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Aquifer building and Apennine tectonics in a Quaternary foreland: the southernmost Lodi plain of Lombardy

Origine degli acquiferi e tettonica appenninica in un avampaese quaternario: la pianura lodigiana meridionale in Lombardia

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ABSTRACT - Syndepositional tectonics competes with climate and eustasy in shaping hydrostratigraphy of foreland basins. In the Po plain basin, Quaternary thrust-folding of the outer Apennine arcs contributed to alluvial evolution, both on the Apennine and the Alpine side. A N-S geological transect in Lombardy, from the former sites of the glacial mouths (North) to the present-day Po river (South), shows the competition of subsidence, glacial evolution and base-level dynamics in delineating aquifer building processes during the Quaternary. Surface geology and geomorphology, subsurface stratigraphy, age constraints from radiocarbon data and palinology, permitted to sketch the architecture and evolution of hydrostratigraphy, above the Lower Pleistocene marine shales that form the regional aquiclude in the Lodi area. Subsurface mapping of the top boundary of the aquiclude shows that this erosion surface is gently folded and progressively lowered from SW to NE, in a sequence of *en-echelon* thrust-related folds. Transitional to alluvial sands and shales (Early to Middle Pleistocene in age) filled local depocentres in the intervening gentle hangingwall synclines, during the decline of folding and uplift rates. Growth of the northernmost and youngest WNW-ESE striking Apennine folds was accompanied by erosion at their flanks and hinges and regressive deposition in coastal to alluvial plain environments. The resulting aquifer bodies are wedges that pinch-out towards the uplifted marine aquicludes and fill incised valleys in their depocentres. The Middle Pleistocene alluvial succession was uplifted by the northernmost Apennine thrusts and locally crops out (San Colombano al Lambro, Zorlesco, Casalpusterlengo). It was eroded during the syn-glacial entrenchment of the river network. Fluvial sands, gravels and intervening mud, filled the local depocentres during three pulses of the Late Pleistocene glaciations. Summing up, the Early-Middle Pleistocene Apennine tectonics acted to: 1) confine the aquifer systems into different depocentres, 2) raise buried hydrogeological divides, 3) force the erosion of hydrogeologic windows, shaping the lateral contacts between pervious alluvial bodies of different ages and 4) constrain aquitard/aquiclude building during the recovery stages of the river network.

KEY WORDS: aquifers, hydrostratigraphy, Lombardy Italy, Northern Apennines, Quaternary, sedimentation and tectonics.

RIASSUNTO - La tettonica sinsedimentaria contribuisce con l'evoluzione climatica ed eustatica a determinare l'architettura idrostratigrafica dei bacini di avampaese. Nel bacino del Po la progradazione verso Nord dei sovrascorrimenti appenninici ha controllato la dinamica alluvionale su entrambi i margini strutturali del bacino. In Lombardia, un transetto N-S dagli anfiteatri glaciali settentrionali all'attuale posizione del Po, illustra la competizione tra subsidenza, dinamica dei livelli di base ed evoluzione glaciale nel delineare i processi genetici dell'idrostratigrafia durante il Quaternario. Geomorfologia, geologia di superficie e di sottosuolo, vincoli cronostratigrafici (date radiocarbonio) e analisi palinologiche consentono di descrivere l'architettura e l'evoluzione idrostratigrafica di un segmento di questo transetto nella pianura Lodigiana meridionale. I sedimenti fini del Pleistocene inferiore marino, costituiscono l'acquicludo basale della successione considerata. La ricostruzione nel sottosuolo del tetto dell'acquicludo mostra il blando piegamento di questa unità, che risulta erosa e progressivamente ribassata da Sud-Ovest a Nord-Est, in una sequenza di pieghe e sovrascorrimenti disposti *en-echelon*. Sedimenti fini e sabbie da litorali ad alluvio-

