro* River between the villages of *Santa Vittoria d'Alba* and *San Damiano d'Asti*. This aquifer system, located in the sand bodies of the *Argille Azzurre A* Hydrogeologic Unit, is artesian along the main valley bottom and is under pressure in the other zones. The groundwater flow is completely different from the main aquifer system with prevalent directions towards the west and a rather complex recharge mechanism due to recurrent leakage from the aquifers above. This aquifer system is intercepted by deep wells that reach the waterlogged sand bodies below a thick succession of silty clays.

The chemical facies of the waters from this aquifer system are very different one from the other. The presence of chloride-sodic facies shows the existence of marine water that was trapped in the sediment at the moment of the deposition and which still has not been completely displaced by continental water. These latter have been identified in several wells and have bicarbonate-calcic and bicarbonate-magnesium-calcic facies. Bicarbonate-alkaline facies have also been found that can be explained by to cationic exchange with the clayey confining layers favoured by long permanence times in the aquifer. The quality of the water is generally poor because of the ammonium, iron and manganese ion contents.

Other less important aquifer systems are present in the *Poirino* Plateau sector in the Villafranchiano C Hydrogeologic Unit and in the Terraced Quaternary Alluvium Hydrogeologic Unit. The piezometry of the latter indicates flow directions opposite to the main aquifer system below and poor quality waters because of high nitrate contents.

KEY WORDS: aquifers, hydrogeochemistry, hydrogeology, stratigraphy, Tertiary Piedmont Basin.

RIASSUNTO - Lo studio interessa l'assetto idrogeologico di una vasta area (circa 1000 km^2) compresa tra l'Altopiano di Poirino, il fondovalle del Fiume Tanaro e la zona collinare tra le città di Bra e Asti.

L'assetto stratigrafico di quest'area, relativo alla successione plio-pleistocenica, è stato ridefinito da uno studio multidisciplinare che ha interessato l'intero settore occidentale del Bacino Terziario Piemontese. Per lo studio, condotto da un gruppo di ricercatori di Eni, Politecnico di Torino e Università di Torino, sono stati utilizzati dati di superficie e di sottosuolo che hanno permesso di definire uno schema stratigrafico di dettaglio della successione studiata. Al di sopra dei depositi messiniani della Formazione della Vena del Gesso, sono state riconosciute tre unità stratigrafico-sequenziali principali separate da importanti discontinuità di natura tettonica così denominate: Allogruppo Late Messinian (LM), Allogruppo Early Pliocene (EP) e Allogruppo Late Pliocene (LP). Tali allogruppi sono costituiti da differenti unità stratigrafico-deposizionali riconducibili a uno o più ambienti di deposizione marini o continentali (sistemi deposizionali fluviali, deltizi, di piattaforma, ecc.). Tali unità si caratterizzano per una relativa omogeneità litologica e sono state elevate al rango di unità litostratigrafiche informali.

La correlazione tra la geologia di superficie e i dati di sottosuolo ha permesso di definire un modello idrostratigrafico dell'intera area in esame, in cui le unità litostratigrafiche informali riconosciute nello studio multidisciplinare sono state correlate alle corrispondenti unità idrogeologiche, indicate ove possibile con la stessa nomenclatura utilizzata per le unità litostratigrafiche informali. Alle diverse associazioni di facies costituenti le varie unità idrogeologiche sono stati assegnati valori di conducibilità idraulica desunti da prove in situ o da letteratura. Sulla base della geometria dei livelli acquiferi, semipermeabili ed impermeabili, della natura e geometria dei loro contatti, dei dati idrodinamici e idrogeochimici sono quindi stati identificati una serie di sistemi acquiferi.

Il sistema acquifero principale è impostato negli orizzonti basali dell'Unità Idrogeologica del Villafranchiano B e dei livelli permeabili dell'Unità Idrogeologica delle Sabbie d'Asti B. La piezometria di tale sistema acquifero è fortemente condizionata, nel settore sud-occidentale dell'area studiata, dalla giacitura dell'unconformity che separa l'Allogruppo EP dal sottostante Allogruppo LM e, nel restante settore, dalla geometria sinclinalica che caratterizza il contatto stratigrafico tra le Sabbie d'Asti B e le Argille Azzurre B. L'assetto piezometrico presenta linee di flusso idrico sotterraneo dirette dal settore dell'Altopiano di Poirino – Colline di Bra verso la Valle Versa (in prossimità di Asti) dove in passato era presente un'importante sorgente captata ad uso idropotabile e attualmente sono in funzione numerosi pozzi che sovrasfruttano l'acquifero in esame provocando un vistoso cono di depressione. Il sistema acquifero è in pressione e a valle della "Scarpata Orientale" dell'altopiano di Poirino è generalmente artesiano. La chimica di queste acque è sostanzialmente uniforme con facies bicarbonato-calcica, bicarbonato-calcico-magnesiaca, contenuti di nitrati decisamente bassi e tenori di ferro e manganese sovente più alti della concentrazione massima ammissibile per la normativa italiana vigente.

Un secondo sistema acquifero, ora di modesta importanza ma che in passato ha rappresentato l'unica risorsa idrica disponibile per la popolazione locale, è presente nel settore collinare in sinistra Tanaro tra i centri abitati di Santa Vittoria d'Alba e San Damiano d'Asti. Tale sistema acquifero, impostato nei livelli sabbiosi di mare profondo dell'Unità Idrogeologica delle Argille Azzurre A, è artesiano in corrispondenza dei principali fondovalle e in pressione nelle restanti zone. Il flusso sotterraneo presenta un andamento del tutto differente rispetto al sistema acquifero principale con direzioni prevalenti verso ovest e una ricarica piuttosto complessa legata ad una serie di travasi provenienti dai sistemi acquiferi sovrastanti. Questo acquifero è intercettato da pozzi profondi che attraversano potenti intervalli di argille siltose per raggiungere i corpi sabbiosi acquiferi con acque aventi facies chimiche molto diverse tra loro. La presenza di facies cloruro-sodiche evidenzia l'esistenza di acque marine intrappolate nel sedimento all'atto della deposizione e non ancora completamente sostituite da quelle della circolazione attiva. Queste ultime sono state individuate in numerosi pozzi e presentano facies bicarbonato-calcica e bicarbonato-magnesiaco-calcica. Si rinvengono, inoltre, facies bicarbonato-alcaline imputabili a fenomeni di scambio cationico con i sedimenti argillosi e quindi caratterizzate da tempi di permanenza in acquifero decisamente lunghi. La qualità delle acque è generalmente scadente a causa degli alti contenuti di ione ammonio, ferro e manganese.

Nel settore dell'Altopiano di Poirino sono presenti altri sistemi acquiferi di secondaria importanza impostati nell'Unità Idrogeologica del Villafranchiano C e nell'Unità Idrogeologica Alluvionale dei Terrazzi Alti. La piezometria di quest'ultima presenta linee di flusso diametralmente opposte (verso ovest) rispetto a quelle dell'acquifero profondo principale e acque di scarsa qualità a causa degli alti contenuti di nitrati.

PAROLE CHIAVE: acquiferi, Bacino Terziario Piemontese, idrogeochimica, idrogeologia, stratigrafia.

1. - INTRODUCTION

The examined area covers a vast portion of the Piedmont territory (about 1000 km^2) and falls roughly between the Turin Hill reliefs to the north, the western sector of the Turin-*Cuneo* plain to the west, the *Tanaro* River to the south-east and the *Asti* reliefs to the north-east (fig. 1).

Faced with the necessity of examining the hydrogeology of an area characterised by a rather complex geological and structural framework as the Piedmont Tertiary Basin (PTB), the work has been performed in different stages in order to correlate the tectono-stratigraphic model with the hydrogeologic context, applying the principle of "*aquifer analogues"* proposed by BERSEZIO (2007).

First, all the data obtained from a multidisciplinary study related to the Pliocene-Pleistocene succession of the western sector of the Piedmont Tertiary Basin (PTB), in which some sequence-stratigraphic (i.e. allogroups and sequences) and lithostratigraphic units were identified (GHIELMI *et alii*, 2002; GHIELMI *et alii*, in preparation), have been analysed. The informal lithostratigraphic units of the geological model has been ascribed to the respective hydrogeologic unit. Finally the identification of the main aquifer systems in the studied succession has been carried out on the basis of the geometry of the different aquiferous horizons, their connection, their lower and upper boundaries (identified by the presence of aquicludes or aquitards), the piezometric levels that has been measured in the wells and the chemistry of the waters.

2. - GEOGRAPHIC SETTING

From the morphological point of view (fig. 2), this area includes the entire *Poirino* Plateau, which constitutes a sub-level portion of the same area. It slopes slightly towards the west and is bordered on the north by the Turin Hill reliefs and on the south by the *Bra* Hills with topographical altitudes that vary between 265 (near *Dusino*) and 230 (near *Santena*) m a.s.l. This area has a surface drainage network that collects the water from the Turin Hills, the *Braidese* reliefs and from the plateau itself through two main collectors (the *Banna* Stream and the *Melletta* Stream) and sends it towards the Turin-*Cuneo* Plain. The eastern margin of the plateau is represented by a clear morphological escarpment (referred to as the Eastern Escarpment) that separates it from the *Asti* reliefs. These reliefs are characterized by a lower topographical altitude (between 260 and 150 m a.s.l.) than that of the plateau. They are connected to the diversion of the *Tanaro* River and therefore are interested by the consequent deepening and rejuvenation of its catchment as far as the Eastern Escarpment. The remaining part of the territory is made up of a wide hilly area, deeply incised by several streamlets that flow into the *Tanaro* River that comprises the *Asti*, *Roero* and *Bra* hills. Geographically speaking, the *Roero* Hills correspond to a vast portion of land between *Bra*, *Montà* and the *Tanaro* River.

3. - METHODOLOGY

In the areas characterised by a remarkable stratigraphic and tectonic complexity, hydrogeologic studies should involve a specific sequence of operative phases. First, it is of fundamental importance to reconstruct in detail the stratigraphic setting of the area through classical geological studies based on biostratigraphic, sedimentologic, structural and sequence stratigraphic analysis of the sedimentary succession, in order to recognize the main stratigraphic units, their sedimentary environments and associated facies, their lateral and vertical stratigraphic and tectonic relationships. Each stratigraphic unit is converted in an hydrogeologic unit (aquifer analogues). The proper hydraulic conductibility value is attributed to each constituent facies of an hydrogeologic unit through the use of literature data or direct in situ measurements (permeability tests, grain-size analysis, slug-tests, aquifer tests). Therefore, different permeability values can be assigned to each hydrogeologic unit and these values can identify aquifers, aquitards, aquicludes and aquifuges.

An aquifer system is characterised by a hydrogeologic structure of known geometry, including the unsaturated zone, the saturated zone and its recharge area (CIVITA, 2005) and it is made up of a set of different hydrogeologic units hydraulically connected to each other. Each aquifer system is therefore recognised on the basis of its hydrodynamic situation and of its hydrogeochemical characterisation and is bounded by aquicludes or aquifuges. Aquifer systems can also be made up of one or several hydrogeologic units characterised by the presence of aquitards and numerous aquifers of small volume so that they can hardly be mapped.

The studied area has proved to be particularly suitable for the application of this approach that also benefitted of the detailed multidisciplinary studies carried out in the western TPB by GHIELMI *et alii*, 2002 and in preparation.

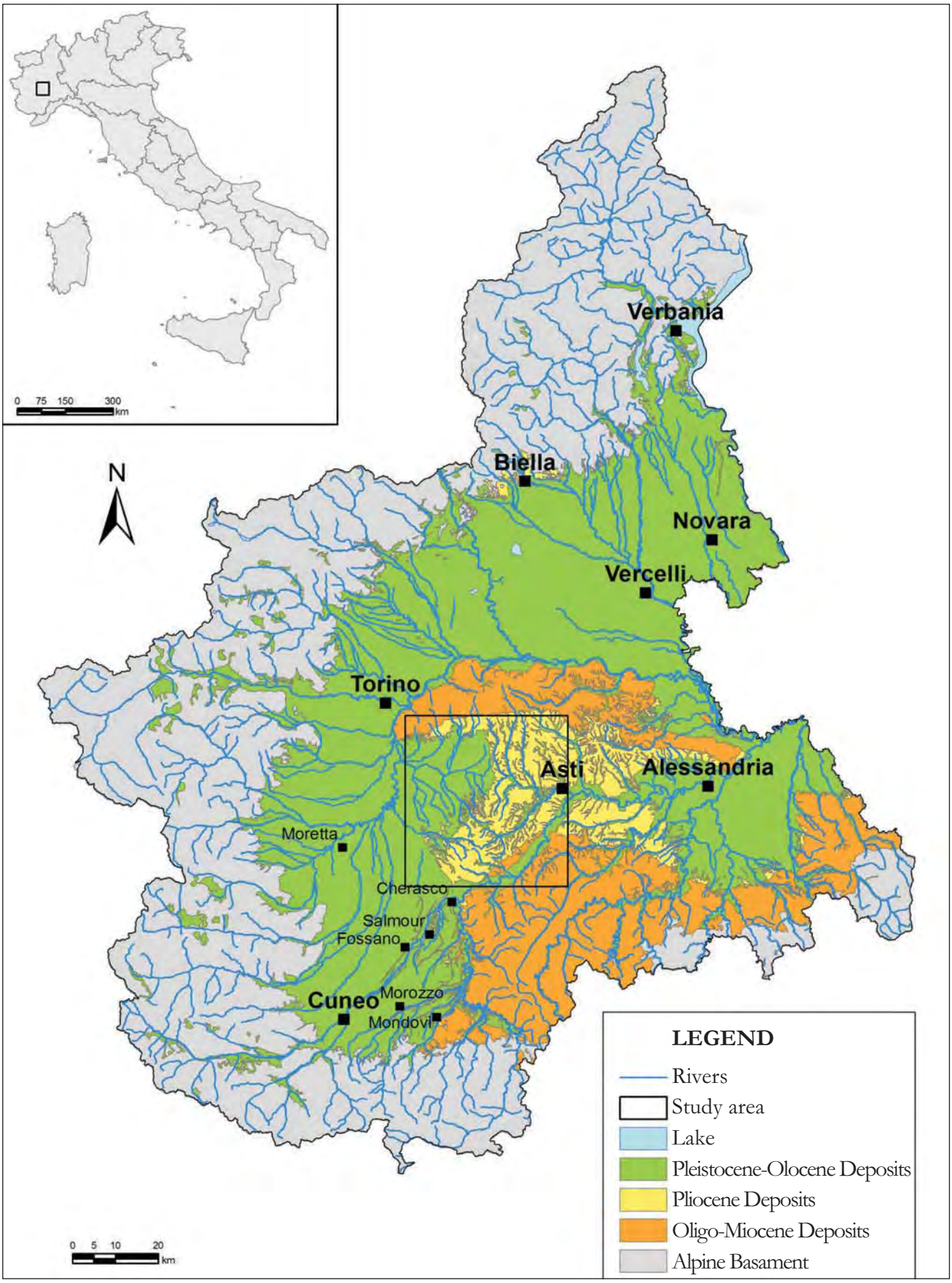

Fig. 1 – Location of the study area on the Lithologic Unit map of Regione Piemonte (Italy) (modified after Regione Piemonte C.S.I., 1990).
– *Ubicazione dell'area in studio sulla Carta delle Unità Litologiche della Regione Piemonte (Regione Piemonte C.S.I., 1990 - modificata).*

