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figg. 9

Hydrostratigraphy of the late Messinian-Quaternary basins in southern Piedmont (northwestern Italy)

Idrostratigrafia dei bacini messiniano-quaternari del Piemonte meridionale (Italia nord-occidentale)

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ABSTRACT - An integrated stratigraphic approach has been adopted to define the 3D hydrostratigraphic regional framework of the fresh-water aquifers of the Savigliano and Alessandria Basins, in southern Piedmont.
In the present work, the Aquifer Groups represents the "fundamental" hydrostratigraphic units, since they physically correspond to synthems, that have been recognized both in the subsurface and outcrops.

Each Aquifer Group is characterized by Hydrogeologic Units (HU) defined on the basis of lithofacies associations that display homogeneous hydrogeologic properties (e.g. permeability ratio, storage coefficient). Four main typologies of Hydrogeologic Units have been distinguished, on the basis of their hydrogeologic characteristics: HU I) unconfined aquifers, HU II) multi-layered "discontinuous" aquifers, HU III) multi-layered "continuous" aquifers, HU IV) aquitards/aquicludes.

It has been assumed in this work that, due to its peculiar stratigraphic architecture (i.e. internal stratal organization) each Aquifer Group has a distinctive response to the regional groundwater flow system. In this sense, each main type of Hydrogeologic Unit will present a peculiar and distinctive instance in each single Acquifer Goup. Consequently, the Aquifers Groups can be subdivided into lower rank hydrostratigraphic units, here defined as "Synthemic Hydrogeologic Units". These units, although encompassed in the four main typologies of Hydrogeologic Units, do inherit the peculiar architectural properties of the Aquifer Group they belong to. In this sense, each main type of Hydrogeologic Unit will present its own instance within the different Aquifer Groups. Following these criteria, nineteen Synthemic Hydrogeologic Units, grouped into seven Aquifer Groups were recognized within the Savigliano and Alessandria Basins.

The reconstruction of the hydrostratigraphic model allowed to portray, for the first time, the geometry and architecture of the Aquifer Groups of the whole upper Messinian-Quaternary successions in southern Piedmont and to reconstruct the regional distribution and characteristics of potentially exploitable aquifers.

Moreover, the use of stratigraphic constraints (i.e. distribution of depositional systems and lithofacies associations) led to the reconstruction of the geometry of the fresh-salt water interface, also in those areas with scarce well data, and to better estimate the maximum thickness of deep fresh-aquifers that, up to date, are still unexploited.

The hydrostratigraphic reconstruction here proposed constitutes a forward step with respect to the previous knowledge on Piedmont subsurface hydrogeology, and cast the bases for future development of water exploitation and water flow modeling.

KEY WORDS: Aquifer Groups, Fresh-salt water interface, Hydrogeologic Synthemic Units, Hydrostratigraphy, Messinian-Quaternary Piedmont Basins, Physical stratigraphy, Synthems.

RIASSUNTO - È stato utilizzato un approccio stratigrafico integrato per definire il quadro idrostratigrafico a scala regionale degli acquiferi permeati da acqua dolce dei Bacini di Savigliano ed Alessandria, nel Piemonte meridionale.

In questo lavoro, i Gruppi Acquiferi rappresentano le unità idrostratigrafiche "fondamentali", dal momento che essi corrispondono ai sintemi che sono stati riconosciuti sia nel sottosuolo che in affioramento.

Ogni Gruppo Acquifero è caratterizzato da Unità Idrogeologiche (HU), definite sulla base delle associazioni di litofacies, che mostrano proprietà idrogeologiche omogenee (per es. grado di permeabilità, coefficiente di immagazzinamento). Sulla base del loro ruolo idrogeologico sono state riconosciute quattro tipologie principali di Unità Idrogeo-

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giche: HU I) acquifero monostrato, HU II) acquifero multistrato "discontinuo", HU III) acquifero multistrato "continuo", HU IV) acquitardo/acquicludo.

Nel presente lavoro si è assunto che, a scala regionale, ogni Gruppo Acquifero mostri un comportamento distintivo in risposta al sistema di flusso sotterraneo, a causa della sua peculiare architettura stratigrafica (ovvero organizzazione stratale interna). Secondo tale assunto, ogni tipologia principale di Unità Idrogeologica presenterà caratteristiche uniche e contestuali all'interno di ogni singolo Gruppo Acquifero. Di conseguenza, i Gruppi Acquiferi possono essere suddivisi in unità idrostratigrafiche di rango inferiore, qui definite come "Unità Idrogeologiche di Sintema". Nonostante tali unità siano sempre inquadrabili all'interno di una delle tipologie principali di Unità Idrogeologiche sopra definite, esse ereditano le caratteristiche architetturali del Gruppo Acquifero di appartenenza. In tal senso, ogni tipologia principale di Unità Idrogeologica presenterà la sua particolare istanza all'interno dei diversi Gruppi Acquiferi.

Seguendo tali criteri, nei Bacini di Savigliano ed Alessandria sono state riconosciute diciannove "Unità Idrogeologiche di Sintema", raggruppate in sette Gruppi Acquiferi.

La ricostruzione del modello idrostratigrafico ha consentito di ritrarre, per la prima volta, la geometria e l'architettura interna dei Gruppi Acquiferi dell'intera successione di età messiniana superiore-quaternaria nel Piemonte meridionale e di ricostruire a scala regionale la distribuzione e le caratteristiche degli acquiferi potenzialmente sfruttabili.

Inoltre, l'utilizzo di vincoli stratigrafici (quali la distribuzione dei contesti deposizionali e delle associazioni di litofacies) ha permesso di ricostruire la geometria dell'interfaccia acqua dolce-salata, anche in quelle aree con dati di pozzo scarsi o mancanti, e di stimare quindi con maggior precisione lo spessore massimo di acquiferi profondi dolci, che finora non erano stati studiati e che tuttora non sono ancora sfruttati.

La ricostruzione idrostratigrafica proposta rappresenta un miglioramento delle precedenti conoscenze sull'idrogeologia del sottosuolo piemontese e getta le basi per lo sviluppo futuro di modelli di potenziale di sfruttamento e modelli di flusso.

PAROLE CHIAVE: Bacini messiniano-quaternari piemontesi, Gruppi Acquiferi, Idrostratigrafia, Interfaccia acqua dolce-salata, Sintemi, Stratigrafia fisica, Unità Idrogeologiche di Sintema.

1. - INTRODUCTION

The knowledge on Piedmont subsurface hydrogeologic systems mainly regards, up to date, only the uppermost portion of the Pliocene-Quaternary sedimentary pile, namely the first 200-300 m from the ground level. This knowledge essentially derives from hydrogeologic reconstructions, based on simple lithostratigraphic correlations of poor-quality well data, often reducing the reliability of the hydrogeologic models themselves.

Only few studies in Piedmont (BOTTINO *et alii*, 1994a; VIGNA, 1996) have described in detail the aquifer architecture of Pliocene-Quaternary deposits, through the application of a hydrostratigraphic approach, that considers the definition of the actual genetic relationships and geometries of sedimentary bodies as the essential step to elaborate reliable hydrogelogic and flow system models. Unfortunately, these studies have focused only on local scale.

Owing to the increasing demand of groundwater and the necessity of the Regional Administration (Regione Piemonte) to have a reliable tool for a comprehensive knowledge of all fresh-groundwater resources, a regional hydrostratigraphic study on fresh-water aquifers of the whole upper Messinian-Quaternary successions has been carried out in the southern sector of the Piedmont region. This study focuses on the two main fresh-water reservoirs in southern Piedmont, the Savigliano and Alessandria Basins, and enlarges the investigations up to those depths (namely ca. 1500-2000 m), that were still unexplored for fresh water research purposes.

The aims of this paper are:
- to present the integrated approach used to elaborate the hydrostratigraphic model;
- to illustrate the hydrostratigraphic framework of the Savigliano and Alessandria Basins, by describing the architectural elements of recognised Aquifer Groups;
-to estimate the maximum thickness of potentially exploitable aquifers, illustrating the distribution of the fresh-salt water interface.

2. - GEOLOGICAL SETTING

The investigated area is subdivided into three principal domains: the Savigliano Basin, the Alessandria Basin and the interposed Asti area. For the sake of simplicity, in the chapters focusing on stratigraphic and hydrostratigraphic architecture, they will be illustrated as a whole.

The Savigliano Basin shows a dominant N-S elongated shape and is laterally bounded by Alpine Basement units to the west and south, by the Tertiary Piedmont Basin (TPB) succession to the east, and by Torino Hill Tertiary sediments and relative western subsurface prolongation to the north.

The Alessandria Basin displays a prevalent ellipsoidal shape with a NW-SE striking major axis. It is bounded by TPB successions to the south and by the Monferrato successions and relative eastern subsurface prolongation to the north (fig. 1A).

In the Savigliano and Alessandria Basins the Messinian-Quaternary basin fill defines two regional synforms (PIERI & GROPPI, 1981; BELLO & FANTONI, 2002; MOSCA, 2006) and displays maximum thickness of 2000-2500 m in depocentral zones, that are roughly located in the central sectors of the basins (figg. 1B, 3). From the buried depocentral areas, the Messinian-Quaternary succession progressively thins toward its present-day borders. In the Asti area, placed between the Savigliano and Alessandria Basins, the Messinian-Quaternary succession displays reduced sediment thickness (ca. 800-1000 m) and depicts a gentle antiform.

On the western border of the Savigliano Basin, the thick pile of Messinian-Quaternary deposits is generally sub-horizontal and displays progressive onlap terminations onto older Oligocene-Miocene deposits or on the Alpine Basement, as already illustrated by previous reconstructions (e.g. PIERI & GROPPI, 1981); such a configuration clearly indicates that the western border of the Savigliano Basin represents a preserved original margin (figg. 1, 3). Toward the eastern border of Alessandria Basin, Messinian-Quaternary successions wedge onto older Oligocene-Miocene deposits or on Ligurian units of the Apennines (figg. 1, 3).

The Savigliano and Alessandria Basins developed onto an Oligo-Miocene tectonic belt at the junction between Alps and Apennine systems. The main tectonic structures of this belt have been active also during the Messinian, Pliocene and Pleistocene, controlling the sedimentary evolution of the studied basins and displacing them along major thrust or fault zones. These mainly consist in buried north-verging thrust systems and high-angle strike-slip faults (PIERI & GROPPI, 1981; GHIELMI *et alii*, 2002; MOSCA 2006).

In the Savigliano Basin, the major tectonic features are: (i) E-W striking thrust fronts developed along its southern border, (ii) the Saluzzo-Sommariva del Bosco faulted anticline ("SDB" in fig. 1A) located in the central sector and (iii) the western subsurface prolongation of Torino Hill-Monferrato thrust front, in the northern part.

In the Alessandria Basin, the major tectonic features correspond to complex NW-SE reverse faults and related structural highs, well developed in its north-eastern sector.

The Asti area corresponds to a fault-bounded structural high (hereafter indicated as Asti high; "AH" in figure 1A), placed in between the two basins (MOSCA, 2006).

In the following, the stratigraphic approach followed to delineate a 3D reconstruction of the hydrostratigraphic architecture of the Savigliano and Alessandria Basins is described.

3. - STRATIGRAPHIC ANALYSIS

Stratigraphic analysis has been carried out through the integration of subsurface and surface data. A grid of 17 seismic reflection lines (fig. 1C), partially published in MOSCA *et alii* (2009) and ROSSI *et alii* (2009), has been re-interpreted for a linear coverage of about 750 km. The seismic grid has been analyzed to ca. 2s TWT.

Ten stratigraphic logs of exploration wells (published in AGIP, 1972; AGIP, 1994), have provided a general calibration for seismic interpretation even if, due to the lack of informations on interval-velocities, time-depth conversion has been achieved by using average values of 1600-1800 m/s for Quaternary successions, 1800-2000 m/s for Pliocene successions and 2500-3500 m/s for Messinian successions.

Because of poor resolution of seismic data in the uppermost 100-200 m, the analysis of uppermost Quaternary deposits has been carried out through the stratigraphic correlations of about 6000 shallow wells, that have been made available by the Department of Earth Sciences–Torino University and Regione Piemonte.