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nali (Pleistocene inferiore – medio), costituiscono il riempimento dei depocentri associati alle sinclinali di *hangingwall*, deposto durante le fasi di declino dei tassi di piegamento e sollevamento. La crescita delle pieghe appenniniche più settentrionali e recenti (Pleistocene medio) fu accompagnata da erosione dei fianchi e delle creste delle strutture, associata a regressione costiera e continentalizzazione. I corpi acquiferi che ne derivano sono cunei che terminano contro l'acquicludo basale piegato e sollevato e raggiungono i massimi spessori ove riempiono le valli incise ed i depocentri sinformi. La successione del Pleistocene medio fu sollevata dai sovrascorrimenti appenninici settentrionali ed affiora localmente (San Colombano, Zorlesco, Casalpusterlengo). Il susseguente approfondimento erosivo sin-glaciale del reticolo idrografico (Pleistocene superiore) determinò l'incisione di paleovalli, che furono colmate da sedimenti fluviali ghiaioso-sabbiosi durante diverse pulsazioni glaciali discrete, di cui tre almeno sono documentabili stratigraficamente. In sintesi, la tettonica appenninica del Pleistocene inferiore - medio contribuì a: 1) confinare i sistemi acquiferi in depocentri differenti, 2) sollevare spartiacque idrogeologici, deformando l'acquicludo basale, 3) forzare l'erosione di finestre idrogeologiche, originando contatti tra sistemi acquiferi di età differenti e 4) delimitare l'origine degli acquitardi/acquicludi alle sole fasi di recupero fluviale del reticolato idrografico.

PAROLE CHIAVE: acquiferi, Appennino settentrionale, idrostratigrafia, Lombardia, Quaternario, sedimentazione e tettonica.

1. - INTRODUCTION

In Quaternary foreland basins, building of alluvial aquifers is controlled by competing syn-depositional tectonics, glacial cycles and the dynamics of regional vs. local base-levels. The Po plain hydrostratigraphic basin is an important European example of this complex interplay. Since the Miocene, the basin represented the foredeep of the northward advancing Apennine thrusts, that loaded and down-flexured the former Southalpine foreland and thrust belt (PIERI & GROPPI, 1981) (fig. 1).

The influence of Plio-Quaternary Apennine tectonics on aquifer development has been recently illustrated by the regional reconstruction of hydrostratigraphy proposed by ENI-REGIONE EMILIA ROMAGNA (1998) and ENI-REGIONE LOMBARDIA (2002) in the central-eastern Po basin. In Lombardy, a N-S transect from Alps to Apennines clearly shows the interplay among Apennine syn-depositional thrusting, the inherited and active Alpine structures, glacial and base-levels dynamics (glacial pulses on the alpine side, isostatic response to glacial cycles, regression of the Adriatic coastline) (ARCA & BERETTA, 1985; BINI, 1997; CARMINATI *et alii*, 2003; MUTTONI *et alii*, 2003; BARLETTA *et alii*, 2006; SCARDIA *et alii*, 2006), sedimentation rates and sources.

The Quaternary hydrostratigraphic systems of Lombardy formed above the Southalpine thrusts and the interference zone between them and the northernmost Apennine fronts; only the southernmost plain sits on the buried Apennine structures (fig.1). Sediment supply is mostly from the Alpine side and from the axial Po drainage system, the Apennine Quaternary sediments forming a narrow apron to this southern mountain belt (ORI, 1993).

Aiming to investigate the role of the different controls on aquifer building, we are studying a N-S transect from Lake Lario to Po river, encompassing the southern Adda valley and the Adda – Lambro interfluve (PRIN 2007 Project: *Integrated geophysical, geological, petrographical and modelling study of alluvial aquifer complexes characteristic of the Po plain subsurface: relationships between scale of hydrostratigraphic reconstruction and flow models*).

Here we focus on the relationship between Apennine tectonics and the development of Quaternary Alpine-sourced depositional and hydrostratigraphic systems, based on the study of the Lodi segment of the regional transect, that is the region entirely belonging to the Apennine structural domain (fig.1).

The study is based on the traditional integration of surface geology (1:10.000 geomorphological and geological mapping, fig.2) with subsurface reconstruction (correlation of borehole and well data). Age constraints could be obtained from palynological analyses on a deep well close to Lodi, some radiocarbon datings on peat and wood fragments and from published archaeological findings and historical reports about recent hydrography.