4. - TECTONO-STRATIGRAPHIC MODEL OF THE PLIO-PLEISTOCENE SUCCESSION OF THE WESTERN TERTIARY PIEDMONT BASIN

The Pliocene-Pleistocene succession of the Tertiary Piedmont Basin (TPB) has been the subject of numerous geological studies, starting from the works of SACCO (1890, 1912, 1924, 1933), until the recent monographic revision of the Villafranchiano in the type-area by CARRARO (1996). The TPB is considered as an epi-sutural basin, according to the definition given by BALLY & SNELSON (1980), formed in a collisional regime behind the front of the *Monferrato* Front overthrusting the Insubric foreland (GELATI & GNACCOLINI, 1988; BOCCALETTI & MARTELLI, 2004). The oligo-miocenic sedimentary succession of the TPB rests unconformably upon the Alps and the Northern Apennines structural units, hiding their complex geometrical relationships.

The Plio-Pleistocene strata of TPB are bordered towards south and west by the Alpine Units and towards east and northeast by the Oligo-Miocene successions of the TPB (the Turin, *Monferrato* and *Langhe* Hills). The Pliocene and Pleistocene sediments outcrop principally in the area between the towns of *Asti, Villafranca* and *Bra.*

They are also exposed on the southern limb of the Turin Hills, on the edges of the *Langhe* hills, along the valley bottoms of the *Tanaro* River and of its main tributary streams as far as the town of *Mondovì*. In the *Cuneo* plain and in the plain to the south of Turin, the Pliocene deposits are overlain by a thin succession of Pleistocene deposits.

Starting from the Upper Miocene and going on until the Pliocene and part of the Pleistocene, various severe phases of structural deformation, connected in the western sector of TPB to some compressive fronts with northwest vergence, led to the creation of a wide sedimentary basin filled with a succession of both marine and continental deposits. The thickness of these deposits reaches 1200-2200 m in the main depocenters of the basin (in the *Moretta* and *Savigliano* sectors) (GHIELMI *et alii*, 2002). As a result of the phases of growth of the compressive fronts, the western TPB is subdivided in a few sub-basins referred to as the *Savigliano* Sub-basin, comprising the central-southern part of the western TPB, the *Moretta* Sub-basin, in the north-western part, and the *Asti* Sub-basin in the north-eastern part (GHIELMI *et alii*, 2002). The northernmost Turin Hills fronts separate these sub-basins from the coeval Western *Po* Plain Foredeep located in the central Piedmont (MINERVINI *et alii*, 2008). The Pliocene-Pleistocene succession is represented by an overall transgressive-regressive cycle made up of (from base to top) relatively deep marine clays (*Argille Azzurre* or *Lugagnano* Formations), shelfal to nearshore sands (*Sabbie d'Asti* Formation), deltaic and continental sands, gravels and clays (Villafranchiano). A major unconformity, the *Cascina Viarengo* Surface, subdivides the Villafranchiano succession into two sedimentary units, which are referred to as the Lower Complex and Upper Complex (CARRARO, 1996). The Lower Complex includes two units (from base to top): the Ferrere Unit made up of delta-front sands with tidal influence which, according to BONI *et alii* (1970), belongs to the *Sabbie d'Asti* Formation, and the *San Martino* Unit referred to a delta plain environment (CARRARO, 1996). Also the Upper Complex includes two units: the *Cascina Gherba* Unit, represented by fluvial deposits and the *Maretto* Unit, made up of continental flood-plain deposits (CARRARO, 1996).

In the past the stratigraphic relationships between the different Pliocene-Pleistocene lithostratigraphic units of the western TPB were always considered the record of the aggradational infilling of the basin expressed by a layer-cake stratigraphy. The study presented by GHIELMI *et alii* (2002), based on both outcrop and subsurface data, highlighted, for the first time, the existence of lateral stratigraphic relationships between the *Argille Azzurre* Fm., the *Sabbie d'Asti* Fm. and the Villafranchiano deposits. Moreover these lithostratigraphic units, that seem to show significantly different ages in the different parts of the basin, are framed into different sequence-stratigraphic units (allogroups). As documented in the 2002 study and particularly in a new publication which is presently in preparation by the same authors, during the Messinian and Pliocene the western TPB underwent a few severe phases of compressive and transpressive Apennine structural deformation as suggested by the presence of major unconformities of tectonic origin. Therefore, in these studies, the sequence-stratigraphic analysis was based on the recognition of stratigraphic units bounded at base and top by tectonically-induced major unconformities: the allogroups. Two major unconformities subdivide the Pliocene-Pleistocene succession of the western TPB into three different allogroups: the Late Messinian Allogroup (LM), the Early Pliocene Allogroup (EP) and the Late Pliocene Allogroup (LP). The succession of each allogroup, deposited in relative continuity of sedimentation and attributed to a well defined stratigraphic interval on the basis of the biostratigraphic data, is made up of sediments referred to genetically related depositional environments.

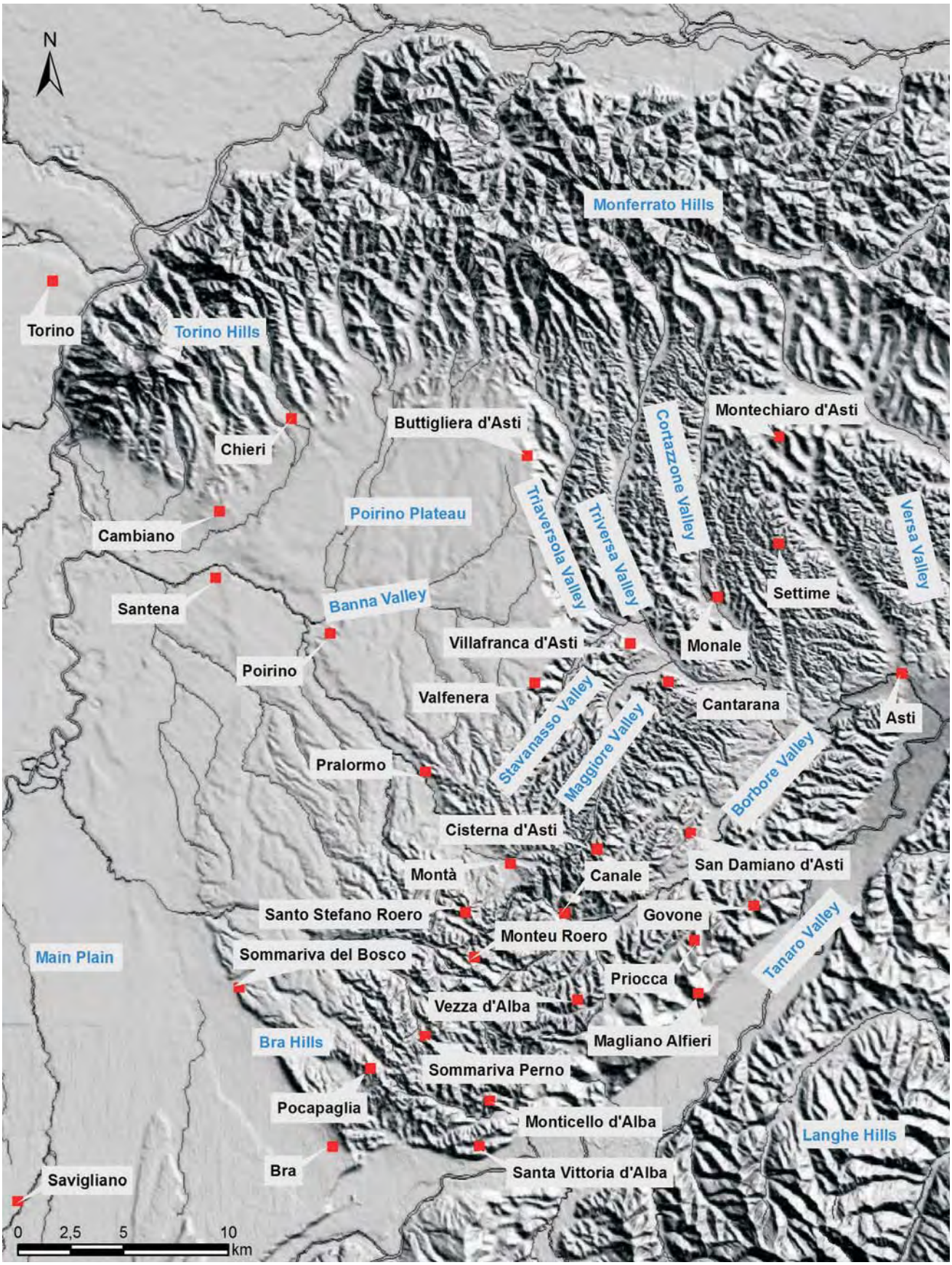

Fig. 2 - Morphologic setting of the study area (processing by Digital Terrain Model of Regione Piemonte 1985 - 1994).
- Assetto morfologico dell'area di studio (elaborazione da modello altimetrico digitale della Regione Piemonte 1985 - 1994).

4.1. - Late Messinian Allogroup (LM)

The LM Allogroup includes the post–evaporitic Messinian and Lower Pliocene sediments. The allogroup boundary is represented by a major tectonic unconformity referred to as the "Intra-Messinian Unconformity". The sediments of the allogroup unconformably overlie the pre- and syn-evaporitic Messinian succession or older Miocene deposits. The Intra-Messinian severe phase of structural deformation caused, in some marginal sectors of the basin, the re-sedimentation of part or, sometimes, of the entire evaporitic succession (with blocks and olistoliths of gypsum and carbonates incorporated in a fine matrix) into the lower part of post-evaporitic succession. These mass-deposits, already described in the outcrops of the southern limb of the Turin Hills front and of south-western *Langhe* Hills as the Chaotic Complex of the Versa Valley (Dela Pierre *et alii*, 2002, 2003), have also been recognized in the subsurface of other sector of the western TPB (Ghielmi *et alii*, in preparation). The post-evaporitic Messinian succession is made up of gravel, sand and silt of the *Cassano Spinola* Formation (Boni & Casnedi, 1970). These sediments, characterized by very variable thicknesses, have been interpreted as delta-fan deposits associated to lacustrine and palustrine facies (Ghibaudo *et alii*, 1985). The "*lago-mare* facies", deposited in a brackish environment and predominantly made up of greenish clay, belong to the same formation.

The regressive post-evaporitic Messinian succession is overlain, through an sharp lithologic, by transgressive Lower Pliocene deposits mostly represented by relatively deep marine clays with an abundant marine microfauna. These sediments show an abrupt return, in most of the basin, to a rather deep marine sedimentation in consequence of the Pliocene transgression.

Once the basal Pliocene transgressive phase had run out, an important regressive phase started (referred to as "Pliocene progradation" by Ghielmi *et alii*, 2002). This phase gradually led to a partial filling of the western TPB during the first part of Lower Pliocene. Towards the end of the LM Allogroup the basin was characterised by a somewhat complex environmental framework. In the southernmost portion of the western PTB, close to the Alpine basement (between the towns of Cuneo and Mondovì), a deposition of alluvial fan, fluvial and flood-plain sediments took place. These continental sediments have been attributed, by Ghielmi *et alii*, (2002 and in preparation), to the informal Villafranchiano A Unit. Towards the north, in the area roughly between *Fossano* and *Salmour*, the continental deposits of the allogroup first grade laterally into deltaic and shelfal facies mostly made up of sands, that have been included in the informal *Sabbie d'Asti A* Unit, then into outer shelf, slope and basinal deposits of the informal *Argille Azzurre A* Unit (Ghielmi *et alii*, 2002). The slope deposits consist of clays, locally chaotic, with intercalations of sands and gravels (outcropping above all in the area between the towns of *Morozzo* and *Cherasco*). The basinal sediments (exposed in particular in the study area between *Bra* and *Canale*), are represented by 5-30 m thick sandy bodies alternating with 10-80 m thick clay and silty clay layers. The sand bodies are mostly represented by packages of amalgamated medium to thick sandy beds deposited in a relatively deep water environment by sediment of gravity flows. Moving towards the town of *Asti*, these sediments grade into distal fine-grained basin plain deposits made up of clay with intercalations of thin-bedded silt.