Correlation between subsurface and surface geology has been based on local field observations performed along the southern border of the studied basins and integrated with new biostratigraphic analyses, as well as on a critical review of some sheets of the geological maps of Italy: F67 Pinerolo, F80 Cuneo, F56 Torino, F68 Carmagnola, F 57 Vercelli, F58 Mortara, F70 Alessandria, F69 Asti, F71 Voghera at 1:100.000 scale (SERVIZIO GEOLOGICO D'ITALIA, 1913, 1931, 1969a, 1969b, 1969c, 1969d; 1970a, 1970b, 1971) and at 1:50.000 scale, F157 Trino (SERVIZIO GEOLOGICO D'ITALIA, 2003).

In this study, seismic stratigraphic analysis has been used as fundamental tool to reconstruct a reliable 3D stratigraphic reference frame of basins fill and to better characterize the major tectonic structures.

Seismic profiles have been analysed on the basis of conventional seismo-stratigraphic criteria (MITCHUM *et alii*, 1977; BADLEY, 1987). The analysis of reflection terminations has allowed the identification of discontinuity surfaces of regional extent and the subdivision of basins fill into major synthems.

Interpretation of seismic facies has led to identification of major internal patterns and then to preliminary delineation of major depositional systems and lithofacies associations.

The calibration of seismic data with exploration well logs and outcrop features has allowed tracing of those discontinuity surfaces that are not clearly imaged in seismic profiles and defining the distributions of depositional systems and lithofacies associations.

The discontinuity surfaces and synthems have been dated according to the ages proposed by AGIP (1972; 1994) in the exploration wells, as well as those based on biostratigraphic analyses.

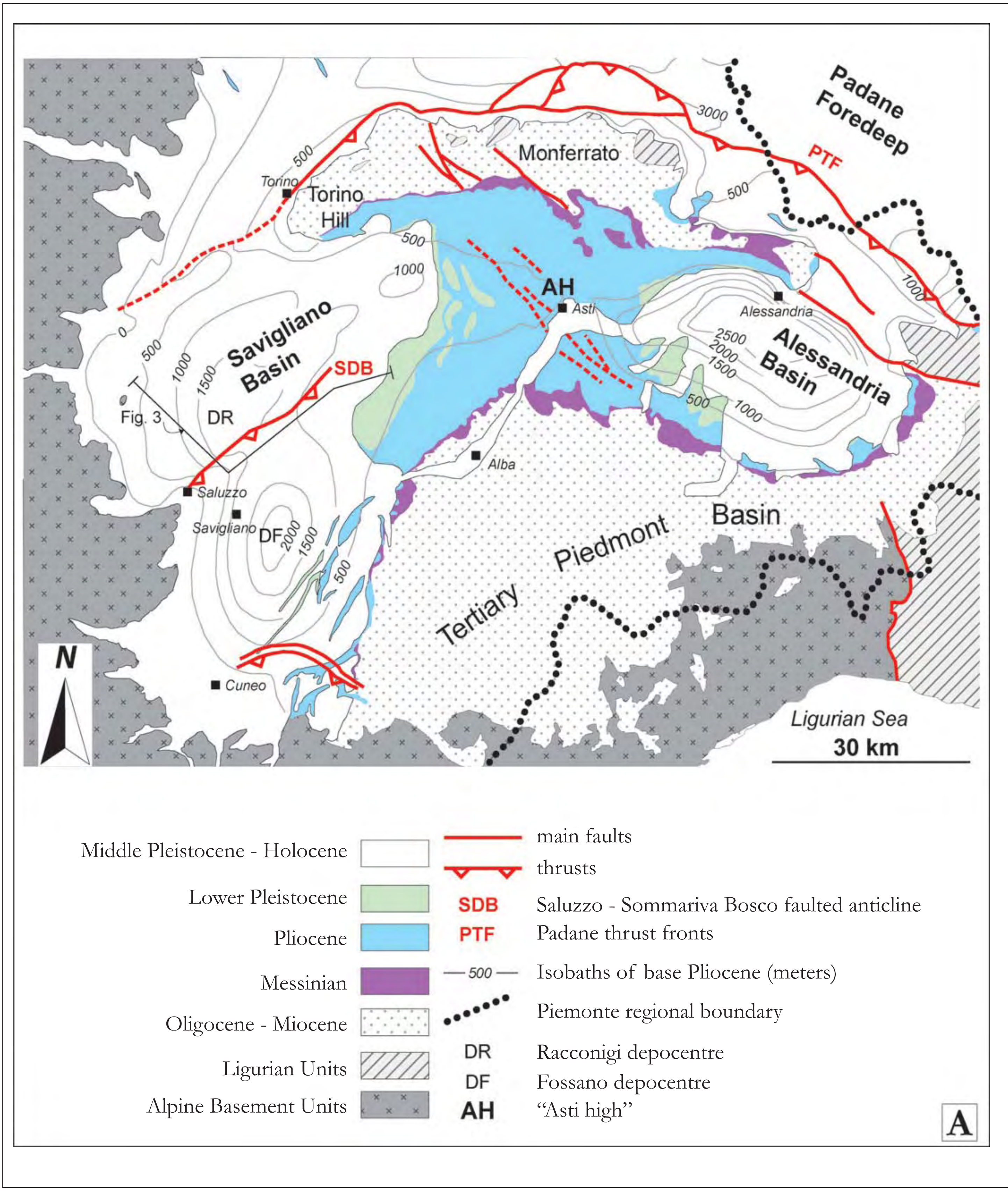
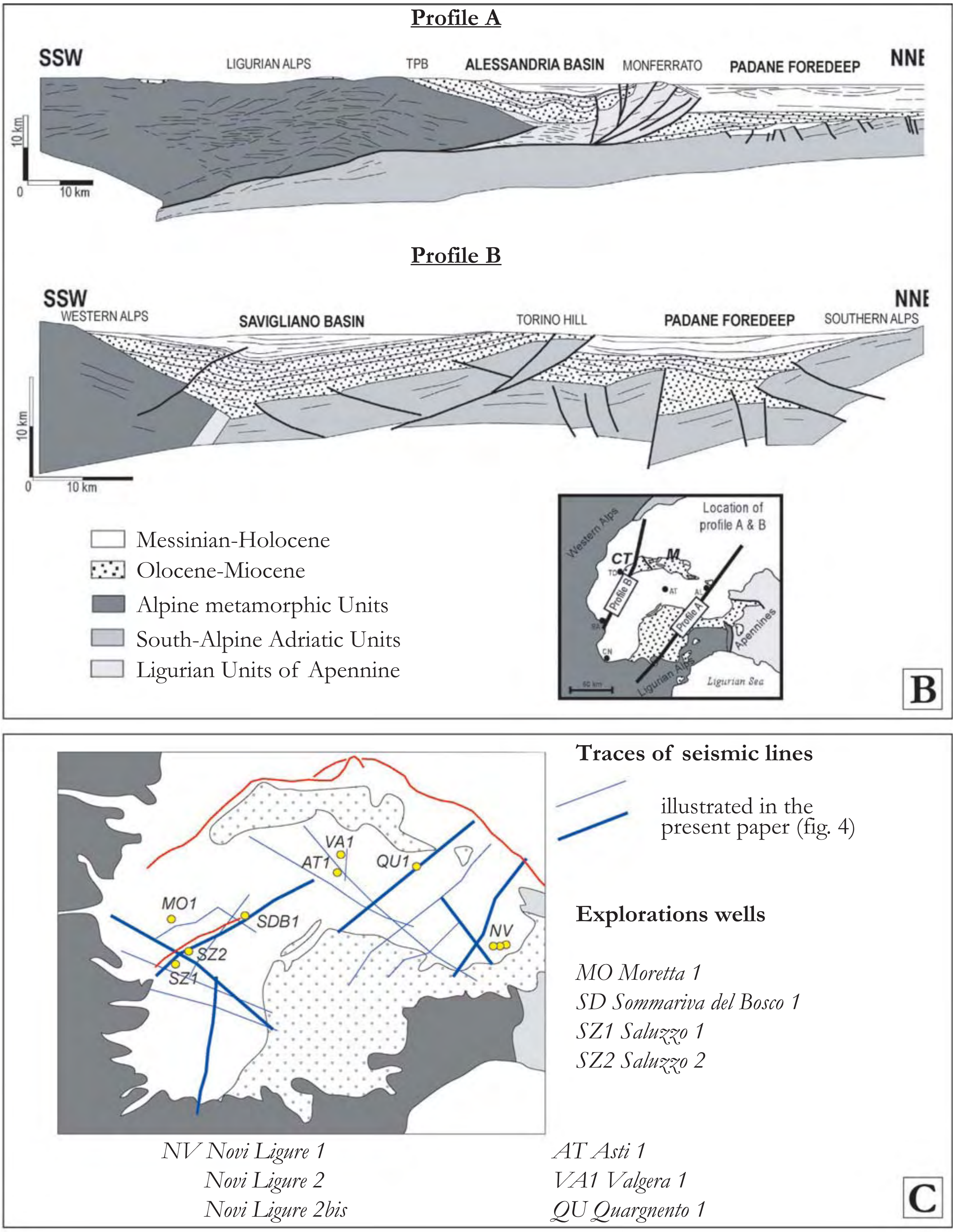


Fig. 1 - (A) Schematic geologic map of southern Piedmont showing the distribution of Alpine metamorphic Units, Ligurian Units of the Apennines, outcrops of Oligocene-Miocene, Pliocene and Quaternary successions and buried Pliocene-Quaternary depocentres, which represent the major fresh-water reserves of this area (modified from BIGI *et alii*, 1990). (B) Regional geologic profiles across main structural domains of Western Po Plain, showing the Alessandria and Savigliano synforms, that can be considered as "piggy back" basins, overthrusted onto the Padane Foredeep (modified from CASSANO *et alii*, 1986; FALLETTI *et alii*, 1995; MOSCA, 2006). (C) Location of seismic reflection lines and exploration wells used in this study.



- *(A) Schema geologico semplificato del Piemonte meridionale in cui sono rappresentati: le unità metamorfiche della catena alpina, le unità Liguri-Appenniniche, le successioni oligocenico-mioceniche, plioceniche e quaternarie affioranti e i depocentri plio-quaternari sepolti, in cui risiedono i principali acquiferi della regione (modificato da* Bigi et alii*, 1990). (B) Profili geologici schematici attraverso i principali elementi strutturali della Pianura Padana occidentale: essi mostrano le sinclinali regionali di Alessandria e Savigliano, che a grande scala costituiscono bacini di "piggy-back" sovrascorsi verso nord sulle successioni dell'Avanfossa Padana (modificato da* Cassano et alii*, 1986;* Falletti et alii*, 1995;* Mosca*, 2006). (C) Ubicazione delle linee sismiche e dei pozzi esplorativi utilizzati nel presente lavoro.*

The stratigraphic analysis has allowed to reconstruct a regional depositional framework of the Savigliano and Alessandria Basins that will be briefly illustrated below.

3.1. - Stratigraphic framework of Savigliano and Alessandria Basins and of the Asti Area

The Messinian-Quaternary succession has been subdivided into 7 unconformity bounded stratigraphic units, corresponding to synthems (Chang, 1975), that can be correlated across the entire studied area (figg. 2, 3). They include, in stratigraphic order, synthem M1 (upper Messinian), synthem M2 (upper Messinian), synthem P1 (lower Pliocene), synthem P2 (lower-middle Pliocene), synthem P3 (middle-upper Pliocene), synthem Q1 (lower Pleistocene) and synthem Q2 (middle Pleistocene-Holocene).

A complete discussion of the sedimentary and tectonic evolution of the investigated area is well beyond the scope of this paper, which is mainly focused on hydrostratigraphy. Therefore, these topics will be treated only in their general aspects.

The vertical stacking of these synthems represents the product of a large scale regressive-transgressive-regressive cycle, that resulted from the complex interaction between tectonics, relative sea-level variations and climatic changes. Essentially, the basin fill records periods of intense subsidence in depocentral areas (that remained roughly fixed in the central portions of the basins) concomitant with strong tectonic uplift along basin margins (now mainly eroded) and periods of general subsidence (also along the margins) both in the Alessandria and Savigliano Basins and in the interposed Asti area.