2. - THE SOUTHERN LODI PLAIN

The southern Lodi plain is the region between Adda and Lambro rivers, bounded to the South by the present-day Po river course. The so-called "*Livello Fondamentale della Pianura*" *Auct.* (LFP) (CASTIGLIONI & PELLEGRINI, 2001, with references) is the widest morphological unit of the area. The Post-glacial to recent valleys of the major rivers (Adda, Lambro, Po) are entrenched within LFP, into a series of lowered terraces. The isolated relief of San Colombano al Lambro (fig. 1) elevates above LFP at the western end of the area. Together with the subdued relic relieves of Zorlesco and Casalpusterlengo, they correspond to structural culminations of different Apennine thrusts (DESIO, 1965; PIERI & GROPPI, 1981) (fig. 1). The San Colombano hill exposes the uplifted and gently folded marine Miocene and Lower Pleistocene units (Marne di S. Agata Fossili, Formazione di San Colombano; SERVIZIO GEOLOGICO D'ITALIA, 1967), unconformably overlain by the Middle Pleistocene alluvial deposits that form two gently tilted and partly suspended terraces (Invernino Unit and Cascina Parina Unit, in ascending

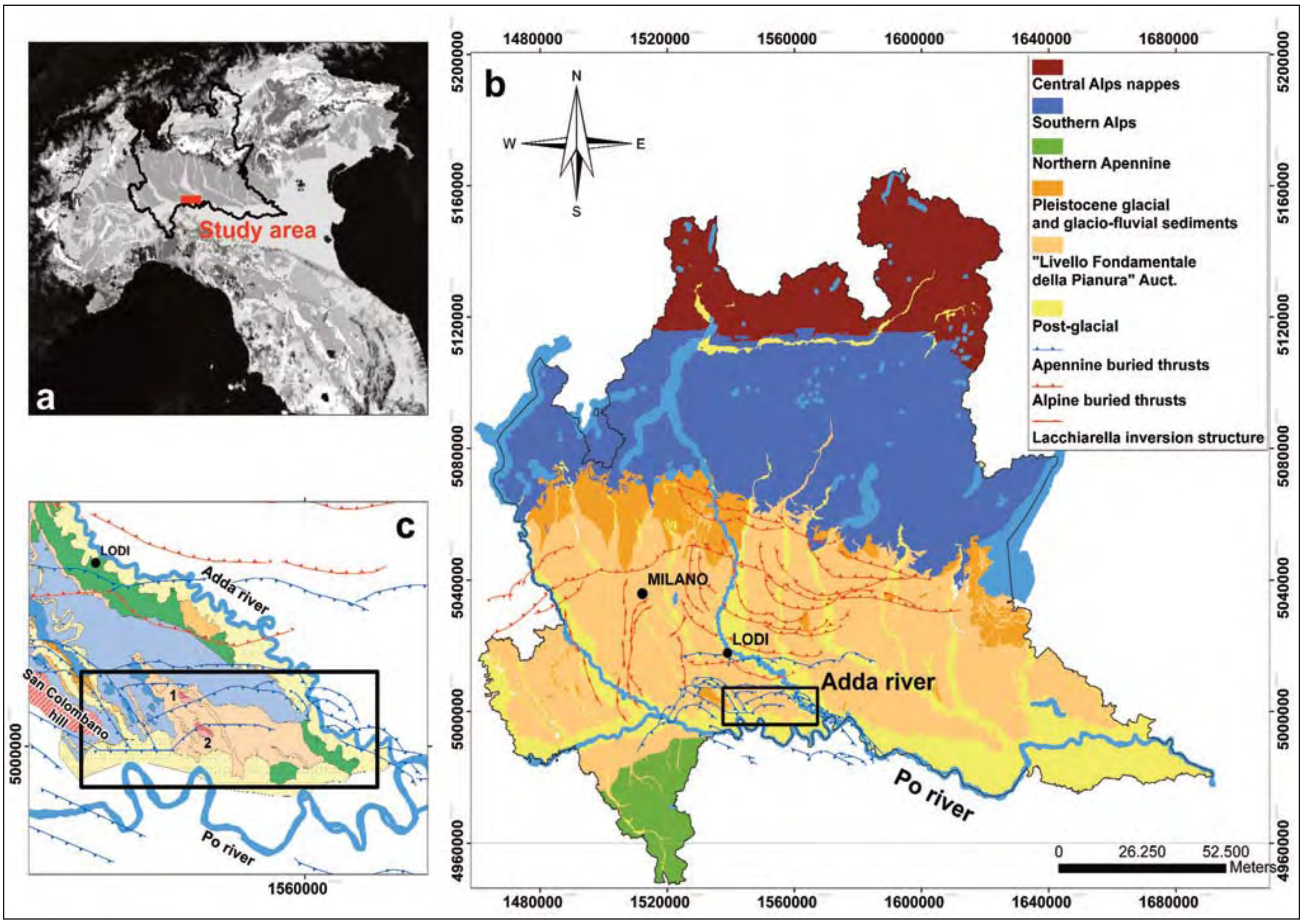

Fig. 1 – (a) Location map of the study area; (b) subsurface structural setting of the area (modified after BIGI *et alii*, 1992 and FANTONI *et alii*, 2004); (c) simplified structural map of the study area (subsurface structures after BIGI *et alii*, 1992 and FANTONI *et alii*, 2004); 1) Zorlesco relic relief; 2) Casalpusterlengo relic relief. Same legend as in figure 2(b).