4.2. - Early Pliocene Allogroup (EP)

This allogroup consist of Lower and Middle Pliocene sediments. The lower boundary of the allogroup corresponds to an important tectonic modification phase of the basin and to a growth phase of the main structural fronts. Throughout the studied area, the boundary is characterized by a pronounced angular unconformity (*Pocapaglia* unconformity) and by a sharp change in the sedimentary facies indicating an abrupt reduction of water depth in consequence of the uplift of the eastern margin of the basin. In the area between the towns of *Bra* and *Monteu Roero*, the continental and deltaic gravels and sands, belonging to the Villafranchiano B informal unit, unconformably overlie the shelfal sands and silts attributed to the *Sabbie d'Asti A* informal Unit (Allogroup LM). To the southwest of the town of *Asti* yellow-brown laminated silty clays of the *Argille Azzurre B* informal unit overlie the deeper typically grey-blue clay of the *Argille Azzurre A*, interpreted as basinal deposits. The EP Allogroup is also made up of deposits that ranges from continental to coastal and marine facies. Moving from the southwest towards the northeast in a basinward direction, continental, fluvio-deltaic and tide-dominated deltaic deposits of the informal Villafranchiano B Unit (corresponding to the "*Complesso Inferiore*" of the Villafranchiano type-area; Carraro, 1996), predominantly sandy shelfal deposits of the informal *Sabbie d'Asti B* Unit, outer shelf, slope and basinal silty shales of the informal *Argille Azzurre B* Unit outcrop between *Bra* and *Asti*.

4.3. - Late Pliocene Allogroup (LP)

The LP Allogroup is made up of Upper Pliocene and Pleistocene continental sediments. The allogroup boundary corresponds to a severe phase of compressive deformation of the western TPB. A dramatic uplift (referable to the Late Pliocene) interested many sectors of the basin, including also the study area, which were consequently interested by a long period of no deposition and of sub-aerial erosion of the underlying older successions. In the Villafranchiano type-area, the allogroup boundary should correspond to the "*Cascina Viarengo* surface", angular unconformity identified in the area by Carraro (1996). This unconformity often represents an important hiatus that can locally encompass the entire Upper Pliocene and part of the middle Pliocene and Pleistocene (Carraro, 1996; Ghielmi *et alii*, 2002 and in preparation). The sedimentation of upper Pliocene-lower Pleistocene fluvial and flood-plain deposits of the informal Villafranchiano C Unit took place only in the westernmost *Moretta* sub-basin, and in a little sector of the Asti sub-basin (Ghielmi *et alii*, 2002 and in preparation). In the type-area of the Villafranchiano, these strata were included by Carraro (1996) into the "*Complesso Superiore*" (*Cascina Gherba* and *Maretto* Units).

The LP Allogroup also includes the middle-upper Pleistocene coarse-grained fluvio-glacial deposits of the "Quaternary Alluvium" (alternatively referred to as the "Terraced Fluvial Deposits" following the terminology proposed by Carraro (1996). The "Quaternary Alluvium" sedimentation, predominantly made up of gravels, mostly developed in the *Cuneo* and Turin plain. Fluvio-glacial deposits are also present, to a certain extent, in the *Poirino* Plateau area and in the valley floors of the watercourses. In these areas it is possible to recognize at least three main morphological units: 1) the high terraces, 2) the principal plain (*Cuneo* and Turin plain), 3) the present valley floor deposits and the suspended terraces (Cavalli & Vigna, 1992). The three units, bounded at the base by erosional surfaces, are interpreted as the result of as many major phases of erosion and subsequent fluvio-glacial deposition controlled by Middle Pleistocene climatic cyclicity.

5. - HYDROGEOLOGIC FRAMEWORK

The first hydrogeologic entry to describe the area was the study by Bortalami *et alii*, (1989). The authors showed how the *Cassano-Spinola* conglomerates constitute the deepest aquifer complex, with modest aquifers and rather poor-quality water quality, while the clays of the *Lugagnano* Formation represent a thick impermeable succession with the presence, on the top of the formation of some sandy intercalations that house limited confined aquifers of limited production. The *Sabbie d'Asti* result to be an aquifer with a remarkable production and which, in the *Versa* Valley zone, house important aquifers under pressure. The Lower Villafranchiano deposits also house aquifers of some importance, while the Upper Villafranchiano ones have a very low production. The deep wells in the *Poirino* Plateau zone exploit the Lower Villafranchiano and the *Sabbie d'Asti* layers and have fair flows. The ancient alluvial sediments (Upper Villafranchiano) constitute an impermeable complex with totally negligible water reserves. In the aforementioned work, there is no mention of the piezometry of the different aquifers, but the quality of the water of the different aquifers was analysed and the results have shown the presence of several very different hydrogeochemical facies.

A subsequent contribution, by Canavese *et alii* (1999), analysed the stratigraphy and the aquifer distribution in the subsurface of the central sector of the *Poirino* Plateau. The authors identified the presence of two main aquifers. The first is a shallow aquifer located in the terraced fluvial deposits (Term 4) and, in the southern sector, in the Upper Villafranchiano deposits (*Maretto* Unit) with a flow, strongly conditioned to a great extent by the morphology of the area, from south-east towards north-west and from east towards west in the direction of the Turin plain. A second deeper aquifer is located in the Term 1 (*Sabbie d'Asti* and *Ferrere* Unit) and Term 2 (*San Martino* Unit) deposits as well as in the lower part of the Term 3 (*Cascina Gherba* Unit). The deep water flow is in a west to east direction, that is, overall in an opposite direction compared to the shallow aquifer. The two aquifers are probably separated by an impermeable layer belonging to the upper part of Term 3 (*Maretto* Unit). Chemical analyses were also carried out on the groundwater and different chemical characteristics were encountered for the two aquifers.

5.1. - Hydrogeologic Units

In this study several hydrogeologic units have been identified in the test area on the basis of the previously briefly described stratigraphic model of the Pliocene-Pleistocene succession of the western PTB (aquifer analogues). These hydrogeologic units show rather different hydrogeologic characteristics in comparison with those recognised in the previous investigations. An example of the many differences concerns the *Argille Azzurre* Formation

(or *Lugagnano* Formation). In the study area, the clayey succession of the formation is intercalated with numerous sandy aquifer layers previously never recognised. In former studies, this hydrogeologic unit was in fact considered completely impermeable and to play the role of an aquiclude.
In the present work, the main sedimentary facies of the different hydrostratigraphic units have been distinguished. Then a value of hydraulic conductibility has been attributed to the sedimentary facies on the basis of direct measurements or of bibliographic data. The hydrogeologic characteristics of the main stratigraphic units identified in the three allogroups are here briefly described (from the bottom to the top):

- *Cassano-Spinola* Hydrogeologic Unit;
- *Argille Azzurre A* Hydrogeologic Unit;
- *Sabbie d'Asti A* Hydrogeologic Unit;
- *Argille Azzurre B* Hydrogeologc Unit;
- *Sabbie d'Asti B* Hydrogeologic Unit;
- Villafranchiano B Hydrogeologic Unit;
- Villafranchiano C Hydrogeologic Unit;
- Ancient terraced Pleistocene Alluvium Hydrogeologic Unit;
- Fluvial channel Holocene Alluvium Hydrogeologic Unit.

The Hydrogeologic Units map and the Hydrogeologic Units cross-section are shown in figures 3 and 4 respectively.

5.1.1. - *Cassano-Spinola Hydrogeologic Unit*

The unit is made up of alternating sand, gravel and clay of the *Cassano-Spinola* Formation that outcrop in a narrow belt between the villages of *Santa Vittoria d'Alba* and *Magliano Alfieri*, close to the *Tanaro* River valley floor. The thickness of the formation is variable, with an average value in the outcrops of some tens of metres. The sands and gravels, interpreted as fan-delta deposits, are characterized by a rather low permeability due to the presence of a fine matrix, while the fine-grained facies referred to brackish lagoon, lacustrine and swamp environments are completely impermeable.

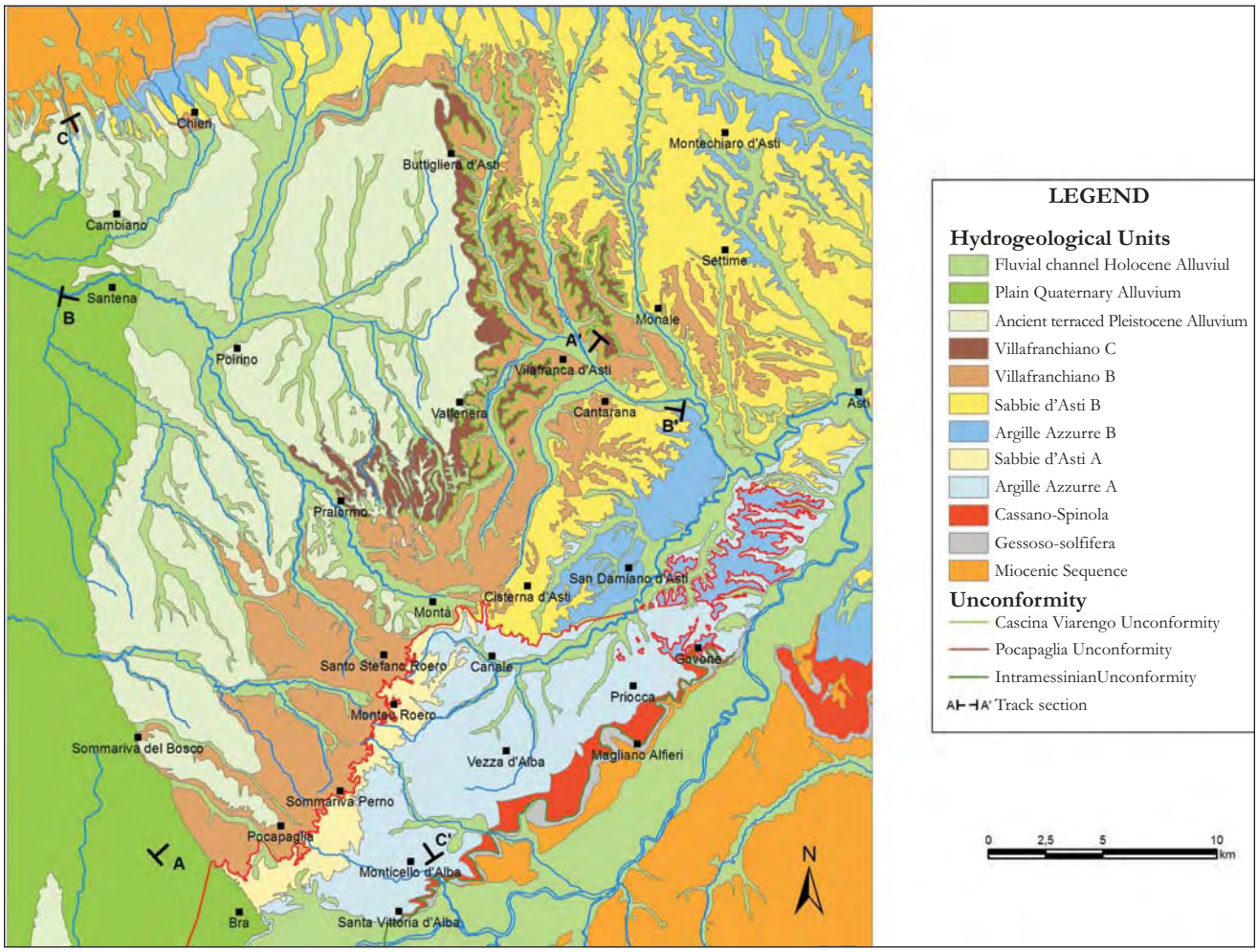

Fig. 3 – Hydrogeologic Units map.
– Carta delle Unità Idrogeologiche affioranti nell'area in esame.