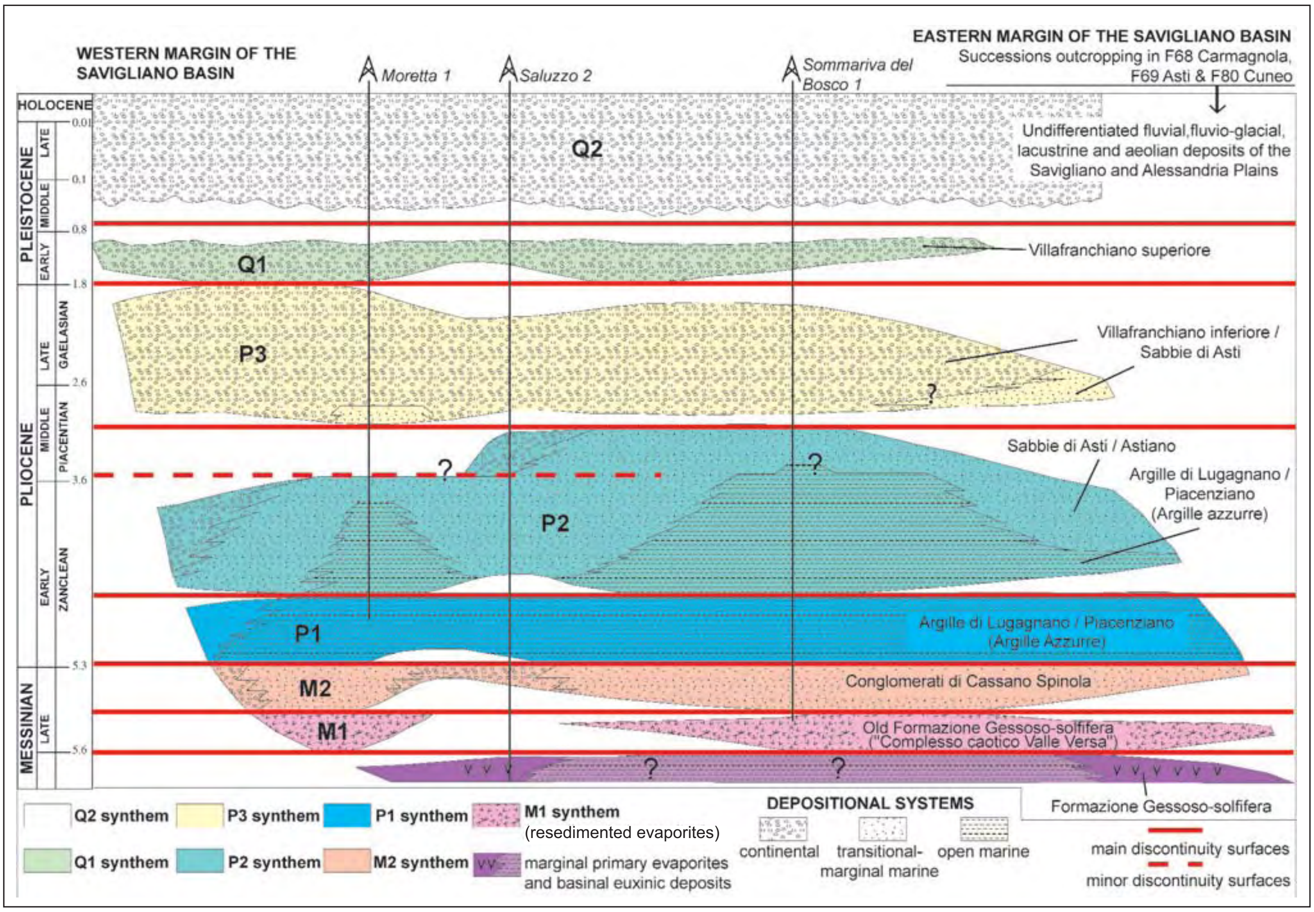


Fig. 2 - Roughly W-E striking chronostratigraphic framework of the Savigliano Basin, connecting its western margin, the depocentral area, and the present-day eastern border (see location in figure 1). Distribution of main depositional systems is illustrated within each synthems. On the right, classic formational names of *Carta Geologica d'Italia* at 1:100.000 scale are indicated for sediments that crop out along the eastern border of the basin. In the present work, continental deposits of P2 are correlated to the lower portion of the "*Villafranchiano*" in the sheet n. 80 *Cuneo* (Savigliano Basin). The SZ2 well is located on the *Saluzzo-Sommariva del Bosco* faulted anticline.

- Quadro cronostratigrafico del Bacino di Savigliano, elaborato lungo un transetto orientato circa W-E (l'ubicazione è indicata in figura 1), congiungente il margine occidentale sepolto, l'area depocentrale settentrionale e l'attuale margine orientale. All'interno di ogni sintema è illustrata la distribuzione dei principali contesti deposizionali. Sulla destra sono indicati i classici nomi formazionali utilizzati nella Carta Geologica d'Italia alla scala 1:100.000 per le successioni affioranti lungo il margine orientale del bacino. Nel presente lavoro i depositi continentali del sintema P2 sono correlati alla porzione inferiore delle successioni cartografate come "Villafranchiano" nel Foglio n. 80 Cuneo (Bacino di Savigliano). Il pozzo SZ2 è ubicato sull'anticlinale fagliata di Saluzzo-Sommariva del Bosco.

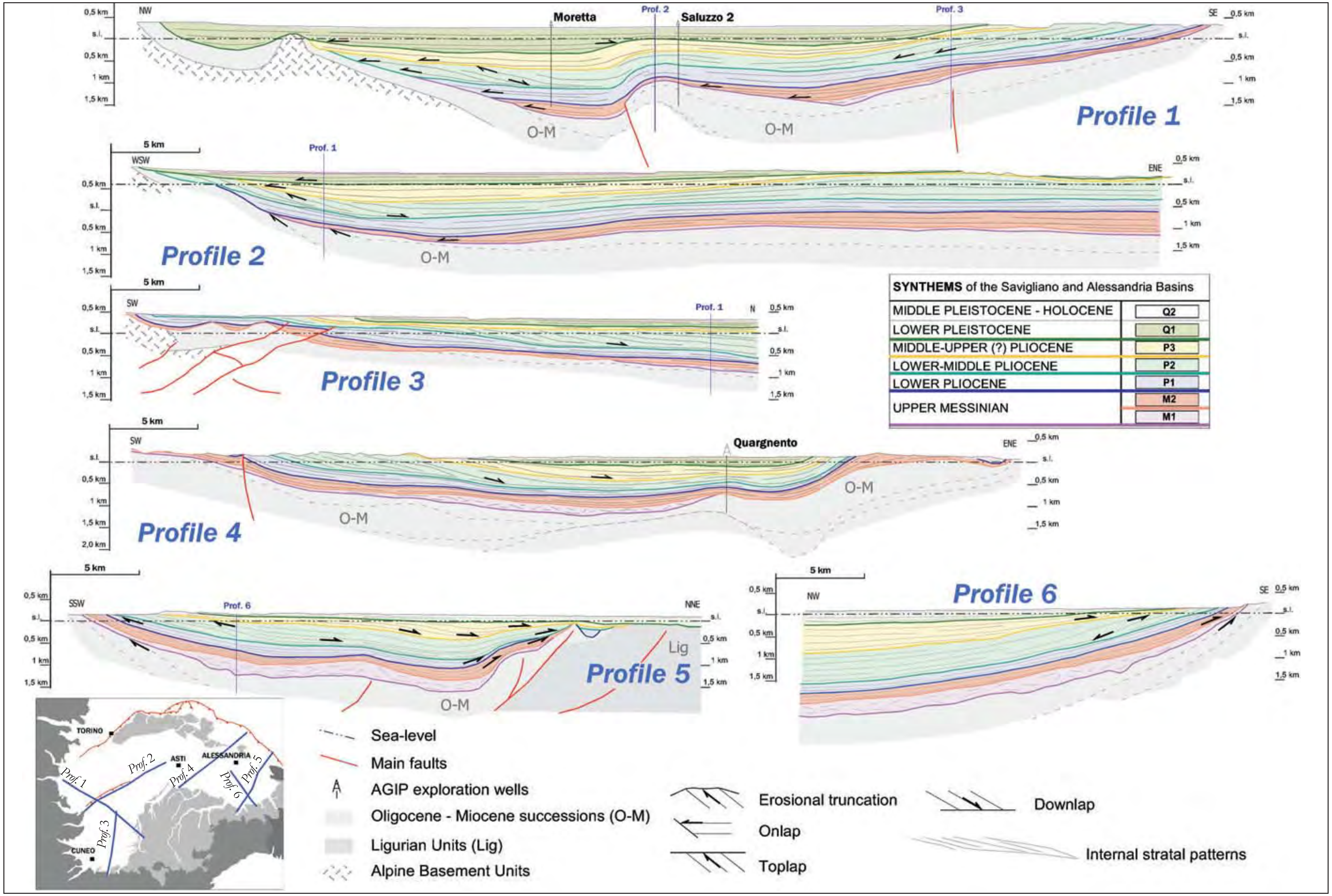


Fig. 3 - Geologic cross-sections showing thickness changes, external geometries and internal configurations of synthems recognized in the Savigliano and Alessandria Basins. Geologic profiles 1 to 6 derive from the seismic stratigraphic analysis of the grid shown on the lower left.

- Profili geologici interpretativi, in cui sono illustrati lo spessore, la geometria esterna e l'architettura interna dei sintemi riconosciuti nei Bacini di Savigliano ed Alessandria. Questi profili derivano dall'analisi sismico-stratigrafica della maglia di profili sismici mostrata in basso a sinistra.

Synthem M1 records a major phase of tectonic uplift ("intra-Messinian tectonic phase"; e.g. GELATI *et alii*, 1987; ROVERI *et alii*, 2003) and erosion of marginal primary evaporites resulting in emplacemet of huge complex of resedimented eva-porites, the major accumulations of which are located in depocentral areas (figg. 2, 3 - profiles 1,4-6).

Synthem M2 records a relative sea-level rise (i.e. transgressive phase) linked to a period of enhanced subsidence and basin widening (ROVERI *et alii*, 1998). This is documented by the deposition of backstepping wedges of fluvio-deltaic deposits, onlapping against basin margins, which were subject to local tectonic uplift (figg. 2, 3 - profiles 1, 2, 5). The transgressive trend culminated with the sharp deposition of open marine P1 sediments, that mark the re-establishment of fully marine conditions in the Mediterranean, at the end of the Messinian salinity crisis (IACCARINO *et alii*, 1999).

Synthem P2 records periods of renewed sediment flux related to southernmost margins uplift and a strongly increasing volume of sediment supply from the southern areas, through the northward progradation ("forced regression", see also GHIELMI *et alii*, 2002) of basin-margin and deltaic systems (figg. 2, 3).

Synthem P3 (fig. 2) appears to represent a period of general tectonic subsidence and minor uplift of the margins, concomitant with a progressively increasing supply and aggradation of continental deposits, that were probably fed by the uplift of most internal sectors of the Alps.

Synthem Q1 is introduced by a tectonic pulse responsible for accelerated uplift along basin margins (see also CARRARO, 1996) as well as Asti high (sharp basal angular unconformity in most of profiles of fig. 3), but mainly records a period of general tectonic subsidence (suggested by strong aggradational patterns) and final transition to continental conditions (fig. 2).

Synthem Q2 marks the "closure" of the regressive evolution and records multiple events of continental sedimentation and erosion (BOTTINO *et alii*, 1994b; CAVALLI & VIGNA, 1995).

In the Savigliano Basin, sedimentation was strongly controlled by the Saluzzo-Sommariva del Bosco faulted anticline (fig. 1A; fig. 3 - profile 1, 2). Continued growth of the anticline was coeval with Messinian-Pleistocene regional subsidence, as it is clearly shown by thinning of synthems at the anticlinal crest and by the occurrence of distinct depocentral areas to the north and the south of this structure ("DR" e "DF" in figure 1A).