– *(a) Ubicazione dell'area in studio; (b) inquadramento strutturale dell'area (modificato da* BIGI et alii*, 1992 e* FANTONI et alii*, 2004); (c) carta strutturale semplificata dell'area in studio (strutture di sottosuolo da* BIGI et alii*, 1992 e* FANTONI et alii*, 2004); 1) dosso relitto di Zorlesco; 2) dosso relitto di Casalpusterlengo. La legenda dei colori è la stessa di figura 2(b).*

order; PELLEGRINI *et alii*, 2003, with references). The Casalpusterlengo and Zorlesco gentle relieves expose deeply weathered Middle Pleistocene alluvial units ("Mindel" *Auct.*) with a loess cover (CREMASCHI, 1987). Hence, Quaternary uplift subsequent to Pliocene thrust-folding is documented by this structural and stratigraphic framework. The alluvial Middle to Upper Pleistocene succession covers and surrounds the relieves in the subsurface, resting above the Pliocene-Lower Pleistocene marine clays and sands ("*Villafranchiano*" *Auct.*). At the LFP surface, current literature reports LGM and post-glacial sediments (SERVIZIO GEOLOGICO D'ITALIA, 1967; CASTIGLIONI & PELLEGRINI, 2001; PELLEGRINI *et alii*, 2003) that have been named S.Cristina and Bissone Units by PELLEGRINI *et alii* (2003) in the southernmost sector surrounding the San Colombano hill. The low terraces within the major river valleys are formed by Holocene and recent alluvial deposits (SERVIZIO GEOLOGICO D'ITALIA, 1967; CASTIGLIONI & PELLEGRINI, 2001; PELLEGRINI *et alii*, 2003).

2.1. - SURFACE GEOLOGY

The new geomorphological and geological survey at 1:10.000 reveals the complex patchwork of morphological and stratigraphic units of the region (fig. 2). Based on cross-cut and elevation relations among fluvial traces and terrace scarps, six morphological units have been mapped, forming the LFP surface (LFP 1 to LFP 6 in ascending elevation order; fig. 2). In the same way, the alluvial valley terraces have been subdivided into ten terraced units, pertaining to the different major and minor river domains (fig. 2). Three different orders of relieves elevate above LFP: 1) the very low and deeply carved by human activity relic relieves of Maleo and Meleti (1-3 m above LFP), 2) the well known Casalpusterlengo and Zorlesco relic relieves (DESIO, 1965; CREMASCHI, 1987) and 3) the eastern termination of the San Colombano hill.

Combining the morphological features with sediment descriptions obtained at any exposure and with systematic mapping of surface soil tex-