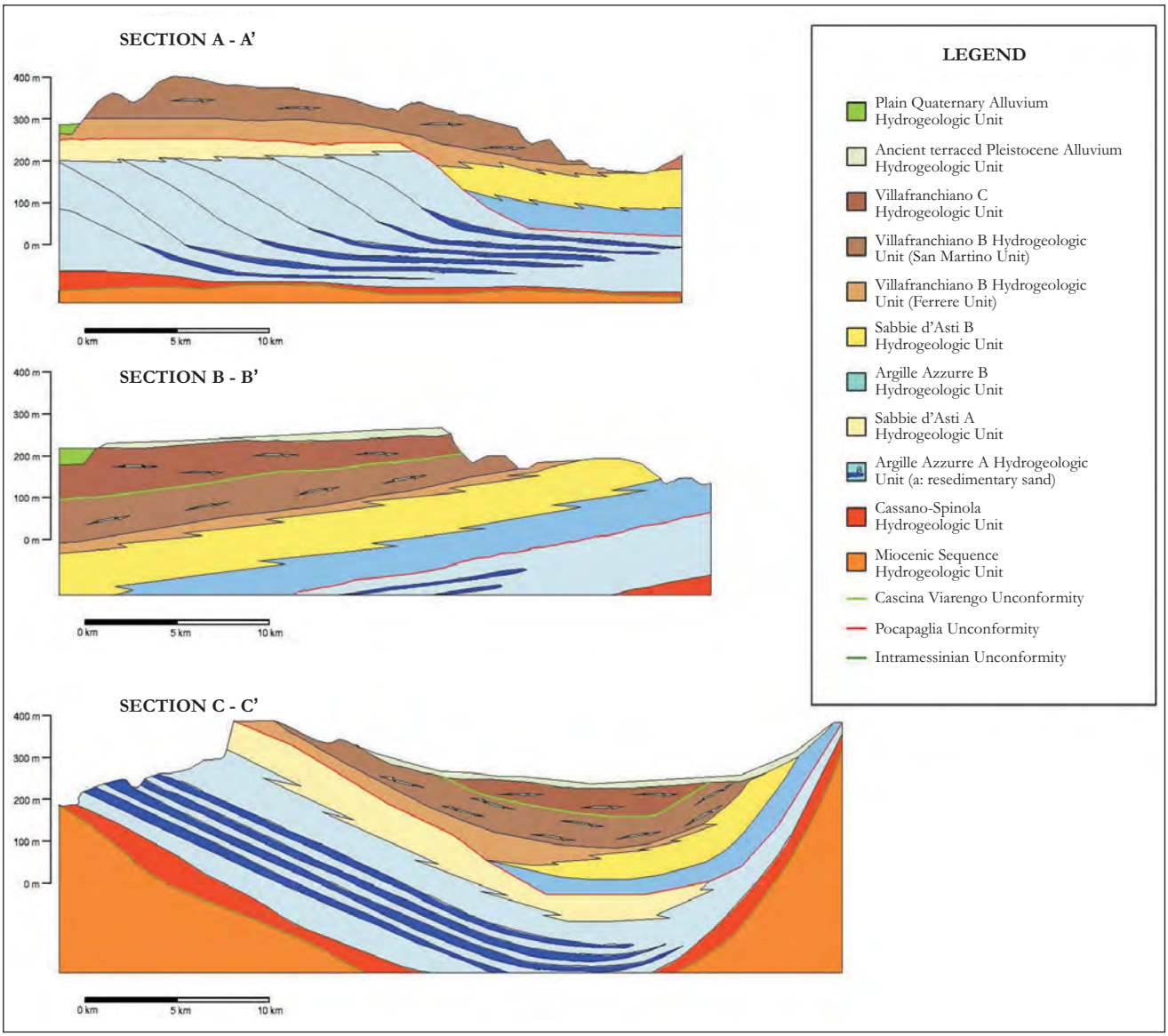

Fig. 4 – Hydrogeologic Units cross-sections. Location in figure 3.
– *Sezioni schematiche delle Unità Idrogeologiche. Ubicazione in figura 3.*

5.1.2. - *Argille Azzurre A Hydrogeologic Unit*

The *Argille Azzurre A* Hydrogeologic Unit is represented by a thick succession of alternating clay and fine- to medium-grained sand of the *Argille Azzurre A* informal unit which outcrops between the villages of *Santa Vittoria d'Alba-Pollenzo* and the towns of *Canale* and *Priocca*. The sand bodies, with individual thickness between 5 and 30 m, are mostly represented by packages of amalgamated medium to thick sand beds (fig. 5). From the *Borbore* Stream to the northeast, the examined unit, masked by the overlying *Argille Azzurre B* deposits, is not exposed. The sand bodies, that reach their maximum thickness in the sector between *Monticello d'Alba* and *Vezza d'Alba*, gradually thin and shale out in a northeast direction towards the city of *Asti*, where the succession is represented by clays with intercalations of thin-bedded very fine-grained sands. The thickness of the entire hydrogeologic unit ranges between 300 m, in correspondence to the eastern margin of the basin, and some tens of metres in the Turin Hill sector.

The permeability of the sands, that depends on the grain-size (ranging predominantly between fine- and medium-grained sand), the compaction (generally elevated) and the presence of silt matrix, usually shows quite low values. A series of hydraulic jump tests carried out in wells of the area has supplied transmissivity values of between 10^{-5} and 10^{-6} m/s, and hydraulic conductivity values, obtained using the QSPEC calculation code (Civita, 2005), of between 10^{-4} and 10^{-5} m/s. The

Fig. 5 – Argille Azzurre A Hydrogeologic Unit: grey -blue silty clays alternating with yellowish sand bodies.
– Unità Idrogeologica delle Argille Azzurre A: alternanze di argille siltose grigio-blu e bancate di sabbie giallastre.

clay intercalations and two thicker clay layers at the top and bottom of the unit are completely impermeable and play an aquiclude role, separating the different sandy aquifer layers.

5.1.3. - *Sabbie d'Asti A Hydrogeologic Unit*

This hydrogeologic unit outcrops between the towns of *Pocapaglia* and *Montà*, along the Eastern Escarpment of the *Poirino* Plteau, locally known as the *"Rocche di Pocapaglia"*. In the staudy area, the succession consist of prevailing yellowish bioturbate fine-grained sand and clayey silt (fig. 6), interpreted as outer shelf deposits and characterised by a very low permeability. The thickness of the sequence ranges between 60 and 100 m. In the area of main plain close to the town of *Bra*, the unit, which underlies a thin sequence of quaternary alluvium, seems to be made up of coarser-grained and relatively permeable sand.

This unit therefore takes on the role of acquitard in the *Roero* area and controls the water flow trend of the main aquifer system which is located in the overlying aquifer layers of the Villafranchiano B and *Sabbie d'Asti B* Hydrogeologic Units.

5.1.4. - *Argille Azzurre B Hydrogeologic Unit*

In the study area this hydrogeologic unit is made up of a monotonous succession of clay and silty clay belonging to the informal *Argille Azzurre B* informal unit. These deposits, interpreted as outer shelf, slope and basin deposits, are characterised by a nil permeability, with the exception of thin-bedded, fine-grained sand layers, that can host aquifers. The unit outcrops in the eastern sector between *San Damiano d'Asti* and the town of *Asti*, by the side of the valleys of the main streams of Asti area (*Borbore* Valley) and on the southern flank of the Turin Hill. The thickness of the sequence is of the order of some hundreds of meter. The hydrogeologic unit, which assumes the role of an aquiclude, influences in the central-eastern sector the circulation of the main aquifer system located in the Villafranchiano B – *Sabbie d'Asti* B hydrogeologic units.

5.1.5. - *Sabbie d'Asti B Hydrogeological Unit*

The *Sabbie d'Asti B* outcrop in the entire sector in the *Asti* hills, between the villages of *Cisterna d'Asti* on the south, the town of *Asti*, the village of *Montechiaro d'Asti* on the north and on the sides

Fig. 6 – Sabbie d'Asti A Hydrogeologic Unit: burrowed fine-grained sands and silts.
– *Unità Idrogeologica delle Sabbie d'Asti A: sabbie fini e silt bioturbati.*

of the reliefs of the Turin Hill. The unit is made up of yellowish, medium to coarse-grained sand intercalated with silt. The sand is locally cemented and is characterized by the presence of layers with high concentrations of macrofossils. The *Sabbie d'Asti B* sequence reaches a thickness of less than 100 m (fig. 7). These sediments were deposited by the catastrophic floods of the Villafranchiano fluvio-deltaic system in a shelf environment. The permeability of the different sandy layers results to be somewhat variable and ranges from relatively high values, for the coarser-grained sand (deposited by high-energy and large-volume floods), to lower values for the finer-grained sand (deposited by relatively low-energy and small-volume floods) with hydraulic conductivity between 10^{-4} and 10^{-6} m/s.

5.1.6. - *Villafranchiano B Hydrogeologic Unit*

The succession of this unit is represented by relatively coarse sediments. It consists, in the lower part, of gravel and medium-grained sand of the *Ferrere* Unit (Carraro, 1996) interpreted as mouth-bar deposits (*Pocapaglia – Montà* area) and tide-dominated delta-front deposits (*Cantarana* area), and in the upper part, of delta-plain fine-grained sand and gravel (fig. 8) intercalated with lacustrine clay of the *San Martino* Unit. The thickness of the unit ranges between some tens of metres, in the examined area, and up to more than 300 m in the buried basin depocenter (area between the villages of *Sommariva del Bosco* and *Poirino*). The succession outcrops from the hills close to the town of *Bra* as far as the Villafranchiano type-area (*Villafranca d'Asti*, *Cantarana*). The permeability of the hydrogeologic unit is variable: it is quite high for the coarser and well-sorted mouth-bar deposits (hydraulic conductivity between 10^{-3} and 10^{-4} m/s), decreases for the delta plain sand and gets nil for the fluvio-lacustrine clay.

5.1.7. - *Villafranchiano C Hydrogeologic Unit*

The unit is made up of alternating lacustrine clay, prevalently, intercalated with fluvial thick-bedded

Fig. 7 – Sabbie d'Asti B Hydrogeologic Unit: medium- and coarse-grained sands and silts.
– *Unità Idrogeologica delle Sabbie d'Asti B: alternanze di sabbie medie e grossolane e silt.*

sand and gravel belonging to the Upper Villafranchiano sequence (*Cascina Gherba* and *Maretto* Units, CARRARO, 1996). These deposits only outcrop along the syncline axis of the *Asti* sub-basin and presents a reduced thicknesses of the order of some tens of metres. They are still present in the core of the same syncline in the *Poirino* Plateau sector, where they are overlain by a thin sequence of Quaternary alluvial sediments. The coarser layers show a relatively low permeability, because of the abundant fine matrix, while the thick sequence of clay and silt play the role of either aquitard or aquiclude.

5.1.8. - *Ancient terraced Pleistocene Alluvium Hydrogeologic Unit*

This unit, outcropping only in the *Poirino* Plateau, is represented by a thin sequence (about 10 m) of prevailing fine-grained deposits (i.e. fine-grained sand, silt and clay) intercalated with thin layers of gravel. The permeability of the sedimentary succession is somewhat low because of the presence of an abundant fine matrix. A thick clayey-silt horizon, produced by Pleistocene weathering processes, overlies the whole plateau sector.

5.1.9. - *Fluvial channel Holocene Alluvium Hydrogeologic Unit*

The unit is prevalently made up of fine sediments (fine-grained sand and silt). It outcrops along the incised valleys of the numerous secondary water flows that drain the *Poirino* Plateau (belonging to the hydrographical networks of the *Banna* and *Melletta* streams) and the *Asti* hills (belonging to the hydrographical networks of the *Traversola*, *Triversa*, *Cortazzone, Val Andona, Stanavasso, Maggiore, Borbore* and *Versa* streams). The deposits are only some metres thick and their permeability is low.

5.2. - AQUIFER SYSTEMS

On the basis of the permeability of the main sedimentary facies forming the hydrogeologic

Fig. 8 – Villafranchiano B Hydrogeologic Unit: sands and gravels interpreted as tide-dominated delta-front deposits (Ferrere Unit).
– Unità idrogeologica del Villafranchiano B: sabbie e ghiaie e di fronte deltizio dominato dalle maree (Unità di Ferrere).

units, and of their geometric relationships, it has been possible recognize the presence of different of aquifer systems in the Pliocene-Pleistocene succession of the study area. These aquifer systems, that can involve one or a part of a hydrogeologic unit, or a complex of two or more of them, are characterised by a piezometric network, a recharge area and specific hydrogeochemical characteristics (fig. 9). They are interested by numerous wells used for drinking water, irrigation and industrial uses.

5.2.1. - *Villafranchiano B – Sabbie d'Asti B aquifer system*

This aquifer system is located in the lower part of the Villafranchiano B Hydrogeologic Unit (*Ferrere* Unit) and in the coarser layers of *Sabbie d'Asti B* whose facies are heteropic. The deep water circulation of the aquifer is strongly influenced by a syncline, with a east-west axes that gently dips towards the west, involves the whole Pliocene-Pleistocene succession. In the south-eastern sector of the area, corresponding to the escarpment of the *"Rocche di Pocapaglia"*, the direction of the water flow is controlled by the geometry of the unconformity that separates the EP and LM allogroups (fig. 9) with the basal Villafranchiano aquifer layers in contact with the silty sand of the *Sabbie d'Asti A* Hydrogeologic Unit (aquitard). The deep water circulation in the *Asti* area is controlled by the heteropy contact between the *Sabbie d'Asti B* Hydrogeologic Unit and the time-equivalent *Argille Azzurre B* Hydrogeologic Unit which represents the main aquiclude. The aquifer system is present in almost the whole study area, starting from the *Poirino* Plateau and *Bra* hills, where it is intercepted by deep wells at a depth of more than 250 m. In this sector the aquifer is in pressure and is bordered by thick clayey layers of the middle-upper part of Villafranchiano succession (lacustrine and swamp deposits of the *San Martino*, *Gherba* and *Maretto* Units), with risings of some tens of meter. In the valley bottoms of the *Asti* hills sector, the aquifer system is reached by shallower drillings (between

40 and 80 m) and show artesian conditions in correspondence to the *Stavanasso*, *Traversola* and *Cortazzone* Valleys sectors. In the *Maggiore* Valley area, before the drilling (in 1933) of the numerous wells for human supply of the many municipalities in the area, a spring was present (*Cascina Bonoma* Spring) with a somewhat abundant discharge which was tapped to supply the town of *Asti* (SACCO, 1933).

This spring was located roughly in correspondence to the stratigraphic contact between the aquiferous layers of the basal Villafranchiano B Unit and the *Sabbie d'Asti B* Unit. The wells reach depths of 100 m and intercept several aquiferous layers in the *Sabbie d'Asti B* Unit, which were artesian in the past (up to 18 m above ground level) and now, in consequence of their over-exploitation, level out at about 40 m below the ground level. The aquifer system also extends in the *Asti* hills sector where is only located in the *Sabbie d'Asti B* Unit in consequence of the complete absence of the Villafranchiano deposits.