Thrust fronts to the south also exerted an important control on sedimentation. The growth of these structures caused the sudden uplift of the southern margin of the basin that led to the infill of northern depozones with widespread progradational systems (synthem P2; fig. 3 - profile 3).

In the Alessandria Basin, sedimentation was strongly controlled by NW-SE reverse faults and related structural highs, that constantly bounded the basin in its northern-east sector (fig. 3 - profile 5). The continued growth of these structures is clearly indicated by progressive syn-tectonic angular unconformities, with local erosional truncation, and by the overall geometry wedging of synthems to the east.

The Asti area was characterized during the Late Messinian, and during the Middle Pliocene and Pleistocene by the growth of a "high" (the "Asti high") acting as an intrabasinal divide between the Savigliano Basin to the west and Alessandria Basin to the east (fig. 1A). The growth of this high during Pliocene-Pleistocene is strongly supported by the progressive lateral thickening of synthems P2 and Q1 from the "Asti high" toward the central sectors of the Savigliano and Alessandria Basins (fig. 3 - profiles 2,4).

4. - HYDROSTRATIGRAPHY

In this work, due to the poor quality of available subsurface data (e.g. low number of deep cores and absence of core samples; low resolution seismic profiles) as regards the regional scale and the great depths of investigation, it has been assumed that the synthem represents the "operational unit" of the hydrostratigraphic model (fig. 4).

A synthem is a complex sedimentary prism bounded above and below by discontinuity surfaces of regional extent and composed of genetically related strata-sets with variable lithology and geometry, conformably deposited in different but adjoining depositional systems. Internal bedding surfaces can touch but can not intersect the bounding discontinuity surfaces (CHANG, 1975).

4.1. - HYDROSTRATIGRAPHIC VALUE OF SYNTHEMS

Here it has been assumed that the hydrostratigraphic value of synthems mainly depends on their stratigraphic architecture and lithofacies associations (fig. 4).

The stratigraphic architecture is defined by the internal geometry (i.e. internal stratal patterns, imaged by seismic reflectors) of synthems, including for example parallel/aggradational, divergent, progradational or chaotic patterns (for a complete discussion see MITCHUM *et alii*, 1977 and BROWN & FISHER, 1980). A generic hydrostratigraphic value has been assigned to the stratigraphic architecture, since it is known that internal stratal pattern re-pre-

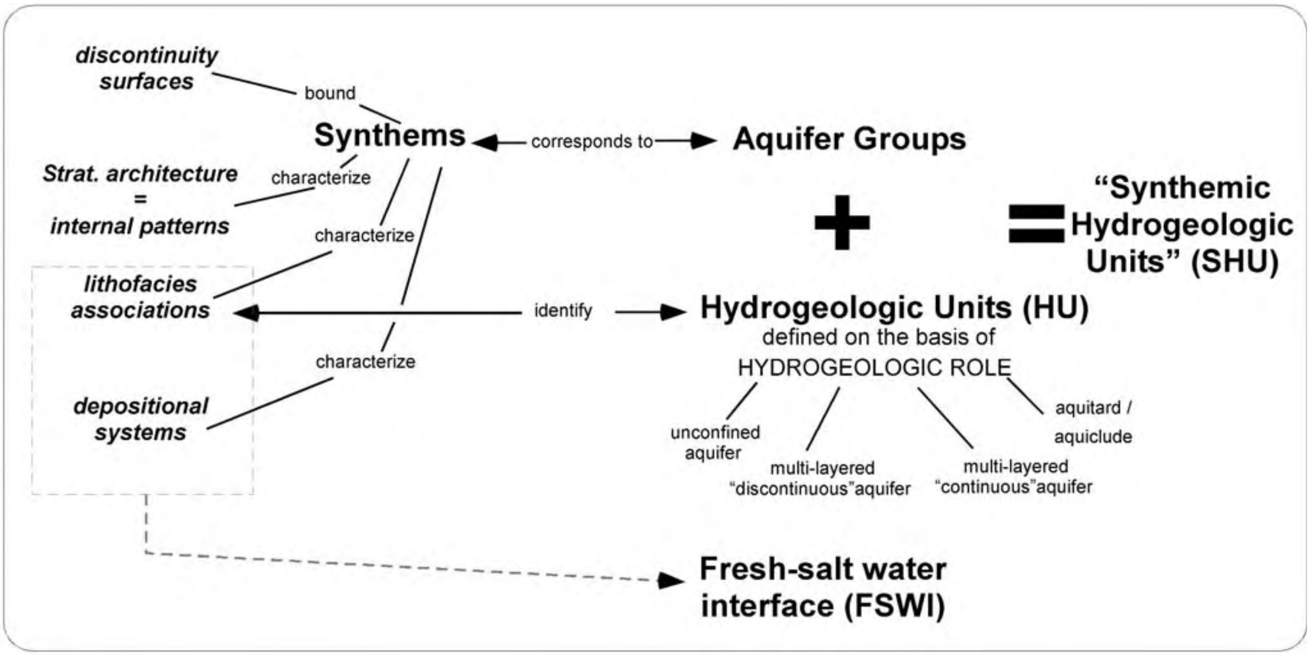


Fig. 4 - Scheme of the relationships between geologic and hydrogeologic concepts adopted for the reconstruction of the hydrostratigraphic framework of the Savigliano and Alessandria Basins.
- *Schema delle relazioni tra i concetti geologici e idrogeologici utilizzato per definire il quadro idrostratigrafico dei Bacini di Savigliano ed Alessandria.*

sents a prominent factor in controlling main regional groundwater flow directions.

Lithofacies associations (fig. 5) are volumes of sediments, that show homogeneous lithologic properties such as grain size, composition and bedding style.

Eight different lithofacies associations (lf 1 to lf 8) have been defined on the basis of two criteria:
- grain-size ratio, that is the relative percent of coarse grained (sands and gravel) and fine grained (silts and clays/marls) sediments forming the lithofacies association;
- the degree of lateral persistence of sedimentary bodies (both fine and coarse grained), in alternations (lf 2 to lf 7 in fig. 5); lithologic bodies that are more than 2 kilometers long have been considered as "continuous", whereas those less than 2 kilometers long have been considered as "discontinuous".

In addition, two lithofacies associations have been recognized (lf 9 and lf 10), that are typical features of synthem M1 and consist of resedimented evaporite complexes.

The lithofacies associations (or group of lithofacies associations), have been subdivided into 4 main typologies of "Hydrogeologic Units" (HU; (1)) (fig. 5), distinguished on the basis of their hydrogeologic characteristics, in the sense that they represent rock bodies with different water exploitation potential. The four main HU types are: HU1) unconfined aquifers, HU2) multi-layered "discontinuous" aquifers, HU3) multi-layered "continuous" aquifers, HU4) aquitards/aquicludes that have progressively minor water exploitation potential.

4.2. - Aquifer Group and Synthemic Hydrogeologic Unit

In order to elaborate the hydrostratigraphic scheme, it has been assumed that each synthem is conceptually equivalent to an "Aquifer Group" (concept already used in Regione Emilia Romagna & Eni-Agip, 1998 and in Regione Lombardia & Eni-Agip, 2002) that in this work has been considered as an unconformity bounded sedimentary body (figg. 4, 6), the hydrostratigraphic properties of which are determined by its Hydrogeologic Units, that are in turn dependent on lithofacies associations, and their peculiar stratigraphic architecture.

According to this assumption, hereafter we will use the term "Aquifer Group" instead of "synthem".

At basin scale, an Aquifer Group will show a distinctive hydrogeologic behaviour (that is: a peculiar response to the regional groundwater flow system)

(1) According to the definition of Francani (1985), in the present work, an Hydrogeologic Unit corresponds to a lithofacies association or group of lithofacies associations that shows homogeneous hydrogeologic properties (e.g. permeability ratio, storage coefficient) at regional scale.

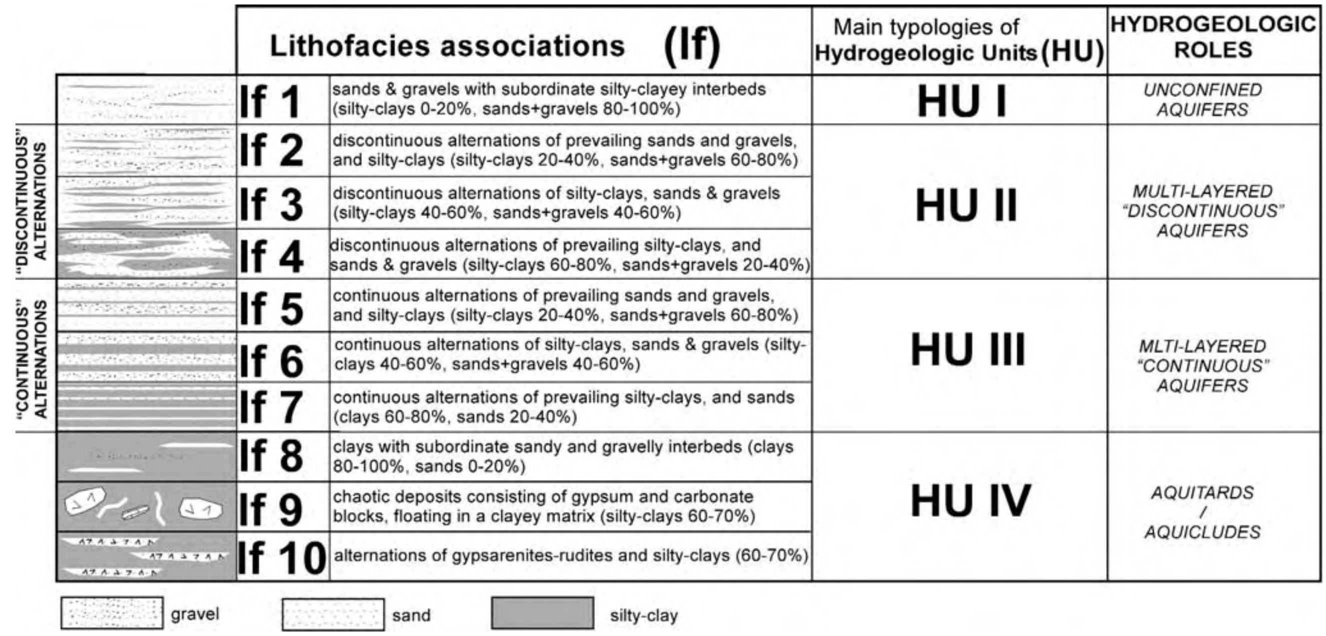


Fig. 5 - Scheme showing the relationships between lithofacies associations (or group of lithofacies associations) and four main typologies of Hydrogeologic Units (HU), that are defined on the basis of their hydrogeologic characteristics. HU I represents an unconfined aquifer with high permeability; HU II & HU III are multilayered aquifers, with median values of permeability (these 2 typologies are differentiated on the basis of the vertical conductivity: good to moderate in HU II and very low in HU III); HU IV represents an aquitard or rarely an aquiclude.

- Schema illustrante le corrispondenze fra associazioni di litofacies (o gruppi di associazioni di litofacies) e le quattro principali tipologie di Unità Idrogeologiche (HU), che sono definite sulla base del loro ruolo idrogeologico. La tipologia HU I rappresenta un acquifero libero, caratterizzato da buona permeabilità; le tipologie HU II e HU III sono acquiferi multistrato, con valori intermedi di permeabilità (queste due tipologie sono state distinte sulla base della diversa conducibilità idraulica verticale: da buona a media per HU II e molto bassa per HU III); la tipologia HU IV ha ruolo di acquitardo o, in casi meno frequenti, di acquicludo.

in comparison with other Aquifer Groups, since each one of them has its own stratigraphic architecture, that strongly control the flow directions.

As a consequence, it is necessary to assume that, within each Acquifer Group, the same Hydrogeologic Unit does present peculiar and contextual properties. In other words, the same tipology of Hydrogeologic Unit will display partially different hydrogeologic features, depending on the characteristics of the Aquifer Group it belongs to.