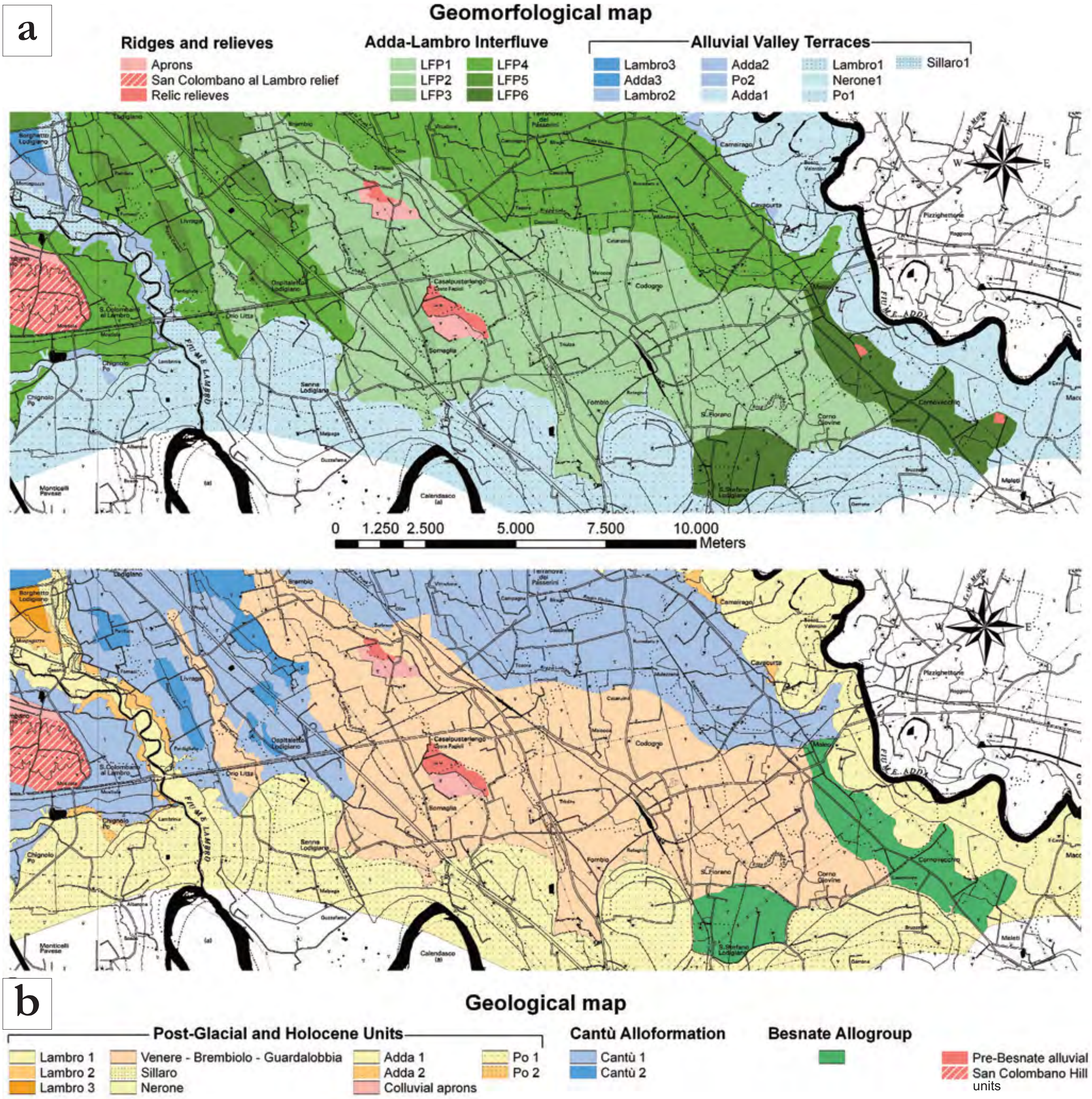

Fig. 2 – (a) Geomorphological map of the study area. Informal geomorphological units are mapped. LFP: "Livello Fondamentale della Pianura" Auct. (b) Geological map of the study area. The allostratigraphic classification has been adopted (regional allostratigraphic scheme after BINI, 1997).
– *(a) Carta geomorfologica dell'area di studio; sono cartografate unità geomorfologiche informali. LFP: "Livello Fondamentale della Pianura" Auct. (b) Carta geologica dell'area di studio; è stata adottata una classificazione allostratigrafica (schema allostratigrafico regionale da* BINI*, 1997).*

ture and Munsell colours, that were collected at every parcel, the frame of surface geological units has been reconstructed (fig. 2).

From the most ancient to the most recent we recognised:

1) San Colombano hill units (undifferentiated in the geological map), including The San Colombano Formation and the Cascina Parina Unit (SERVIZIO GEOLOGICO D'ITALIA, 1967; PELLEGRINI *et alii*, 2003);

2) pre-Besnate alluvial unit (Middle Pleistocene), with loess cover, that is exposed in the Casalpusterlengo and Zorlesco relic relieves ("Mindel" *Auct.*) (fig. 3). The loess weathered profile has been attributed to the last pleniglacial (LGM) by CREMASCHI (1987);

3) Besnate Allogroup (late Middle – Late Pleistocene), that forms two isolated areas cut by the Adda and Po terrace scarps, the former containing the relics of the very subdued relieves of Maleo