The deep water circulation was reconstructed through the measurement of the piezometric levels in more than 190 wells that exclusively involve the tested aquifer system. Other 200 wells can be found in the area which usually interconnect different aquifers of the Upper Villafranchiano succession. These wells were therefore excluded from the calculations relative to the reconstruction of the piezometric network.

The piezometric network of the deep aquifer system (fig. 10) was reconstructed starting from the sector of the Turin-*Cuneo* Plain between the towns of *Bra* and *Cambiano*, where a series of deep wells that reach the aquifer under examination was encountered. In the hilly zone between *Bra*, *Montà*

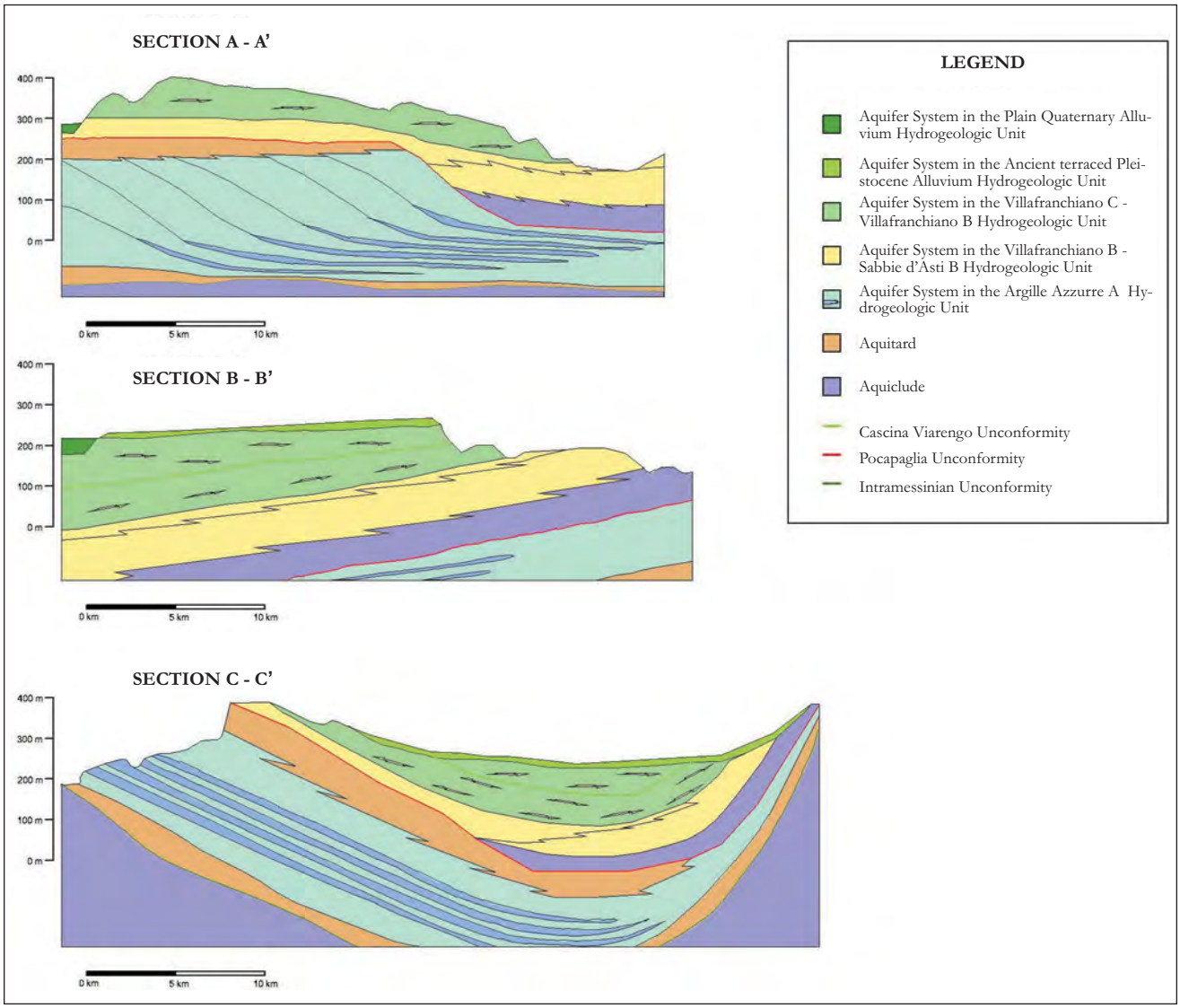

Fig. 9 – Major aquifer systems cross-sections. Location in figure 3.
– *Sezioni schematiche dei sistemi acquiferi maggiori. Ubicazione in figura 3.*

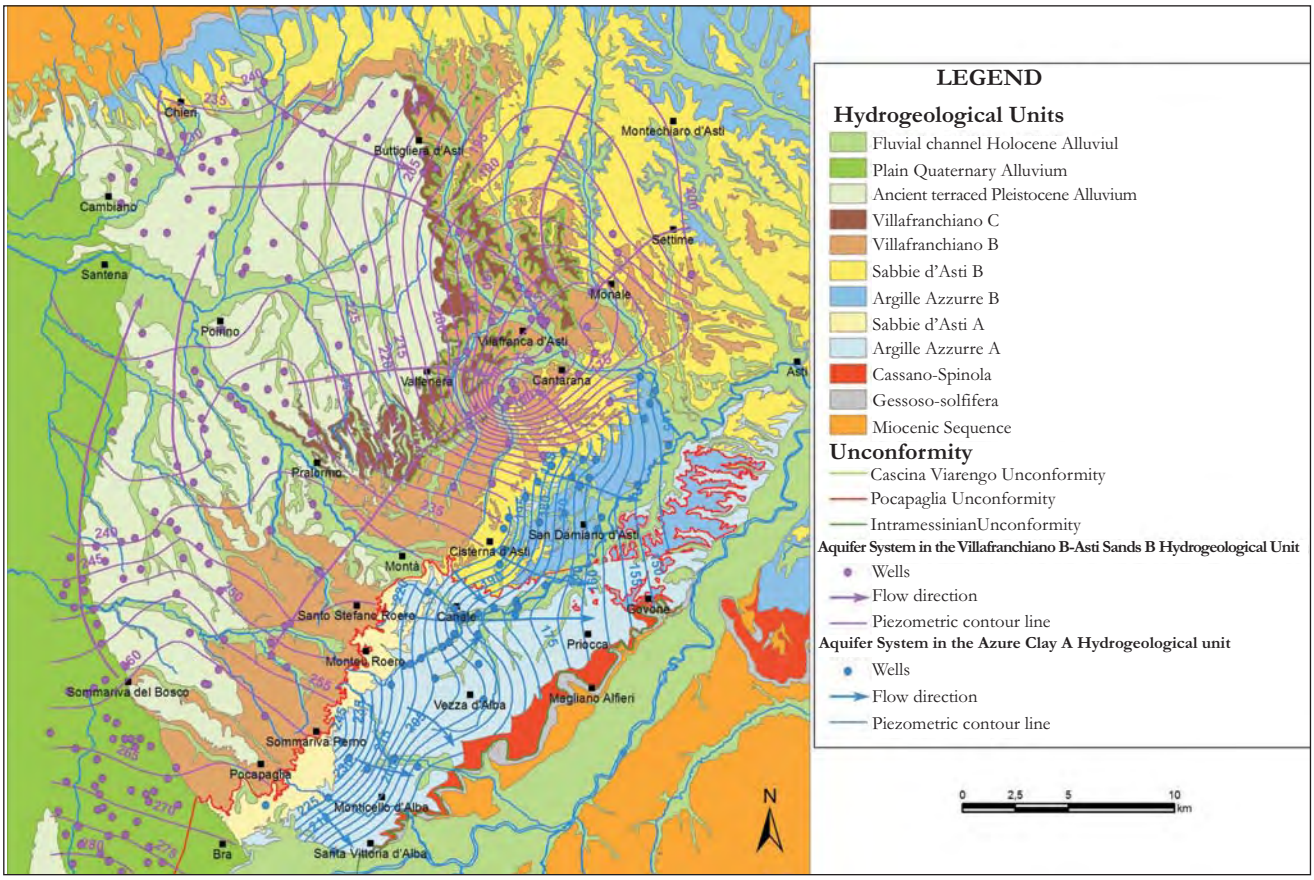

Fig. 10 – Piezometric networks of the main aquifer system in the Villafranchiano B Hydrogeologic Unit – Sabbie d'Asti B Hydrogeologic Unit and of the aquifer system in the Argille Azzurre A Hydrogeologic Unit.
– Piezometria del sistema acquifero principale delle Unità Idrogeologiche del Villafranchiano B – Sabbie d'Asti B e del sistema acquifero dell'Unità Idrogeologica delle Argille Azzurre A.

and *Pralormo*, the direction of the underground flow is towards northeast. As far as *Montà* the flow is conditioned by the contact between the Villafranchiano deposits and the underlying *Sabbie d'Asti A* sediments below, which play the role of aquitard. Instead, from *Montà* to the *Maggiore* Valley, the flow is conditioned to a great extent by the drawing action exerted by the *Maggiore* Valley well field, by the geometry of the unconformity between the LM and EP allogroups and by the local hydrostratigraphic layout.

In the area between the village of *Sommariva del Bosco* and the town of *Poirino*, the prevalent direction of the flow is roughly towards the north. In this area, there are two underground water divides that direct the flow towards the zone between the towns of *Santena* and *Cambiano* where there is a sector that is characterised by relatively homogeneous piezometric levels of between 226 and 228 m a.s.l. Towards the east, starting from the *Riva* village zone, an evident underground drainage axis can be identified, which directs the flow towards the *Traversola* and *Triversa* valleys, where there is a series of artesian wells, and then towards *Villafranca d'Asti*, where several wells are tapped for human supply.

On the basis of the available data at present, it results that this aquifer system is supplied in part by the zenithal recharge in the hilly area between *Bra* and *Montà*, where the Lower Villafranchiano deposits outcrop, and in part by the outflows from the extended Turin-*Cuneo* Plain unconfined aquifer, which is located in the Quaternary Alluvium deposits that rest unconformable on the Villafranchiano succession. The contribution from the hilly sector to the northeast between the villages of *Montechiaro d'Asti* and *Settime*, where the *Sabbie d'Asti B* sequence outcrops, is absolutely negligible. The aquifer system in the Villafranchiano B – *Sabbie d'Asti B* Hydrogeologic Units is the main source of underground water tapped for human supply by numerous waterworks organisations. In the *Roero* hills, well fields are located in the villages of *Pocapaglia*, *Sommariva Perno* and *Santo Stefano Roero*. These wells reach depths of more than 150 m with depth-to-water tables between 60 and 95 m. In the *Poirino* Plateau, the aquifer is exploited by the Municipalities of *Chieri*, *Cambiano*, *Buttigliera d'Asti*, *Santena* and *Poirino* with wells that reach to 300 m of depth with depth-to-water tables between 30 and 70 m. In the *Asti* zone, the aquifer is tapped at dif-

ferent points, in particular by the *Maggiore* Valley well field which supplies the Municipalities of *Asti, Ferrere, Cantarana, Valfenera, San Damiano d'Asti* and *Monale*. The examined aquifer system is also exploited by numerous irrigation and industrial use wells. Such an important water resource, intercepted by numerous artesian wells (*Triversa, Stavanasso* and *Traversola* Valleys), is often not utilised and left to flow towards the secondary water flows.

5.2.2. - *Argille Azzurre A aquifer system*

This aquifer system, which at present is not very important from a production point of view, was in the past the only underground water resource in the *Roero* area used for both human supply and irrigation purposes. The aquifer system, housed in the sandy layers of the *Argille Azzurre A* Hydrogeologic Unit, is confined and is generally artesian in correspondence to the valley bottoms. The discharges from the wells are at present very low also in consequence of the way they were built. These wells, which are known as *"calandre",* were constructed starting from the end of the nineteenth century through striking of small diameter pipes perforated for a length of 1 to 2 m at the point, or through a rotation method without the lining pipe system and filter. A maximum depth of over 200 m could be reached. The *calandre* were located close to the inhabited areas and were used to supply small communities and are still used today to supply the many fountains of those towns. The *Argille Azzurre A* Hydrogeologic Unit, which houses the aquifer system, outcrops in the hills between the villages of *Santa Vittoria d'Alba–Pollenzo* and *Canale-Govone*. The wells in this sector usually have depths of between 100 and 120 m and only exploit a few aquifer layers.

Moving towards north-northeast, the well drillings have to pass a thick clayey succession (*Argille Azzurre B*) before reaching the aquifer layers at a depth of between 160 and 240 m. The sandy layers are almost non existent under the town of *Asti*, due to the diminishing of both the grain-size and the thickness of these levels, where there is an absence of water resources.

The examined aquifer system seems to be located in different sand bodies aquifers separated from each other by thick clayey layers that assume the role of aquiclude.