For example, the HU1) main tipology will display peculiar features (e.g. stratigraphic architecure, compaction and cementation degree) and then will show a different behaviour as regards the regional groundwater flow, depending on wheter it belongs to a shallower aquifer group (e.g. B Aquifer Group) or it belongs to a deeper aquifer group (e.g. D Aquifer Group). For these reasons we coined a new concept labelled as "Synthemic Hydrogeologic Unit" (fig. 4; hereafter SHU). Each SHU will be indicated with an acronym, composed by the capital letter of the Aquifer Group it belongs to and by a roman numeral referred to the main typology of Hydrogeologic Unit it derives from (figg. 6, 7).

The choice of the "Aquifer Group" as a key concept to elaborate the hydrostratigraphic model, is supported by the well known fact that, at basin scale, groundwater flow paths are mainly parallel to internal bedding surfaces (at least for what concerns lateral flow paths, according to the model of TOTH, 1963), and therefore, these flows remain mostly confined within the same Aquifer Group, although vertical exchanges among different acquifer groups can locally take place.

In this sense the concept of "Aquifer Group" has a similar but not equal meaning to that proposed by REGIONE EMILIA-ROMAGNA & ENI-AGIP (1998). In the present work in fact the "Aquifer Group" is defined only on the basis of its bounding discontinuities and internal architecture, whilst in the reconstruction of REGIONE EMILIA-ROMAGNA & ENI-AGIP (1998), the occurrence of regionally extended fine-grained interval (that can guarantee the hydraulic insulation between vertically stacked Aquifer groups) was assumed as key discerning factor.

4.3. - CRITERIA TO IDENTIFY THE FRESH-SALT WATER INTERFACE

The surface that separates fresh- from deeper salt (2)-groundwaters (for brevity fresh-salt water

(2) According to AGIP (1994), salt waters are here considered those showing concentrations of soluted iones heavier than 1 g/l, and then also the brackish waters.

interface; FSWI) is another fundamental key factor that governs the location of groundwater resources.

The reconstruction of geometry and positioning of FSWI is of extreme importance, since it corresponds to the lower boundary of freshwater aquifers that are potentially exploitable for drinking, municipal and agricultural purposes.

The recognition of large scale position and geometry of this surface in Piedmont region subsurface was based, up to date, on core and spring data correlations (Bortolami *et alii*, 1982; Abatucci *et alii*, 2005), performed regardless of complex spatial heterogeneity of sedimentary bodies in the Messinian-Quaternary basins.

In the present work the reconstruction of the distribution and geometry of FSWI was based on the integration of core data and geologic interpretations (i.e.: depositional systems, lithofacies associations and present day position of Aquifer Groups) and it was not supported by hydrogeologic data.

In this study, the concept of depositional system (fig. 4) was used, that is believed to hold, together with the lithofacies associations, a fundamental role on 3D distribution of fresh- and salt- groundwaters. The knowledge of the depositional system is a reliable tool for prediction of FSWI subsurface geometrical trend and distribution, also in those areas with scarce constraints on saltwaters location at depth.

Integrated analysis of available data set made it possible to recognize only major groups of depositional systems, that are: continental systems (co), transitional-marginal marine systems (tm) and open marine systems (om) (fig. 2, 7).

Although transitional-marginal marine sediments are originally permeated by salt-water during deposition, they can be permeated by fresh-water in a second time (Regione Emilia-Romagna & Eni-Agip, 1998). These sediments in fact can receive, directly from continental areas, great amount of recharge (meteoric and alluvial) fresh water, that is able to displace the connate saltwaters.

Moreover, it is known that saltwaters displacement can be more effective during forced regressions (Regione Emilia-Romagna & Eni-Agip, 1998), when FSWI is forced to follow the downward shift of sea-level.

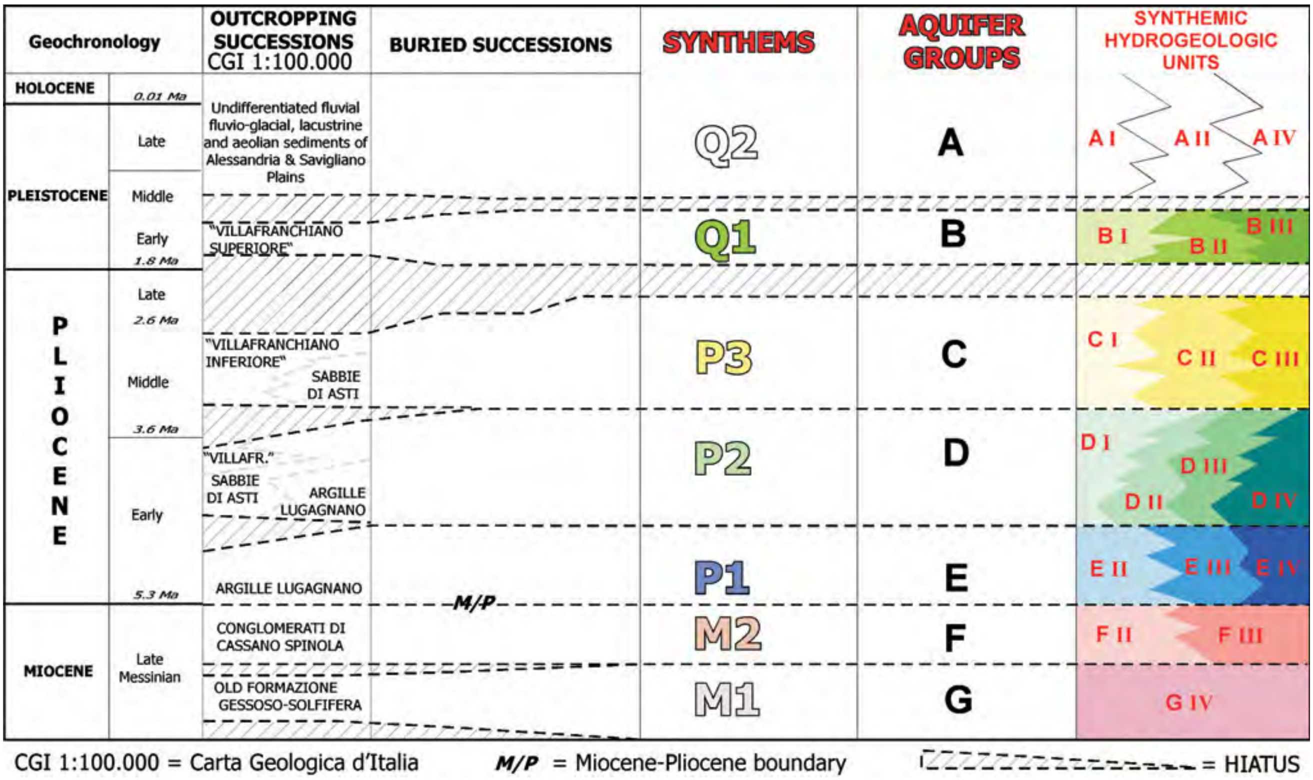


Fig. 6 - Simplified hydrostratigraphic framework of the Savigliano and Alessandria Basins showing the links between synthems, Aquifer Groups and Synthemic Hydrogeologic Units. On the left, classic formational names of *Carta Geologica d'Italia* at 1:100.000 scale are indicated for outcropping successions. Note that, according to present work, the successions mapped as "*Villafranchiano*" are split by 2 discontinuity surfaces and belong to 3 different synthems: P2, P3 and Q1.
- *Quadro idrostratigrafico riassuntivo dei Bacini di Savigliano e Alessandria, in cui sono illustrate le corrispondenze tra sintemi, Gruppi Acquiferi ed Unità Idrogeologiche di Sintema. Sulla sinistra sono indicati i classici nomi formazionali utilizzati, nella Carta Geologica d'Italia alla scala 1:100.000, per le successioni affioranti. Si noti che, secondo il presente lavoro, le successioni "Villafranchiane" s.l. sono suddivise da 2 superfici di discontinuità, venendo così ad appartenere a tre differenti sintemi: P2, P3 e Q1.*

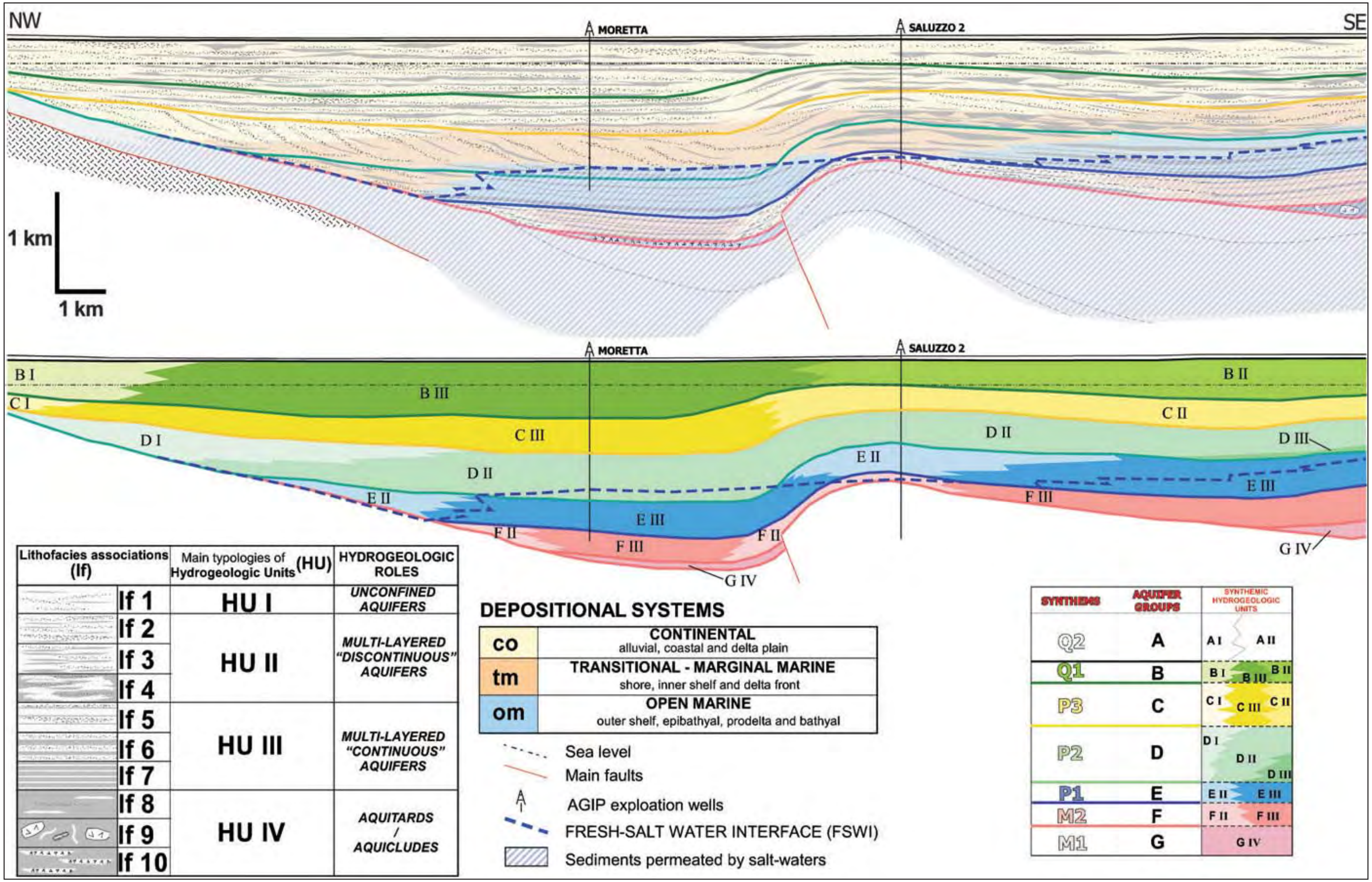


Fig. 7 - Detailed geologic (upper part) and hydrostratigraphic (lower part) section across the Savigliano Basin, portraying the central segment of profile 1 in figure 4. Internal patterns of synthems as well as the spatial distribution of lithofacies associations and depositional systems are illustrated. Note the lateral and vertical stacking patterns of Synthemic Hydrogeologic Units within each Aquifer Group. Note also the "saw-tooth"-like inferred geometry of the fresh-salt water interface (dashed blu line) on the left, where no one constraint on saltwaters location was available.

