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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)

VIGNA B. (*), FIORUCCI A. (*), GHIELMI M. (**)

ABSTRACT - The study concerns the hydrogeologic setting of a vast portion of land, of about 1000 km², 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-
Sul piano Geologico, l’assetto stratigrafico di quest’area, relativo alla successione plio-pleistocenica, è stato definito 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 datazione radiometrica, per un’accurata ricostruzione dello scenario strutturale e stratigrafico del settore. Sulla base della geometria dei livelli acquifere, se possibile con la stessa nomenclatura utilizzata per le unità stratigrafiche, sono state identificate una serie di sistemi acquiferi. Per una relativa omogeneità litologica e sono state assegnate numerose facies con facies bicarbonato-calcica, bicarbonato-calcica-magnesica, contenute di nitrati decisamente bassi e tenori di ferro e manganese sovra al limite di accettabilità per la normativa italiana vigente.

Un secondo sistema acquifero, ora di modesta importanza ma che in passato ha rappresentato l’unico 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 e in corrispondenza dei principali fondovali e in pressione nelle stazioni collinare. Il flusso sottostante presenta un andamento del tutto diverso rispetto al sistema acquifero principale con direzioni prevalenti verso ovest e una ricorrenza 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 il corpo sabbioso acquiferi con acque aventi facies chimiche molto diverse tra loro. La presenza di facies chloruro-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-magnesio-calcica. Si rinvergono, 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 ammionio, 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 rispetto alla vecchia sistemazione che separa l’Allogruppo EP dal sottostante Allogruppo LM e, in particolare, dalla facies “Scarpa Orientale” dell’altopiano di Poirino è generalmente artesiana. La chimica di queste acque è sostanzialmente uniforme con facies bicarbonato-calcica, bicarbonato-calcio-magnesica, contenute di nitrati decisamente bassi e tenori di ferro e manganese sovra al limite di accettabilità per la normativa italiana vigente.
1. - INTRODUCTION

The examined area covers a vast portion of the Piedmont territory (about 1000 km²) 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 Dosino) and 230 (near Sartena) m a.s.l. This area has a surface drainage network that collects the water from the Turin Hills, the Braidei 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 conductivity 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).

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 the 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 Mondovi. 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 transgressive 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).

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 massive 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 overlies 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 Viairengo 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 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 Lagugnaro 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 TPB (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 conductivity 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 allogsroups 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 Hydrogeologic 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.

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**Fig. 3 – Hydrogeologic Units map.**

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**LEGEND**

- Hydrogeological Units
  - Fluvial channel Holocene Alluvial
  - Plain Quaternary Alluvium
  - Ancient terraced Pleistocene Alluvium
  - Villafranchiano C
  - Villafranchiano B
  - Sabbie d’Asti B
  - Argille Azzurre B
  - Sabbie d’Asti A
  - Argille Azzurre A
  - Cassano-Spinola
  - Gessoso-solfifera
  - Miocene Sequence

- Unconformity
  - Cascina Viarengo Unconformity
  - Pocapaglia Unconformity
  - Intramessinian Unconformity

**A1–A6** Track section
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 Borbone 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. 

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**LEGEND**

- Plain Quaternary Alluvium Hydrogeologic Unit
- Ancient terraced Pleistocene Alluvium Hydrogeologic Unit
- Villafranchiano C Hydrogeologic Unit
- Villafranchiano B Hydrogeologic Unit (San Martino Unit)
- Villafranchiano R Hydrogeologic Unit (Ferrere Unit)
- Sabbie d’Asti B Hydrogeologic Unit
- Argille Azzurre B Hydrogeologic Unit
- Sabbie d’Asti A Hydrogeologic Unit
- Argille Azzurre A Hydrogeologic Unit (a: resedimentary sand)
- Cassano Spinola Hydrogeologic Unit
- Miocene Sequence Hydrogeologic Unit
- Cascina Viarengo Unconformity
- Pocapaglia Unconformity
- Intramesinian Unconformity
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 Plateau, locally known as the “Rocche di Pocapaglia”. In the study 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 aquitard in the Roero area and controls the water flow trend of the main aquifer system which is located in the underlying 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 Hydrogeologic 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
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 fluviodeltaic 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 fluviolacustrine clay.

5.1.7. - Villafranchiano C Hydrogeologic Unit

The unit is made up of alternating lacustrine clay, prevalently, intercalated with fluvial thick-bedded
sand and gravel belonging to the Upper Vil-
lafranchiano 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 rela-
tively 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 sedimen-
tary succession is somewhat low because of the
presence of an abundant fine matrix. A thick clayey-silt horizon, produced by Pleistocene weath-
ering processes, overlies the whole plateau sector.

5.1.9. - Fluvial channel Holocene Alluvium
Hydrogeologic Unit

The unit is prevalently made up of fine sedi-
ments (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 hydro-
graphical networks of the Traversola, Triversa, Cortaz-
ze, 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
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
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 Asti zone, the aquifer is tapped at dif-

![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.](image-url)
different points, in particular by the Maggiore Valley well field which supplies the Municipalities of Asti, Ferrera, 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, Stavanaso 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 consequence 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 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–Gorone*. 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 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 Popapaglia” 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–Cameo 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–Gorone* 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-Cameo 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 wents 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-
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 utilisable 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 $\text{Ca}^{2+} > \text{Mg}^{2+} > (\text{Na}^+ + \text{K}^+) > \text{HCO}_3^- > \text{SO}_4^{2-} > \text{Cl}^-$.

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$^{2+}/(\text{Na}^+ + \text{K}^+)$ 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...
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 HCO₃⁻/SO₄²⁻ 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 distributed 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


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-
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 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-
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.
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 characteristics.

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 characterized 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 chloride-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 geo-structural complexity.

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