Through a series of water level measurements carried out in the different wells, it was possible to reconstruct the piezometric network of the aquifer system, which showed a direction of the underground flow roughly from west to east (fig. 10), direction completely different from that encountered in the shallower main aquifer. The trend of the piezometric lines is rather regular and this shows the existence of a multi-layer that is probably supplied by leakage from the *Sabbie d'Asti A* whose facies are in heteropy with the *Argille Azzurre A* deposits. The *Sabbie d'Asti A* deposits, which outcrop in correspondence to the *"Rocche di Pocapaglia"* sector, consist of silty facies and play the role of aquitard, while at a greater depth, towards the depocenter of the basin, they are represented by coarser facies and are therefore waterlogged. The supply of this aquifer system therefore seems to be provided by a rather complex leakage mechanism: fresh water has been intercepted also in the AGIP petroleum exploration wells *Sommariva del Bosco 1*, in the south-western sector of the study area, in correspondence to aquiferous layers of the *Argille Azzurre A* levels at depths of more than 600 m. The displacement phenomenon of the original salty water with the fresh water coming from the sectors below the Turin-*Cuneo* Plain, connected to the remarkable hydraulic charge in this area (more than 270 m a.s.l.), compared to that found in the *Santa Vittoria d'Alba – Pollenzo* and *Canale – Govone* sector (from 190 to 150 m a.s.l.), and to the lateral and vertical continuity of the various water bodies, has played an important role.

5.2.3. - *Villafranchiano C - Villafranchiano B aquifer system*

A multi-level aquifer system under pressure can be found in the Villafranchiano C and in part of the Villafranchiano B (*San Martino* Unit) Hydrogeologic Units. This multi-level aquifer system is located in relatively permeable sandy-gravely horizons of modest thickness. The permeable layers are intercalated with fine-grained sediments, silty sand, sandy silt and clay, which act as an aquitard. It is intercepted by relatively deep wells, prevalently for irrigation or industrial use, in the *Poirino* Plateau which often interconnect the more permeable horizons encountered at different depths. It has a rather poor productivity and the water quality is heavily conditioned by the elevated concentrations of nitrates. The piezometric level has very similar heights to those encountered in the underlying principal aquifer (The aquifer system in the Villafranchiano B – *Sabbie d'Asti B* Hydrogeologic Units), which is directly in contact with the one under examination because of the lack of a laterally continuous seal.

In the available stratigraphic data, obtained from drillings, the sandy-silty-clayey lithologies are usually indicated as clay thus generating erroneous interpretations of the hydrostratigraphic situation. Only a few continuous coring geognostic surveys, carried out to depths of more than 200 m, pro-

vided useful indications on the true hydrogeologic characteristics of these deposits. The role of aquitard that has been assigned to the fine sandy-silty deposits highlights the complexity of the hydrogeologic framework of the tested aquifer system, which seems to be partially supplied by the vertical recharge from the Quaternary aquifer system above, and partially by the overflows from the unconfined aquifer system of the main Turin-*Cuneo* Plain. The wells that intercept the studied aquifer (usually for irrigation and industrial use) can reach depths of more than 100 m and often interconnect this system with that one located in the overlying Quaternary alluvial deposits. For this reason, it has not been possible to reconstruct the piezometric network or identify the main recharge areas. The elevated concentrations of nitrates encountered in the wells that intercept the aquifer system and the reduced productivity of the aquifer layers would seem to indicate a supply that prevalently comes from the sector above relative to the *Poirino* Plateau.

5.2.4. - *Ancient terraced Quaternary Alluvium aquifer system*

An aquifer system exists in the *Poirino* Plateau sector. This system is located mostly in the Ancient terraced Quaternary Alluvium Hydrogeologic Unit, in part in the upper layers of the Villafranchiano C Hydrogeologic Unit and in part in the Fluvial channel Holocene Alluvium Hydrogeologic Unit. The aquifer system, which is locally confined by a thick layer of clay and silt connected to important weathering processes during the Pleistocene, is intercepted by numerous shallow wells that reach depths of between 2 and 20 m used in the past for domestic and/or zootechnical use. They have a very low productivity, while the piezometric network indicates a flow direction that is strongly influenced by the morphology of the slopes and by the surface drainage network and which shows a predominant direction from east to west (fig. 11). This direction is therefore opposite that of the principal deep aquifer. The recharge of the aquifer system under examination is provided by local infiltration phenomena which heavily conditions the quality of the water with high nitrate concentrations.

5.2.5. - *Other aquifer systems*

Apart from those previously described, in the area under examination there are other aquifer systems of limited importance which are located in the shallower part of the previously described Pliocene Units and in correspondence to the thalwegs of the different rivers and streams that can be found in the *Asti* hills area. These aquifer systems are usually intercepted by very shallow wells for domestic use.

Deeper wells intercept an aquifer system under pressure located in the gravel and sand of the Upper Messinian *Cassano-Spinola* Hydrogeologic Unit and which is characterized by very reduced discharges.

6. - GEOCHEMISTRY

The data relative to the water of the deep aquifer systems and in particular those located in the Villafranchiano B – *Sabbie d'Asti B* Hydrogeologic Units and the *Argille Azzurre A* Hydrogeologic Unit are examined in this chapter.

Although a large quantity of chemical analyses was carried out on samples drawn from over 200 wells that intercept the more superficial aquifer systems, these data are here not described or commented on as they are characterised by remarkable human induced impact phenomena, as shown by the high nitrate contents. These wells often have elevated depths, but they also intercept and interconnect different aquifer systems. Thus the drawn samples cannot be considered representative. As the conditioning of most of the wells, in particular the location of the drains and of the plugged levels, was not known, only the chemical analyses enabled us to verify the mixing of the different waters and, when this occurred, to exclude these samples.

6.1. - Villafranchiano B – Sabbie d'Asti B hydrochemistry

The aquifer system located in the Villafranchiano B Hydrogeologic Unit and *Sabbie d'Asti B* Hydrogeologic Unit is intercepted by several wells and the sampling of the water was carried out in many of these together with the relative chemical analyses. Numerous wells, even though reaching remarkable depths, intercept and interconnect the waters from the overlying aquifer systems (the Villafranchiano C Hydrogeologic Unit aquifer system and the Upper Terrace Quaternary Alluvium Hydrogeologic Unit) which are generally characterised by the presence of elevated nitrate contents. For this reason, 72 different analyses carried out in the same number of wells that only intercept the aquifer system under examination and which had a nitrate content of below 5 mg/l (that is, considered without signs of human induced impact) were considered for the geochemical characterisation.

The waters in the Villafranchiano aquifer system have a specific electric conductibility that varies be-

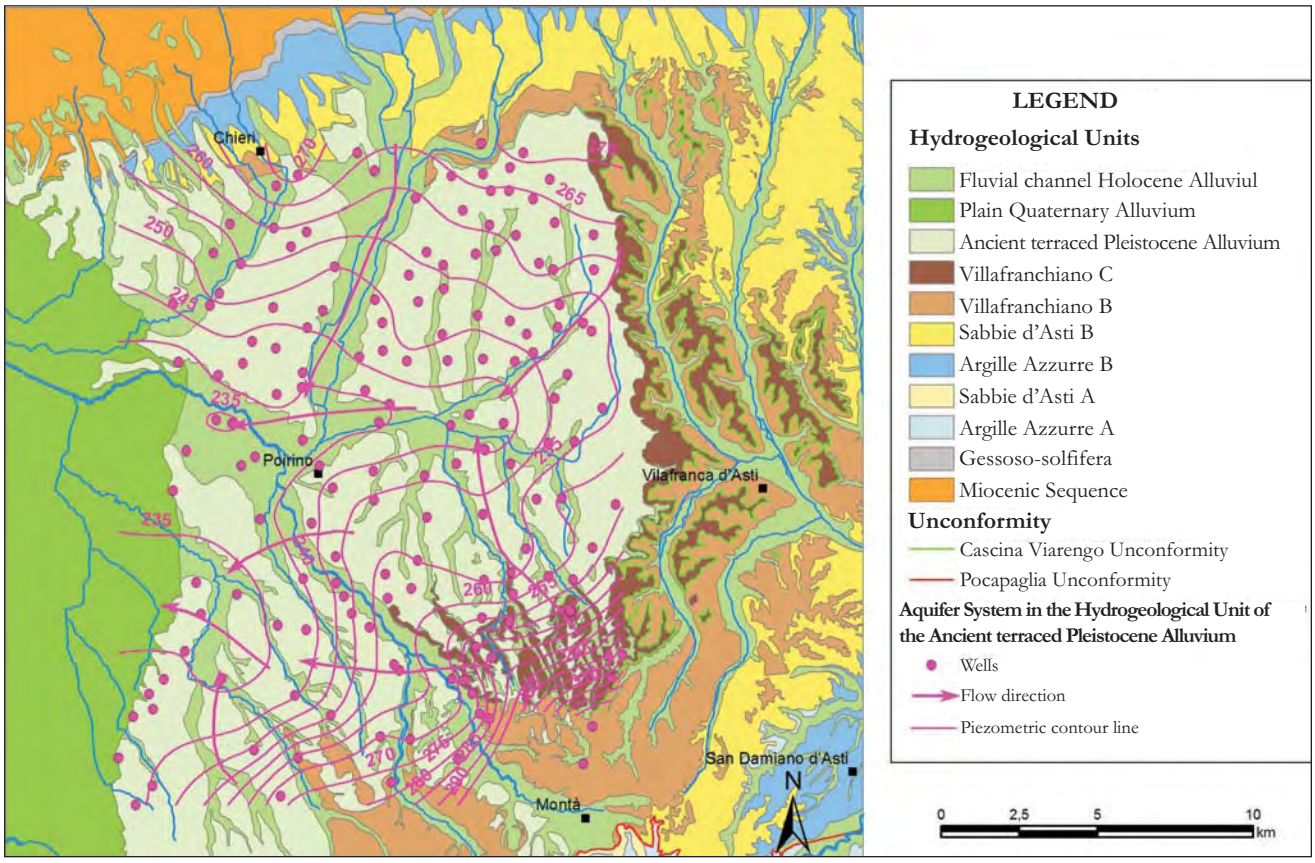

Fig. 11 – Piezometric network of the aquifer system in the Hydrogeologic Unit of the Ancient Terraced Pleistocene Alluvium.
– *Piezometria del sistema acquifero dell'Unità Idrogeologica dei Terrazzi Antichi Pleistocenici.*

tween 284 and 854 μS/cm with a mean value of 417 ± 104 μS/cm. These values make it possible to classify these waters as medium-mineral and are therefore, at least for this parameter, suitable for human consumption. The total hardness values, which fall between 13 and 53 French degrees with a mean value of 22 ± 6 French degrees, also underline a potentially utilizable underground water resource for human supply. Instead, either the iron or manganese values, and in some cases both, are higher than the maximum admissible concentrations for water destined for human consumption, according to the Italian laws currently in force.

Taking into consideration the fact that a sufficient number of data were available, a simple statistical analysis was performed for the principal ions (calcium, magnesium, sodium, bicarbonate, sulphate and chloride), in which not only the mean and standard deviation were evaluated, but also the most frequent values. For this purpose, a range obtained dividing each parameter into ten classes of equal extent was considered and then the percentage of cases that fell into each single class was assessed. The thus obtained frequency diagrams are shown in fig 12. The common factor of all the considered parameters is that more than 75% of the cases fall into three or four contiguous classes that are positioned towards lower values. The only exception is represented by the sodium which presents a typically Gaussian distribution, although with a maximum frequency which is not in the central position but moved slightly towards the lower values. Overall, the values indicate a generally poorly mineralised aquifer with limited cases of higher mineralisation, but always contained within values that can be considered not excessive, as shown by the overall range.

The type of water of all the samples is $Ca^{2+}>Mg^{2+}>(Na^{+} + K^{+}) - HCO_3^{-}>SO_4^{2-}>Cl$. More information can be obtained from some characteristic ratios calculated by expressing the ion concentrations in *meq/1*.

The Mg^{2+}/Ca^{2+} ratio varies from 0.151 to 0.796, thus showing a greater presence of the calcium ion than the magnesium ion. However, in 86% of the cases, this ratio is below 0.500; therefore the facies is generally of a calcium type and calcic-magnesium only to a lesser extent.