Fig. 3 – Exposure of weathered loess (LGM) overlaying deeply weathered alluvial sands (Middle Pleistocene). Casalpusterlengo relic relief (location in figure 2).
– *Esposizione del profilo di alterazione del loess (LGM) che ricopre i sedimenti alluvionali profondamente alterati (Pleistocene medio) del dosso relitto di Casalpusterlengo (ubicazione in figura 2).*

(Cascina Chiesiolo) and Meleti (fig. 2). Poorly preserved weathering profiles with 10YR Munsell colour characterize the top of this alluvial unit of trough cross-bedded sands with minor gravel bars and silty-clay flood plain lenses; very thin, weathered loess cover has been preserved at one site only;

4) Cantù Alloformation (Late Pleistocene, LGM), that represents the surface unit of the northern side of the area. It spreads out of the Sillaro *l.s.* palaeovalley (VEGGIANI, 1982; BERSEZIO, 1986), and flanks the Lambro entrenched course (fig. 2), forming two minor terraced units bounded by a very low scarp (< 1m). At the surface the Cantù Alloformation is made by very poorly weathered cross-bedded sands and sandy silts with clay layers;

5) the Post-Glacial and Holocene units (latest Pleistocene – Holocene and recent) include the terraced alluvial sediments (sands and recycled gravels) of the Lambro, Adda and Po river valleys, the most recent fluvial silts and sands of the Sillaro underfit stream, the veneer of silty and sandy fluvial deposits above the LFP, laid down by the minor natural and agricultural hydrographic network, and the colluvial aprons of the isolated relieves.

The new geological and geomorphological maps show that the subdued complex morphology of the LFP corresponds to a patchwork of Pleistocene units (pre- and post-LGM) cut by the Post-glacial valleys, partly buried by very thin Post-glacial, Holocene and recent alluvial units, above which the uplifted relics of the Middle Pleistocene stratigraphy are elevated.

2.2. - SUBSURFACE ARCHITECTURE

Subsurface geology has been reconstructed and validated by correlation of borehole and well data (fig. 4), in combination with surface geology, adopting the following procedure: i) facies and compositional analysis of logs and cores, calibrated to outcrops and exposures; ii) assessment of vertical textural and compositional trends at each data point; iii) hierarchic classification of sedimentary units and bounding surfaces. An informal stratigraphic classification has been adopted in the sub-