- Sezione geologica (parte superiore) ed idrostratigrafica (parte inferiore) di dettaglio del Bacino di Savigliano, raffigurante la porzione centrale del profilo 1 di figura 4. Sono illustrati la geometria interna dei sintemi, la distribuzione delle associazione di litofacies dei contesti deposizionali. Si notino gli schemi di impilamento laterale e verticale delle Unità Idrogeologiche di Sintema all'interno dei Gruppi Acquiferi. Si noti inoltre verso sinistra l'andamento ipotizzato a "denti di sega" dell'interfaccia Acqua dolce-salata (tratteggio blu). Tale geometria è stata ipotizzata in base ai vincoli stratigrafici forniti dai contesti deposizionali.

For these reasons, it has been operatively assumed that the position of FSWI should be located within open marine settings or at the boundary between marginal marine and open marine settings.

As above mentioned, the distribution of the lithofacies associations (fig. 4) also play an important role on saltwater distribution. In this study, they have been therefore carefully considered in delineating FSWI position. Specifically, since saltwaters appear to be mainly confined in fine grained strata, it has been operatively assumed to trace FSWI within fine-grained lithofacies associations or close to the boundary between fine-grained lithofacies associations and coarse-grained lithofacies ones, which are more water-transmissive and then they are likely permeated by freshwater.

It is important to stress that the above assumptions are reliable only as regard the depocentral zones, whereas they gradually loose validity toward the margins of the basins, in which the original (i.e. syn-depositional) distribution of connate saltwaters could be very likely modified by post-depositional tectonic factors. Specifically, along these margins, tectonics may have caused tilting, uplift and erosion of open marine successions, allowing displacement of connate saltwaters (REGIONE EMILIA-ROMAGNA & ENI-AGIP, 1998).
Therefore, along marginal areas devoid of resolutive core and spring data, it is not always possible to infer the distribution of FSWI, whose positioning is necessarily interpretative.

5. - HYDROSTRATIGRAPHIC ARCHITECTURE

It is here presented the hydrostratigraphic architecture of the Savigliano and Alessandria basins and of the Asti area, in which 7 Aquifer Groups have been defined and labelled with capital letters from G to A, that is from the oldest to youngest one (figg. 6, 7).

It is worth noting that Aquifer Groups A, B, C and D do not physically correspond with the Aquifer Groups A, B, C and D recognized in the adjoining areas (i.e. Regione Emilia Romagna and Regione Lombardia).

In the next sections, the Aquifer Groups are described by (i) their overall stratigraphic architecture and geometry (ii) and their general pattern of distribution of thickness, depositional systems and Synthemic Hydrogeologic Units.

However, the map distribution of all these characters will be portrayed only for one Aquifer Group (i.e. D Group; fig. 8).

5.1. - AQUIFER GROUP G (SYNTHEM M1)

Aquifer Group G is characterized by a chaotic (fig. 3) stratigraphic architecture. It reaches maximum thickness of 400 m in the central portion of the Alessandria Basin (fig. 3, profiles 5,6) and 150 m in the northern sector of the Savigliano Basin.

From depocentral zones, G Group progressively tapers toward the present-day basin margins. It wedges out toward the western margin of the Savigliano Basin as well as on the Asti high. It thins out below the overlying F Aquifer Group, towards the eastern border of the Alessandria Basin.

Aquifer Group G is entirely composed by slope and basin resedimented evaporites, that consist of chaotic sediments (Alessandria B.) and subordinate stratified sediments (central belt of Savigliano B.). Chaotic sediments are made up of m to hm-sized blocks of evaporite rocks (including primary selenite, microcrystalline gypsum and gypsarenites/gypsrudites) and carbonate rocks, randomly distributed in a fine-grained matrix. Stratified sediments consist of laterally discontinuous strata of gypsarenite/gypsrudite, embedded into clayey deposits.

These units can be correlated to the chaotic successions that, in the outcrops, have been historically included (along with in place primary evaporite) into the "Formazione Gessoso-solfifera", but they actually form a younger stratigraphic interval, that has been recently ascribed to the "Complesso caotico della Valle Versa" (DELA PIERRE *et alii*, 2003; IRACE, 2004; IRACE *et alii,* 2005) (figg. 2, 6).

These deposits can thus be considered as time equivalent to the resedimented evaporites recently recognized in most of circum-Mediterranean Messinian basins (ROVERI *et alii*, 2008) and can be referred to the lower part of the post-evaporitic interval (p-ev1 *sensu* ROVERI *et alii*, 2003).

Group G only consists of SHU GIV that, at regional scale, represents an aquitard/aquiclude (figg. 6, 7). By contrast marked permeability, owing to karstification, can locally characterize the large scale evaporite blocks exposed on present day margins (FIORASO *et alii*, 2004).

5.2. - AQUIFER GROUP F (SYNTHEM M2)

Aquifer Group F is characterized by a parallel to basinward-divergent stratigraphic architecture (fig. 3).

It shows maximum thickness of 400m both in the central-northern sector of the Savigliano Basin and in the western area of the Alessandria Basin, close to the eastern side of the Asti high deformational zone. On the latter minor thickness (ca. 150

m) is preserved. Moving from the buried areas to the present-day northern and southern margins, Aquifer Group F progressively thins, up to 100 m, displaying local onlap terminations on the underlying Aquifer Group G (fig. 3). It thins out both toward the western margin of the Savigliano Basin and the eastern border of the Alessandria Basin, through progressive onlap terminations onto older Oligocene-Miocene successions (fig. 3, profiles 1, 5). To the north-east it is also truncated by the erosional unconformity at the base of Aquifer Group D.

Aquifer Group F mainly consists of transitional deposits, represented by regular alternations of sands and clays, that are widespread in depocentral areas. Whereas towards the margin of the Savigliano Basin as well as the northern and southern regions of the Alessandria Basin these facies laterally pass to time-equivalent fan deltas deposits (e.g. GHIBAUDO *et alii*, 1985) that, in the outcrops, have been classically mapped as "Conglomerati di Cassano-Spinola" (fig. 3, 6). All these units can be referred to the "Lago-Mare" interval (p-ev2 *sensu* ROVERI *et alii*, 2003).

Most of Group F consists of SHU FIII (figg. 6, 7), that plays the role of multi-layered "continuous" aquifer, whereas SHU FII, that represents a multi-layered "discontinuous" aquifer, occurs along the western margin of Savigliano Basin and the southern border of Alessandria Basin.

5.3. - AQUIFER GROUP E (SYNTHEM P1)

Aquifer Group E is characterized by a predominant parallel stratigraphic architecture and by aggradational geometries (fig. 3).

Major accumulations are in the order of 400 m in the central-northern part of the Savigliano Basin. They gradually decrease to 300 m on the Asti high, up to 200 m in the central sector of the Alessandria Basin. From depocentral areas, Group E thins toward present day northern and southern margins (fig. 3, profiles 1,3,5,6), where average thickness are of about 100 m. It displays an abrupt thinning out to the north-east (fig. 3, profile 5), being truncated by the basal erosional surface (associated to an angular unconformity) of overlying Aquifer Group D. Moreover, group E wedges out also at the western border of the Savigliano Basin, onlapping onto Oligocene- Miocene successions.

The bulk of the Aquifer Group E consists of open marine (fine to coarse-grained) deposits that, in the outcrops, have been classically ascribed to the "Argille di Lugagnano" or "Piacenziano", and recently to the "Argille Azzurre" (figg. 2, 6).

However, along the western margin of the Savigliano Basin, open marine deposits laterally grade into time equivalent transitional deposits (figg. 2, 7), recognized in the exploration wells sections.

Group E mainly consists of SHU EIII (figg. 6, 7), that represents a multi-layered "continuous" aquifer. In the Asti area as in southern regions of Alessandria Basin and eastern sector of Savigliano Basin, SHU EIV occurs, with the role of aquiclude. Instead, in western margin of SB, Group E comprises SHU EII, that represent a multi-layered "discontinuous" aquifer.

5.4. - AQUIFER GROUP D (SYNTHEM P2)

Aquifer Group D is characterized by a progradational stratigraphic architecture, that originated from progradation of basin-margin and deltaic systems from southern and south-western margins, toward the north/north-east.

Sub-horizontal topset packages (figg. 3, 7) are excellently preserved only in the subsurface of Savigliano Basin (southwestern margin). They consist of coarse-grained delta plain deposits (figg. 7, 8A) that are correlatable to continental successions exposed in the southernmost region of the Savigliano Basin (figg. 2, 6; lower portion of the "Villafranchiano" in the sheet F80 Cuneo (SERVIZIO GEOLOGICO D'ITALIA, 1931) also described by CAVALLI & VIGNA (1995).

Foreset packages (figg. 3, 7) are well-developed throughout the distribution area of Aquifer Group D and consist of marginal marine deposits (fig. 8A). These units can be correlated with sand-rich successions that, in the outcrops, have been classically referred to the "Sabbie di Asti" or "Astiano" (figg. 2, 6).

Foreset packages frontally pass to bottomset strata (figg. 3, 7), which consist of open marine deposits. These sediments are mostly buried in depocentral zones (fig. 8A), but they are locally exposed along southern present-day margins, where they correspond to the uppermost portion of clayey and sandy successions, known as "Argille di Lugagnano" or "Piacenziano" (figg. 2, 6) in the literature (now "Argille Azzurre").

Group D reaches maximum thickness (fig. 8A) on the order of 600-700 m in the north easthern part of the Savigliano Basin, close to the western border of the Asti high and in the central area of the Alessandria Basin. Maximum thickness of 400 m are preserved to the south and to the north of the SDB faulted anticline. On the Asti high, Group D displays thickness of about 200 m. Generally, Group D deposits thin moving from buried depocentral areas to the present day borders (fig. 3, profiles 2, 6; fig. 8A), however considerable thickness can also be locally observed along the margins (e.g. fig. 3, profile 4).