The $Mg^{2+}/(Na^{+} + K^{+})$ ratio is always in favour of the magnesium ion as the values are between 1.072 and 7.538. However, the values are not well distributed, considering that 83% of the cases fall

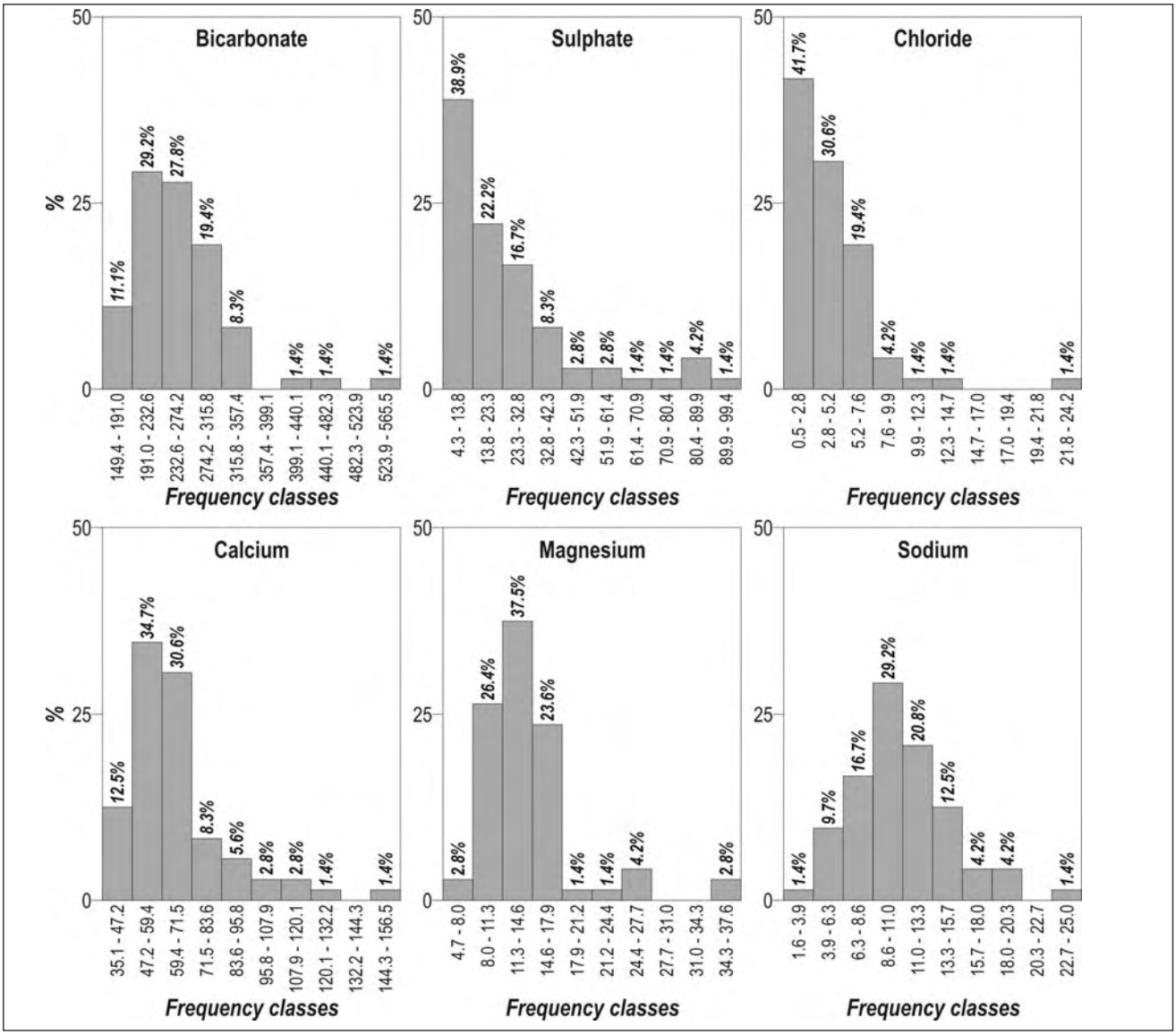

Fig. 12 – Frequency diagrams of the main parameters relative to water chemistry of the aquifer system in the Villafranchiano B Hydrogeologic Unit – Sabbie d'Asti B Hydrogeologic Unit (Values of each class expressed by mg/l).

– Diagrammi di frequenza dei principali parametri relativi alle acque del sistema acquifero delle Unità Idrogeologiche del Villafranchiano B – Sabbie d'Asti B (I valori delle singole classi sono espressi in mg/l).

into the first third of the range (1.072 – 3.227). This shows that the alkaline ions, in the cation component, are not generally negligible.

As far as the alkaline ions are concerned, the $Cl^-/(Na^+ + K^+)$ ratio, which varies between 0.019 and 1.267, is particularly interesting. This ratio is above the unit only in two points (V19 and V41) and below 0.500 in about 88% of the cases. The datum that emerges is that the alkaline ions dissolved in the waters in this aquifer system generally cannot be attributed to the presence of chlorides; therefore the alkaline value should be attributed to other factors such as ionic exchange phenomena or a relevant presence of alkaline feldspatos in the lithic component of the aquifer system.

The HCO_3^-/SO_4^{2-} ratio varies from 1.572 to 37.668 and is widely distributed as it has a mean value of 13.283 ±9.152. As far as the characteristic ratio is concerned, the spatial trend described by the isovalue lines is of particular interest (fig. 13). In fact it can be noted that the values are lower in the southern area of the aquifer and increase following the flow lines of the aquifer. The highest values are distribuited in correspondence to the principal drainage axis. The obtained data are plotted in a Durov diagram (figs. 14 and 15) where a substantial difference is not clearly shown. The individual points in the cation triangle are concentrated towards the calcium ion vertex, with the exception of four samples (V01, V02 V03 e V04) which are moved slightly towards the centre of the triangle, in consequence of a greater presence of magnesium and alkaline ions. In

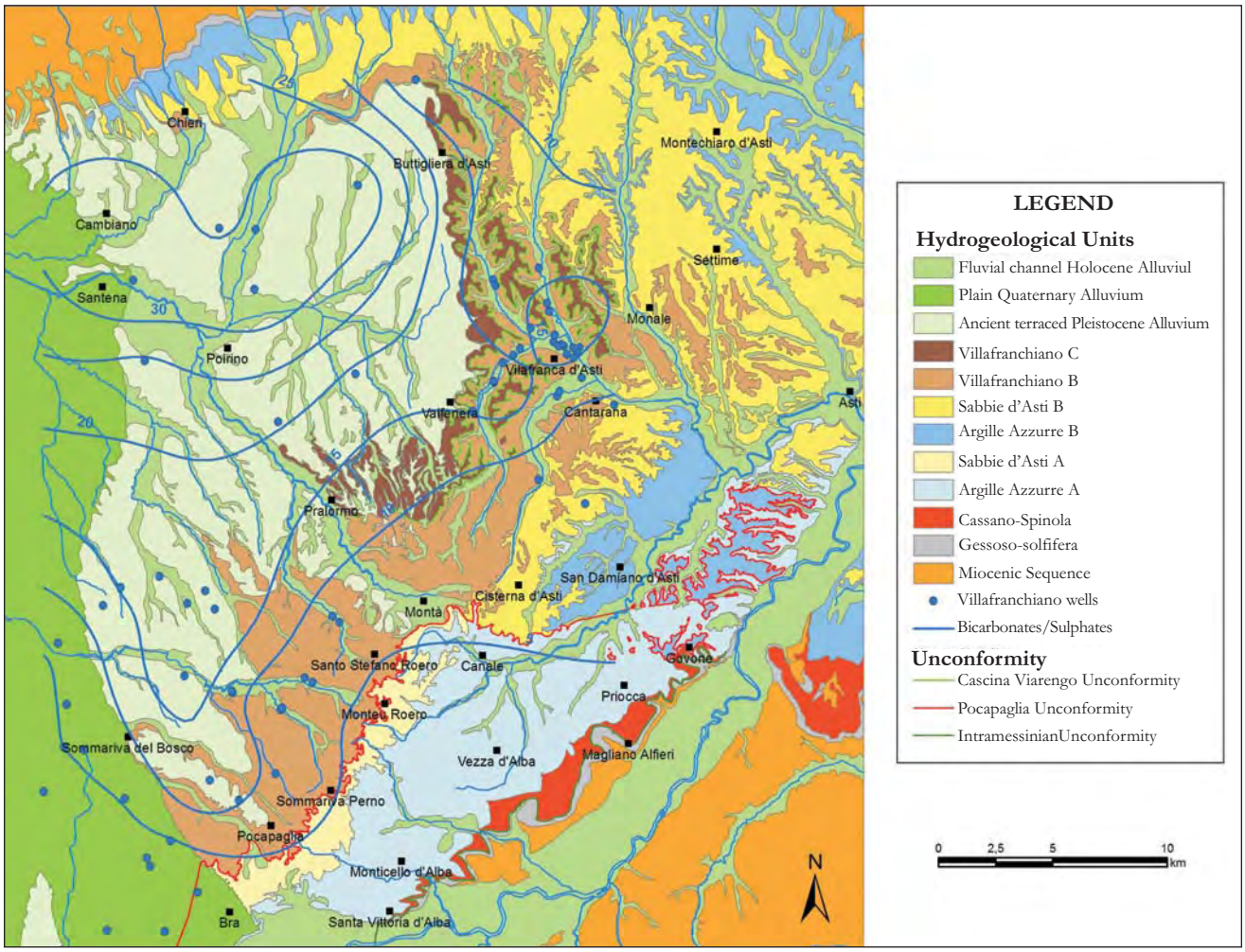

Fig. 13 – Isovalue lines of the HCO3-/SO42- ratio relative to the aquifer system in the Villafranchiano B Hydrogeologic Unit – Sabbie d'Asti B Hydrogeologic Unit. *– Carta degli isovalori del rapporto HCO3-/SO42- relativo al sistema acquifero delle Unità Idrogeologiche del Villafranchiano B – Sabbie d'Asti B.*

the anion triangle, the points are distributed along the bicarbonate-sulphate side, because of the low values of the chloride ions found in all the samples. The points are concentrated towards the vertex of the bicarbonate, with the exception of four samples located in the southern part of the aquifer (V49, V62, V63 and V68) which are moved more towards the sulphates.

6.2. - Argille Azzurre A hydrochemistry

In order to geochemically characterise the aquifer system located in the *Argille Azzurre A* Hydrogeologic Unit, chemical analyses were carried out on 29 samples drawn from the same number of wells that only intercept the studied aquifer system. In consequence of the limited number of samples, a statistical analysis was not carried out.

The obtained data describe a very complex geochemical situation. Six different types of water were encountered:
Type 1 $Ca^{2+}>Mg^{2+}>(Na^{+} + K^{+}) - HCO_3^{-}>SO_4^{2-}>Cl$ (14 samples);
Type 2 $Mg^{2+}>Ca^{2+}>(Na^{+} + K^{+}) - HCO_3^{-}>SO_4^{2-}>Cl$ (3 samples);
Type 3 $(Na^{+} + K^{+})>Ca^{2+}>Mg^{2+} - HCO_3^{-}>SO_4^{2-}>Cl$ (2 samples);
Type 4 $(Na^{+} + K^{+})>Mg^{2+}>Ca^{2+} - HCO_3^{-}>SO_4^{2-}>Cl$ (5 samples);
Type 5 $(Na^{+} + K^{+})>Ca^{2+}>Mg^{2+} - HCO_3^{-}>Cl>SO_4^{2-}$ (2 samples);
Type 6 $(Na^{+} + K^{+})>Mg^{2+}>Ca^{2+} - Cl>HCO_3^{-}>SO_4^{2-}$ (3 samples).

The six types of water that were encountered can be grouped together into three basic hydrogeochemical facies: a bicarbonate calcic facies to which types 1 and 2 belong, a bicarbonate-alkaline facies to which types 3, 4 and 5 belong and a chlorine-alkaline facies to which type 6 belongs.

The obtained data, which are reported in the Durov diagram (fig. 16), clearly shows the presence of the six types of water and the three facies. In the diagram it is also possible to note that intermediate facies exist between the bicarbonate-cal-

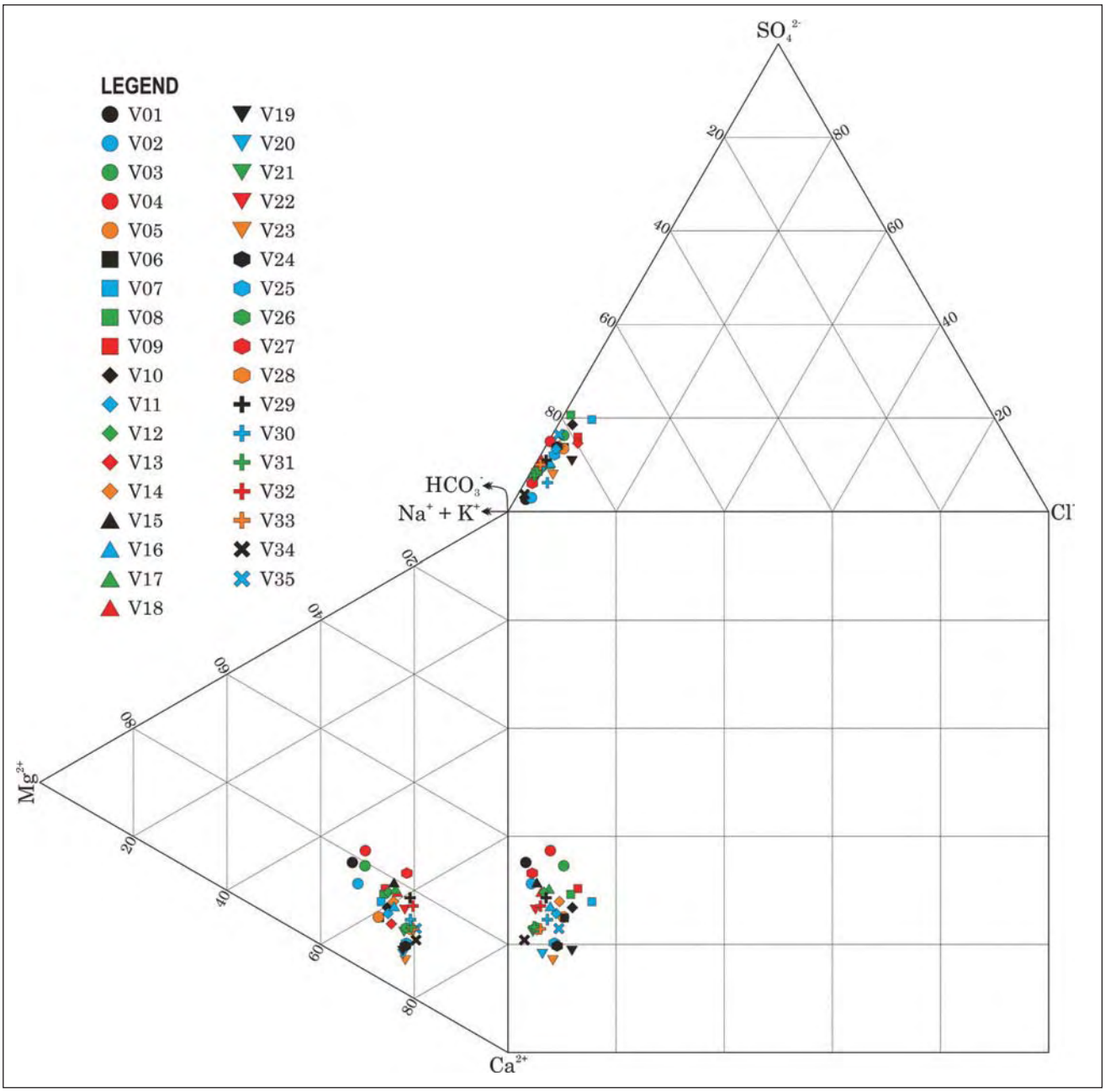

Fig. 14 – Durov diagram of groundwater chemistry in aquifer system of Villafranchiano B Hydrogeologic Unit – Sabbie d'Asti B Hydrogeologic Unit (samples from V01 to V35).