Along the western border of the Savigliano

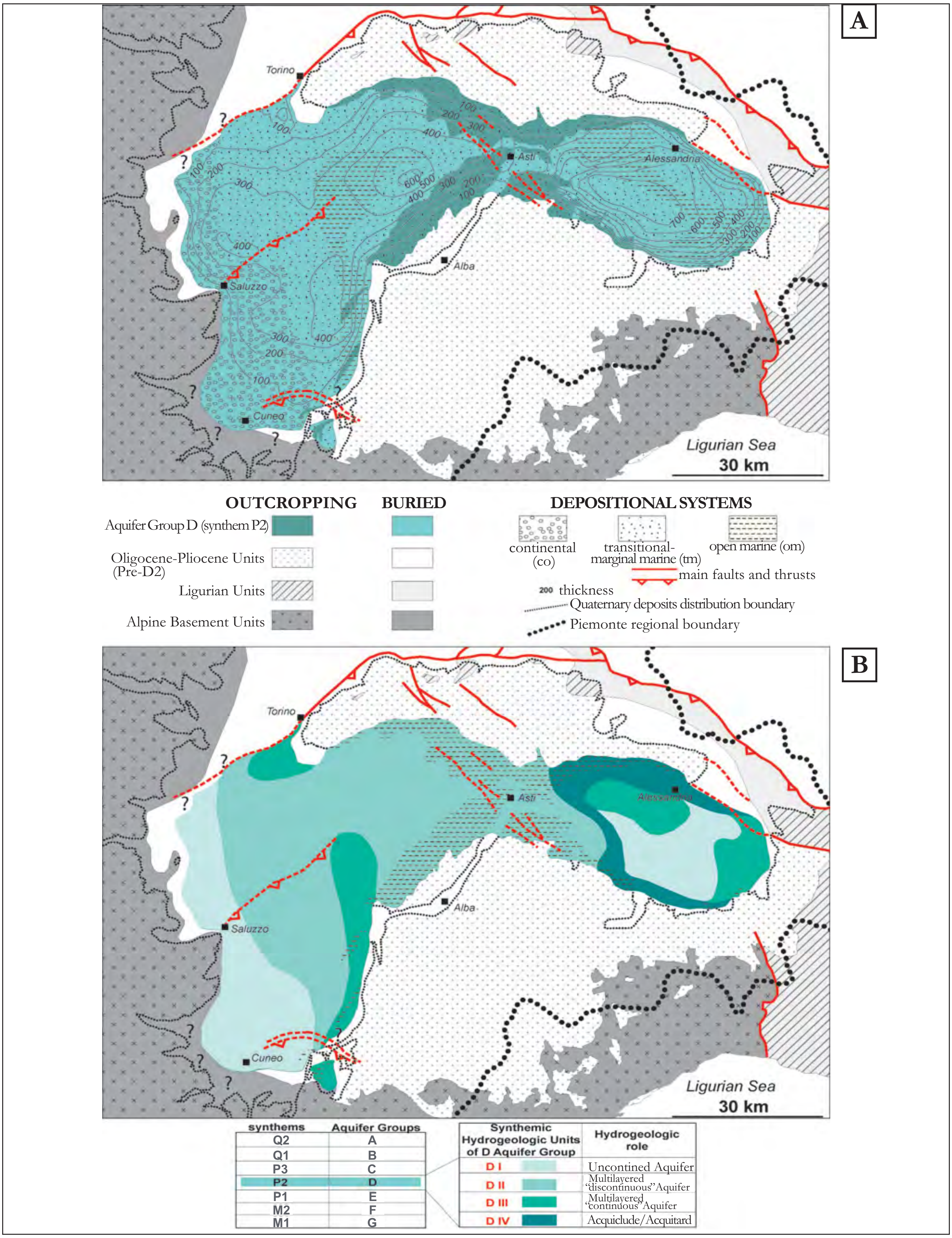


Fig. 8 - (A) Surface and subsurface distribution of the D Aquifer Group (synthems P2: lower–middle Pliocene) in the Savigliano and Alessandria Basins. Thickness values are vertically estimated; spatial distribution of depositional systems are also illustrated. (B) Surface and subsurface distribution of Synthemic Hydrogeologic Units of D Aquifer Group.

- *(A) Distribuzione di superficie e di sottosuolo del Gruppo Acquifero D (sintema P2: Pliocene inferiore-medio) nei Bacini di Savigliano e Alessandria. Sono riportati i valori verticali di spessore ed è illustrata la distribuzione dei contesti deposizionali. (B) Distribuzione di superficie e di sottosuolo delle Unità Idrogeologiche di Sintema del Gruppo Acquifero D.*

Basin, Group D wedges out onlapping onto older Oligocene-Miocene deposits (fig. 3, profiles 1,2). Toward the eastern margin of the Alessandria Basin Group D progressively thins out onlapping, through an angular unconformity, on southwestward tilted Aquifer Groups E and F and Miocene deposits (fig. 3, profile 5).

The articulatedstratigraphic architecture of Aquifer Group D gives rise to a quite composite distribution of synthemic hydrogeologic units (fig. 8B).

The SHU DI (with the role of unconfined aquifer) occurs both along western margin of Savigliano Basin and in the central area of Alessandria Basin, and, more specifically, it is distributed in the upper part of the Aquifer group. The SHU DII (with the role of multi-layered "discontinuous" aquifer) is distributed in large part of Savigliano Basin and in the Asti area. The SHU DIII (with the role of multi-layered "continuous" aquifer) occurs both along eastern margin of Savigliano Basin as well as in the central and eastern areas of Alessandria Basin, and, more specifically, in the lower part of the Aquifer Group D. The SHU DIV (with the role of aquiclude) can be found along most of present-day borders of Alessandria Basin.

5.5. - Aquifer Group C (synthem p3)

At regional scale, Aquifer Group C shows a characteristic divergence of strata packages toward depocentral areas and has an internal aggradational organization, that strongly contrasts with the clinostratified geometry of underlying Aquifer Group D (fig. 3). Only in the Alessandria Basin minor progradational patterns are recognizable (fig. 3, profile 4,5).

Group C reaches maximum thickness of 500 m in the central and northern part of Savigliano Basin (fig. 3, profiles 1,2) and 700 m in the Alessandria Basin (fig. 3, profile 6). From depocentral areas, Group C markedly tapers toward present day northern and southern margins, where thickness are in the order of 100 m. Group C thins out towards the western border of the Savigliano Basin and the eastern border of the Alessandria Basin (fig. 3, profiles 1,2,5), through progressive onlap terminations onto underlying Aquifer Group D and older Miocene strata. On the Asti high, only some tens of meters of Group C successions are preserved, owing to the superimposition of syn-tectonic condensation and post-depositional erosion.

In the Savigliano Basin, Group C consists of peat-rich continental deposits (fig. 7), that progressively pass to transitional sediments in the Asti high and Alessandria Basin. These units can be correlated to the continental lagoon and deltaic successions that, in the outcrops, have been ascribed to the "Villafranchiano inferiore" (figg. 2, 6).

Aquifer Group C is made up of three synthemic hydrogeologic units (fig. 6, 7). SHU CI (unconfined aquifer) occurs in north-western margin of Savigliano Basin, in all the Asti zone and in southern regions of Alessandria Basin. SHU CII (multi-layered "discontinuous" aquifer) constitutes all southern area of Savigliano Basin and also forms a narrow belt in the Alessandria Basin depocenter. SHU CIII (multi-layered "continuous" aquifer) can be found in the northern depocentral zone of Savigliano Basin (fig. 7), and it is also present along Alessandria Basin northern margin.

5.6. - Aquifer Group B (synthem q1)

Aquifer Group B is characterized by parallel-aggradational internal geometries and in the investigated basins forms two large scale lenticular bodies, separated by the Asti high deformational zone.

In the Savigliano Basin, Group B displays maximum thickness of 500-600 m to the south and to the north of the SDB faulted anticline (fig. 3, profile 1), whereas in the Alessandria Basin depocenter it shows maximum thickness of about 300 m (fig. 3, profiles 4, 6).

From depocentral areas, Group B progressively thins towards present day northern and southern margins, where thickness are in the order of 50-100 m. Towards the western margin of the Savigliano Basin, Group B markedly wedges out and unconformably rests, through progressive onlap terminations, onto underlying Aquifer Groups C and D, older miocene strata and also directly onto basement units (fig. 3, profiles 1, 2). At the eastern border of the Alessandria Basin Group B unconformably rests on Ligurian units of the Apennines, and then it become thicker moving to the NE (fig. 3, profile 5).

In most of Savigliano and Alessandria Basins, Group B consists of continental deposits (fig. 7), correlatable to fluvial successions that, in the outcrops, have been referred to the "Villafranchiano superiore" (figg. 2, 6). These deposits grade into transitional (coastal?) facies toward the Alessandria depocenter.

Group B mainly consists of SHU BII. It represents a multi-layered "discontinuous" aquifer, that characterizes all the Alessandria Basin area, as well as the northen margin and a large part of the southern depocenter of Savigliano Basin. SHU BI, corresponding to an unconfined aquifer, constitutes a wide belt along western margin of Savigliano Basin. SHU BIII with the role of multi-layered "continuous" aquifer is restriced to the northern depocenter of Savigliano Basin (fig. 7).

5.7. - Aquifer Group A (synthem q2)

It is the shallowest Aquifer Group recognized. It entirely consists of continental deposits, and groups fluvial/fluvio-glacial, lacustrine and aeolian sediments, on which the present day Savigliano and Alessandria Plain areas rest (figg. 2, 6).

Aquifer Group A shows maximum thickness of about 60-80 m in western and southern borders of the Savigliano Plain and in southern zones of the Alessandria Plain (axial part of alluvial fans and channel belts). It thins up to few meters toward their central and northern areas.

Aquifer Group A mainly consists of (fig. 6) SHU AI (unconfined aquifer) and SHU AII (multilayered "discontinuous" aquifer) and secondarily of SHU AIV (aquitard/aquiclude). SHU AI is well developed in the central-southern areas of Savigliano Basin and in the central sector of Alessandria Basin. SHU AII occurs in the northern part of Savigliano Basin and in most of Alessandria Basin.

SHU AIV is relegated to the northern borders of the basins.

6. - THE FRESH-SALT WATER INTERFACE

On a large scale, the FSWI displays a regular distribution, that appears to mime the synformal geometry of the sedimentary fill in the Savigliano and Alessandria Basins and the gentle antiformal geometry in the Asti area (fig. 9). In general, it results deeper in the depocentral areas, from which it progressively becomes shallower toward present-day borders (structural highs included), along which, the positioning of FSWI is often hampered by the insufficiency of data.

In the Savigliano Basin, the FSWI displays maximum depths from the ground level of about 1800 m in the depocentral zones, while it reaches minimum depths of 70 m, toward the eastern margin.

Along the western margin it usually holds depth in the order of 600-800 m, except on the western culmination of the Saluzzo-Sommariva del Bosco faulted anticline, where it occupies a very shallow depth.

In the Alessandria Basin, the FSWI displays maximum depths from the ground level of about 1500 m in the depocentral area, while it reaches minimum depths of 100 m , both in the south-western border and along the northern margin.

Very low depths are recognizable on the Asti Area.

By excluding the thickness (i.e. 200-300 m) of currently used superficial aquifers, it is therefore possible to estimate the overall thickness of deep fresh aquifers, that have still to be exploited: maximum thickness are in the order of 1200 m in the Alessandria Basin depocenter and 1500 in the central sector of the Savigliano Basin. From these areas, thickness progressively reduces up to some tens/hundreds of meters as regard the present-day margins.

7. - CONCLUDING REMARKS

The proposed reconstruction of the geological setting of the southern Piedmont subsurface Messinian-Quaternary basins represents an improvement of the geological knowledge on the distribution of the main sedimentary bodies and their mutual genetic relations, as well as the pre-

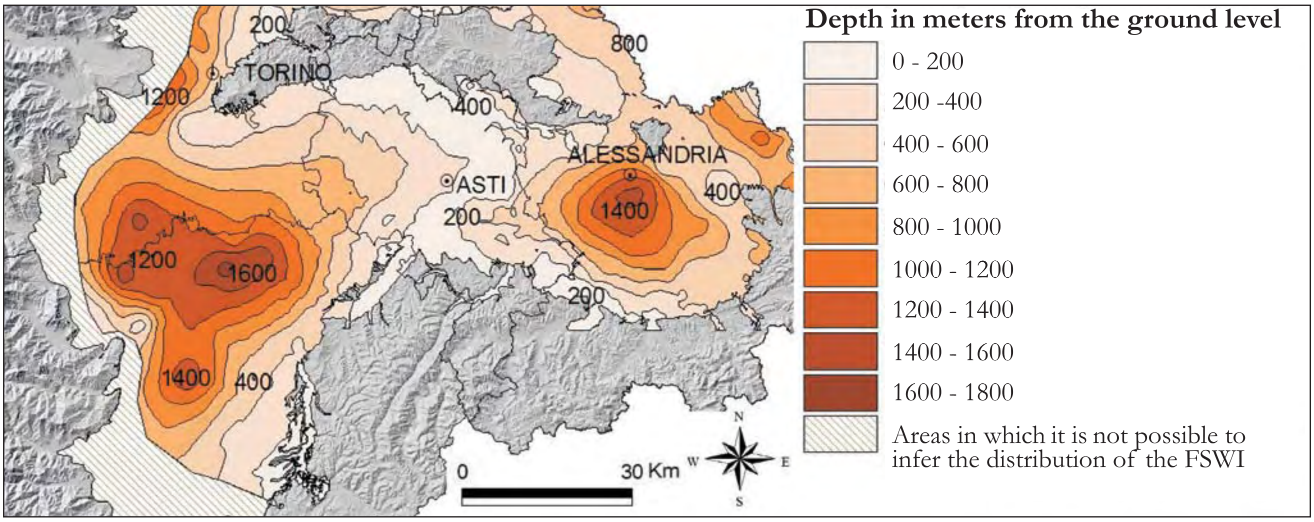


Fig. 9 - Subsurface distribution of the fresh-salt water interface in the Savigliano and Alessandria Basins.
- Distribuzione della superficie di interfaccia acqua dolce-salata nei Bacini di Savigliano ed Alessandria.

sence of the main tectonic features. Although the resulting framework led to a better definition of the subsurface hydrostratigraphy, the suitability of the model is strictly dependent on the project assumptions, namely the choice of delimiting the Aquifer Groups by discontinuity surfaces and basin scale internal patterns, instead of on the occurrence of regionally extended permeability barriers.

The project assumptions were imposed to contextual factors such as the poor quality of available subsurface data and constrained by the detail of the investigation, conducted at regional scale.

These considerations must be carefully taken into account in using the proposed hydrostratigraphic model as a source of input data for further water exploitation evaluations and water flow modeling.

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REFERENCES

ABATUCCI G., CLEMENTE P., DE LUCA D.A., LASAGNA M. & MASCIOCCO L. (2005) - *Deep groundwater resources individuation in Piemonte plane (Northern Italy).* Proceedings of the 6th International Conference "*Sharing a common vision of our water resources*", Menton, France, 7-10 September 2005, Paper EWRA066b, pp. 25.

AGIP (1972) - *Acque dolci sotterranee.* Inventario dei dati raccolti dall'AGIP durante la ricerca di idrocarburi in Italia: pp. 914.

AGIP (1994) - *Acque dolci sotterranee.* Inventario dei dati raccolti dall'AGIP durante la ricerca di idrocarburi in Italia: pp. 515.

BADLEY M.E. (1987) - *Practical seismic interpretation.* AGIP: pp. 274.

BELLO M. & FANTONI R. (2002) - *Deep oil play in Po Valley: deformation and hydrocarbon generation in a deformed foreland.* AAPG Hedberge Conference "*Deformation History, Fluid Flow and Reservoir Appraisal in Foreland Fold and Thrust Belts*", May, 14-18, Palermo (Italy): 1-4.

BIGI G., COSENTINO D., PAROTTO M., SARTORI R. & SCANDONE P. (1990) - *Structural Model of Italy.* Geodynamic project, scale 1:500.000, sheet 1, C.N.R., S.EL.CA., Firenze.

BORTOLAMI G., DI MOLFETTA A. & VERGA G. (1982) - *Il contributo della geotermia al risparmio energetico in Piemonte: il progetto Geotorino.* Estratto da: "*Sistemi Urbani*", rivista quadrimestrale di scienze della città e del territorio, anno IV, **1/2**: 162-181.

BOTTINO G., CAVALLI C. & VIGNA B. (1994a) - *L'analisi di facies nella prospezione idrogeologica.* Geol. Rom., **30**: 515-524.

BOTTINO G., CAVALLI C., EUSEBIO A. & VIGNA B. (1994b) - *Stratigrafia ed evoluzione plio-quaternaria del settore sud-orientale della pianura cuneese.* Atti Tic. Sc. Terra, ser. spec. 1: 153-166.

BROWN L.F. & FISHER W.L. (Ed.) (1980) - *Seismic stratigraphic interpretation and petroleum exploration.* Am. Ass. Petrol. Geol., Continuing Education Course Note, Series 16, Bureau of Economic Geology: pp.181, University of Texas at Austin.

CAVALLI C. & VIGNA B. (1995) - *Il "Villafranchiano" nel sottosuolo della pianura cuneese.* Il Quaternario, **8** (2): 423-434.

CARRARO F. (Ed.) (1996) - *Revisione del Villafranchiano nell'areatipo di Villafranca d'Asti.* Il Quaternario, **9** (1): pp. 119.

CASSANO E., ANELLI L., FICHERA R. & CAPPELLI V. (1986) - *Pianura Padana: interpretazione integrata di dati geofisici e geologici.* AGIP, 73° Congr. Soc. Geol. It., 29 settembre-4 ottobre, Roma: 1-27.

CAVALLI C. & VIGNA B. (1995) - *Il "Villafranchiano" nel sottosuolo della pianura cuneese.* Il Quaternario, **8** (2): 423-434.

CHANG K.H. (1975) - *Unconformity bounded stratigraphic units.* GSA Bull., **86**: 1544-1552.

DELA PIERRE F., PIANA F., FIORASO G., BOANO P., BICCHI E., FORNO M.G., VIOLANTI D., CLARI P. & POLINO R. (2003) - *Note illustrative della Carta Geologica d'Italia alla scala 1:50.000. Foglio 157 "Trino".* APAT, Dipartimento Difesa del Suolo: pp. 147, Litografia GEDA, Nichelino (To).

FALLETTI P., GELATI R. & ROGLEDI S. (1995) - *Oligo-Miocene evolution of Monferrato and Langhe, related to deep structure.* In: R. POLINO, R. SACCHI (Eds.) - Atti Convegno Rapporti Alpi-Appennino, Peveragno (1994), Acc. Naz. Sc., **14**: 1-19.

FIORASO G., BICCHI E., IRACE A. & BOANO P. (2004) - *Manifestazioni carsiche nelle evaporiti messiniane del Monferrato e della Collina di Torino (Italia nord-occidentale): analisi dei meccanismi genetici nel quadro dell'evoluzione pliocenico-quaternaria del Bacino Terziario Piemontese.* Il Quaternario, **17** (2/2): 453-476.

FRANCANI V. (1985) - *Geologia applicata 4. Idrogeologia generale.* CLUP: pp. 316, Milano.

GELATI R., ROGLEDI S. & ROSSI M.E. (1987) - *Significance of the Messinian unconformity-bounded sequences in the Apenninic margin of the Padan foreland basin, northern Italy.* Mem. Soc. Geol. It., **39**: 319-323.

GHIBAUDO G., CLARI P.A. & PERELLO M. (1985) - *Litostratigrafia, sedimentologia ed evoluzione tettonico-sedimentaria dei depositi miocenici del margine Sud-Orientale del Bacino Terziario Ligure-Piemontese (Valli Borbera, Scrivia e Lemme).* Boll. Soc. Geol. It., **104**: 349-397.

GHIELMI M., ROGLEDI S., VIGNA B. & VIOLANTI D. (2002) - *Evoluzione tettono-sedimentaria della successione plio-pleistocenica nel settore del Piemonte centro-meridionale.* 81° Riun. Est. Soc. Geol. It., Riass.: 201-202.

IACCARINO S., CASTRATORI D., CITA M.B., DI STEFANO E., GABOARDI S., MC KENZIE J.A., SPEZZAFERRI S. & SPROVIERI R. (1999) - *The Miocene-Pliocene boundary and the significance of the earliest Pliocene flooding in the Mediterranean.* Mem. Soc. Geol. It., **54**: 109-131.

IRACE A. (2004) - *Il Messiniano Piemontese: nuovi dati da due aree campione.* PhD Thesis: pp. 167, Torino University.

IRACE A., DELA PIERRE F. & CLARI P. (2005) - *Normal and chaotic deposits in the Messinian Gessoso-solfifera Fm. At the north-eastern border of the Langhe domain (Tertiary Piedmont Basin).* Boll. Soc. Geol. It., vol. spec. **4**: 77-85.

MITCHUM R.M., VAIL P.R. & SANGREE J.B. (1977) - *Seismic stratigraphy and global changes of sea-level, part 7: stratigraphic interpretation of seismic reflection patterns in depositional sequences.* In: Seismic Stratigraphy–Applications to Hydrocarbon Exploration. Mem. Am. Ass. petr. Geol., **26**: 135-144.

MOSCA P. (2006) - *Neogene basin evolution in the Western Po Plain (NW Italy).* PhD Thesis: pp. 190, Vrije Universite it Amsterdam.

MOSCA P., POLINO R., ROGLEDI S. & ROSSI M. (2009) - *New data for the kinematic interpretation of the Alps–Apennines junction (Northwestern Italy).* Int. J. Earth Sci. (Geol Rundsch), DOI 10.1007/s00531-009-0428-2.

PIERI M. & GROPPI P. (1981) - *Subsurface Geological Structure of the Po Plain, Italy.* Quad. CNR, Progetto finalizzato Geodinamica, **414**: pp.13, Roma.

REGIONE EMILIA ROMAGNA & ENI – AGIP (1998) - *Riserve idriche sotterranee della Regione Emilia Romagna.* A cura di G. DI DIO: pp. 120, S.EL.CA., Firenze.

REGIONE LOMBARDIA & ENI DIVISIONE AGIP (2002) - *Geolo-*

gia degli acquiferi Padani della Regione Lombardia. A cura di C. Carcano & A. Piccin: pp. 130, S.EL.CA., Firenze.

Rossi M., Mosca P., Polino R., Rogledi S. & Biffi U. (2009) - *New outcrop and subsurface data in the Tertiary Piedmont Basin (NW-Italy): unconformity-bounded stratigraphic units and their relationships with basin-modification phases*. Riv. It. Pal. Strat., **115** (3): 305-335.

Roveri M., Manzi V., Bassetti M.A., Merini M. & Ricci Lucchi F. (1998) - *Stratigraphy of the Messinian post-evaporitic stage in eastern-Romagna (northern Apennines, Italy)*. Giorn. Geol., **60**: 119-142.

Roveri M., Manzi V., Ricci Lucchi F. & Rogledi S. (2003) - *Sedimentary and tectonic evolution of the Vena del Gesso basin (Northern Apennines, Italy): Implications for the onset of the Messinian salinity crisis*. Geol. Soc. Amer. Bull., **115**(4): 387-405.

Roveri M., Lugli S., Manzi V. & Schreiber C. (2008) - *The shallow- to deep-water record of the Messinian salinity crisis: new insight from Sicily, Calabria and Apennine basins*. In: F. Briand (Ed.) CIESM 2008, "*The Messinian Salinity Crisis mega-deposits to microbiology - A consensus report*". CIESM Workshop Monographs, **33**: 73-82.

Servizio Geologico d'Italia (1913) - *Carta Geologica d'Italia alla scala 1:100.000 – Foglio n. 67 Pinerolo*, I edizione, Roma.

Servizio Geologico d'Italia (1931) - *Carta Geologica d'Italia alla scala 1:100.000 – Foglio n. 80 Cuneo*, I edizione, Roma.

Servizio Geologico d'Italia (1969a) – *Carta Geologica d'Italia alla scala 1:100.000 - Foglio n. 56 Torino,* II edizione, Roma.

Servizio Geologico d'Italia (1969b) – *Carta Geologica d'Italia alla scala 1:100.000 -Foglio n. 68 Carmagnola*, II edizione, Roma.

Servizio Geologico d'Italia (1969c) – *Carta Geologica d'Italia alla scala 1:100.000 - Foglio n. 57 Vercelli*, II edizione, Roma.

Servizio Geologico d'Italia (1969d) – *Carta Geologica d'Italia alla scala 1:100.000 - Foglio n. 58 Mortara*, II edizione, Roma.

Servizio Geologico d'Italia (1970a) – *Carta Geologica d'Italia alla scala 1:100.000-Foglio n.70 Alessandria*, II edizione, Roma.

Servizio Geologico d'Italia (1970b) – *Carta Geologica d'Italia alla scala 1:100.000 - Foglio n. 69 Asti*, II edizione, Roma.

Servizio Geologico d'Italia (1971) – *Carta Geologica d'Italia alla scala 1:100.000 - Foglio n. 71 Voghera*, II edizione, Roma.

Servizio Geologico d'Italia (2003) – *Carta Geologica d'Italia alla scala 1:50.000 - Foglio n. 157 Trino*, APAT, Dipartimento Difesa del Suolo, Litografia GEDA, Nichelino (To).

Toth J. (1963) - *A theoretical analysis of groundwater flow in small drainage basins*. J. Geoph. Res., **68**: 4785-4812.

Vigna B. (1996) - *Il contributo dell'analisi sedimentologica nella valutazione della vulnerabilità degli acquiferi.* Atti 2° Convegno Nazionale sulla protezione e gestione delle acque sotterranee: metodologie, tecnologie e obiettivi, Nonantola (Modena) 17-19 Maggio 1995, Quad. Geol. Appl., suppl. 4: 129-141.