- Diagramma di Durov delle acque del sistema acquifero delle Unità Idrogeologiche del Villafranchiano B – Sabbie d'Asti B (campioni V01 – V35).

cic facies and the bicarbonate-alkaline facies, due to the variation in the main characteristic ratios.

The deep marine sand bodies alternated with thick layers of silty clay that characterise the studied aquifer system must originally have been saturated by marine water (chloride-sodium). After the remarkable deformation of the *Argille Azzurre A* succession during the Pliocene, a water flow was activated that progressively substituted the marine water with fresh water from the aquifer system recharge areas. As many of these sand bodies are laterally and vertically sealed by clay, the marine water could not have been washed away completely and some remained trapped within them. The marine water began to be progressively substituted by fresh water only when the sand bodies saturated by marine water were intercepted by the drilling and they were triggered into circulation, even though with slow flow. Documents are available which demonstrate that this salt water was used to make bread during de II World War, when it was particularly difficult to find normal salt. The different chemical facies encountered in the various samples might be therefore connected to the mixing phe-

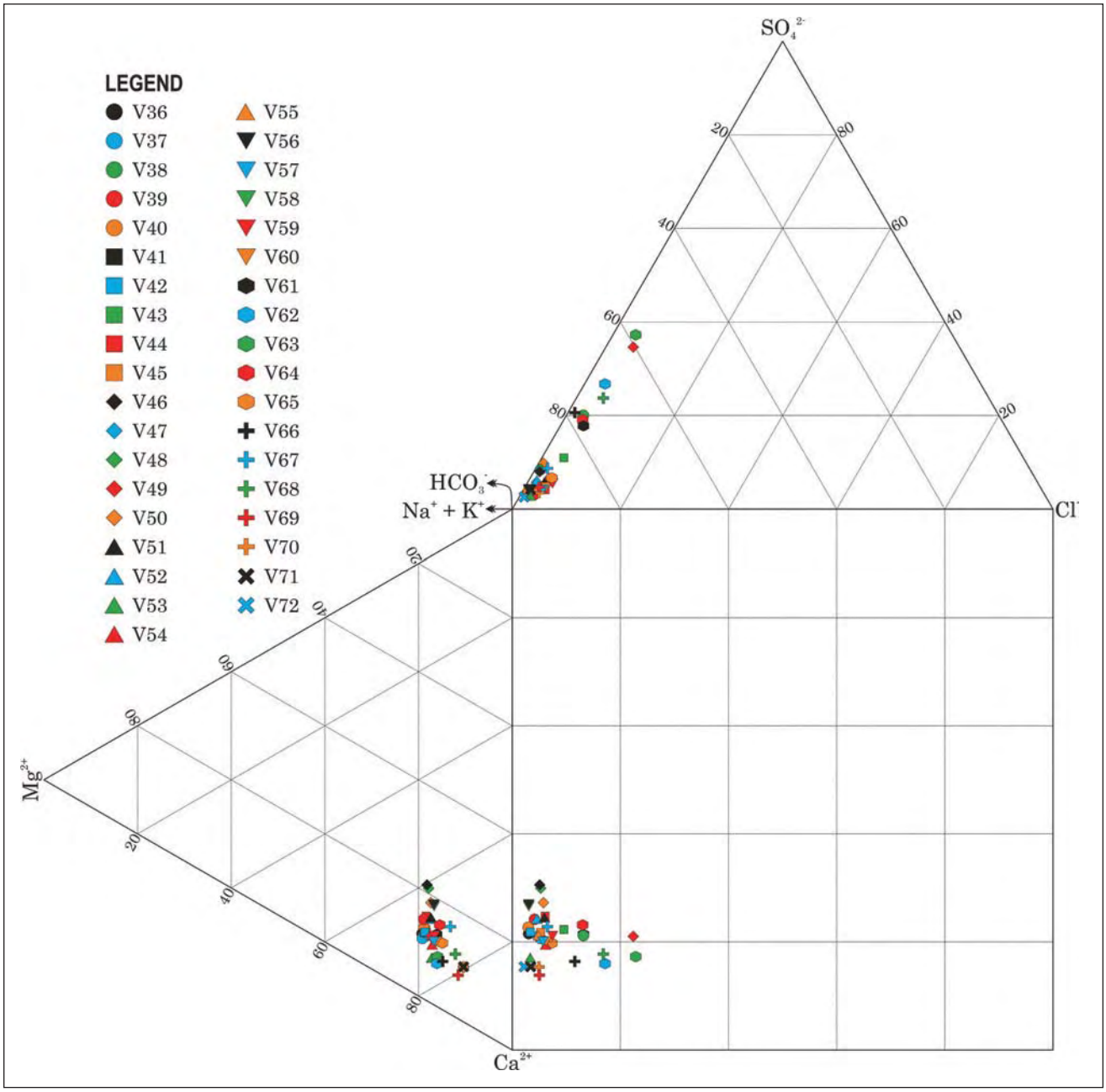

Fig. 15 – Durov diagram of groundwater chemistry in aquifer system of Villafranchiano B Hydrogeologic Unit – Sabbie d'Asti B Hydrogeologic Unit (samples from V36 to V72).

- Diagramma di Durov delle acque del sistema acquifero delle Unità Idrogeologiche del Villafranchiano B – Sabbie d'Asti B (campioni V36 – V72).

nomena generated by the excavation of the wells which interconnect several aquifer levels with different types of water.

The displacement phenomenon is surely fundamental to justify the presence of the bicarbonate-calcic water, but not for the presence of bicarbonate-alkaline water. It is therefore necessary to consider the permanence times of the neo-infiltration water in the aquifer and the cationic exchange phenomena. It is possible that the bicarbonate-calcic water in these sediments progressively become bicarbonate-alkaline because of the presence of clayey deposits with which the cationic exchange processes occur. The cationic exchanges should have been favoured by the extremely slow velocity of the underground flow and by the consequent long permanence times.

The quality of the water extracted from the aquifer system for drinkable purposes is poor because of the high salt content and, above all, due to the abundant presence of iron, manganese and ammonium ions which are very often above the maximum admissible concentrations established by the Italian laws in force for drinkable water.

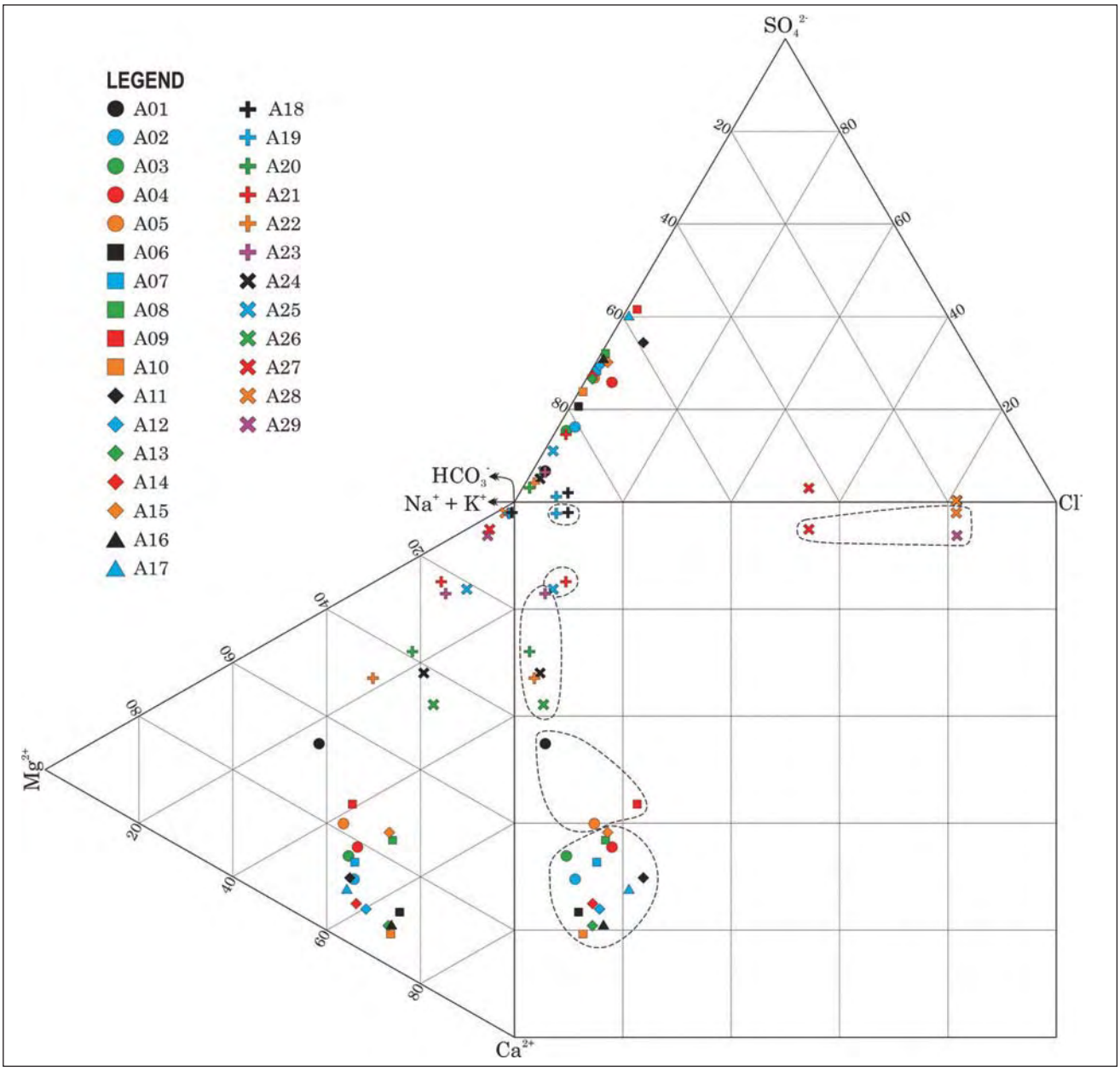

Fig. 16 – Durov diagram of groundwater chemistry in aquifer system of Argille Azzurre A Hydrogeologic Unit.
- Diagramma di Durov delle acque del sistema acquifero dell'Unità Idrogeologica delle Argille Azzurre A.

7. - CONCLUSIONS

The geological model of the upper Messinian to Pleistocene succession is based on a set of informal stratigraphic units corresponding to hydrogeologic units that have been associated to their constituent hydrofacies. The hydrogeologic units that have been recognized in the area are:

- *Cassano-Spinola*;
- *Argille Azzurre A*;
- *Sabbie d'Asti A*;
- *Argille Azzurre B*;
- *Sabbie d'Asti B*;
- Villafranchiano B;
- Villafranchiano C;
- Ancient terraced Pleistocene Alluvium;
- Fluvial channel Holocene Alluvium.

The aquifer systems have been identified by the hydrogeologic correlations of many wells, the analysis of deep subsurface data (ENI deep wells and seismic sections), in situ surveys and the analysis of the water levels measured in numerous wells in the area. On the basis of this large data-base, it has been possible to reconstruct the piezometric network of the major aquifer systems and to define their hydrogeochemical cha-racteristics.

The main aquifer system, which is widely exploited by numerous wells for drinkable water and

irrigation use, is located in the Villafranchiano B Hydrogeologic Unit and the *Sabbie d'Asti B* Hydrogeologic Unit, units which are in hydraulic communication. The main aquifer system is bounded on the top by another aquifer system mainly located in the Villafranchiano C Hydrogeologic Unit and made up of a set of aquifers and aquitards. The hydrodynamic data did not allow a clear distinction between the two superimposed aquifer systems. A distinction between the wells that only intercept the first aquifer system from those that interconnect the two systems has been possible thanks to chemical analysis of groundwater (in particular of the nitrate contents). In fact the waters in the main aquifer system show a rather homogeneous hydrochemical facies, regardless of which hydrogeologic unit is locally intercepted.

A second aquifer system, of local importance, is located in a series of aquiferous horizons separated by thick aquicludes but characterised by a single piezometric network, that have been included into the *Argille Azzurre A* Hydrogeologic Unit. The chemical analyses carried out on the waters sampled in the different horizons have shown the presence of different hydrogeochemical facies. The chlorine-alkaline hydrogeochemical facies are connected to the partial and local displacement of ancient saltwater of marine origin by the flow of the present-day water circulation; the bicarbonate-alkaline ones are due to long permanence times of the neo-infiltration water in the aquifer where it has undergone cationic exchange phenomena, while bicarbonate-calcic and calcic-magnesium facies are typical of the main water flow.

From the results here presented, it is possible to deduce that multi-disciplinary studies, such as those described in this paper, are important to clearly understand water circulation modalities in deep aquifers characterised by a remarkable geological-structural complexity.

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