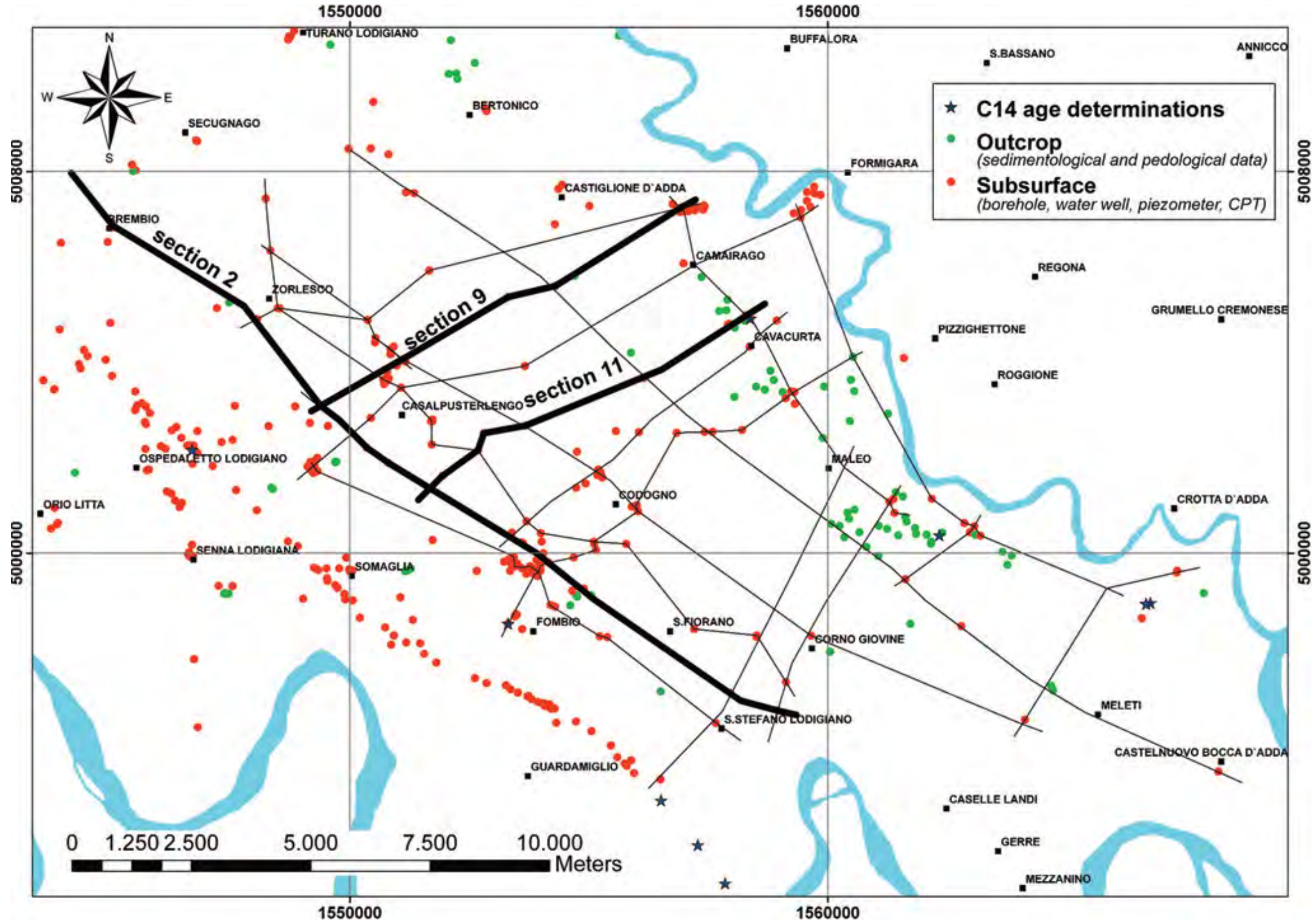

Fig. 4 – Location map of subsurface data and traces of geological and hydrostratigraphic cross-sections. Exposures (outcrops and excavations) and sites of radiocarbon age determinations are reported.
– *Mappa di ubicazione dei dati di sottosuolo e tracce delle sezioni geologiche ed idrostratigrafiche. Sono riportate le esposizioni (affioramenti e scavi) ed i siti per le determinazioni delle età radiocarbonio.*

surface, following the scheme proposed by Bersezio *et alii* (2004); iv) correlation of the highest rank boundaries and sedimentary bodies; v) refinement of correlation, for reconstruction of low rank units and surfaces; vi) assessment of chronostratigraphy, based on radiocarbon data (Latest Pleistocene) and existing palynological data (Middle Pleistocene); vii) stratigraphic interpretation and classification, after integration with surface geology (down-surface tracing of all the emerging Quaternary units and boundaries, with specific emphasis on the Lower Pleistocene marine clays and sands exposed at San Colombano) and regional literature; viii) 3-D mapping and subsurface modelling of the highest rank stratigraphic boundaries and units. A grid of 16 geological cross-sections has been drawn (fig. 4); here we present three cross sections (fig. 5) and the result of 3-D modelling of buried stratigraphy for the entire study area (fig. 6).

Four highest rank stratigraphic units (GU0 to GU 3) have been identified, the outstanding features of which are here described in ascending stratigraphic order.

Geological Unit 0 (GU0) is formed by blue, cyan and dark grey clays with intervening sand and gravel/conglomerate layers. Mollusk shells are recurrently recovered in wells within these clays, that are interpreted as the marine substratum to the Quaternary alluvial succession. Down-tracing from the San Colombano outcrop area permits to correlate this unit with the San Colombano Formation (Early Pleistocene). GU0 is gently folded in a WNW-ESE trending anticline (fig. 5, section 2, and fig. 6), whose hinge plunges towards WNW and ESE (Casalpusterlengo anticline). A very gentle and wide syncline separates this fold from the eastern gentle anticline (Maleo – Chiesiolo anticline). An erosional plateau is carved on the eastern limb of the Casalpusterlengo anticline (surface S10).

Geological Unit 1 (GU1). This unit crops out on the Casalpusterlengo and Zorlesco relic relieves (fig. 2), i.e. on the uplifted hinge of the homonymous anticline. Based on geometry and cross-cut relationships, the lower boundary of GU1 (surface S10) can be interpreted as an erosion surface, that marks the angular unconformity between GU0 and

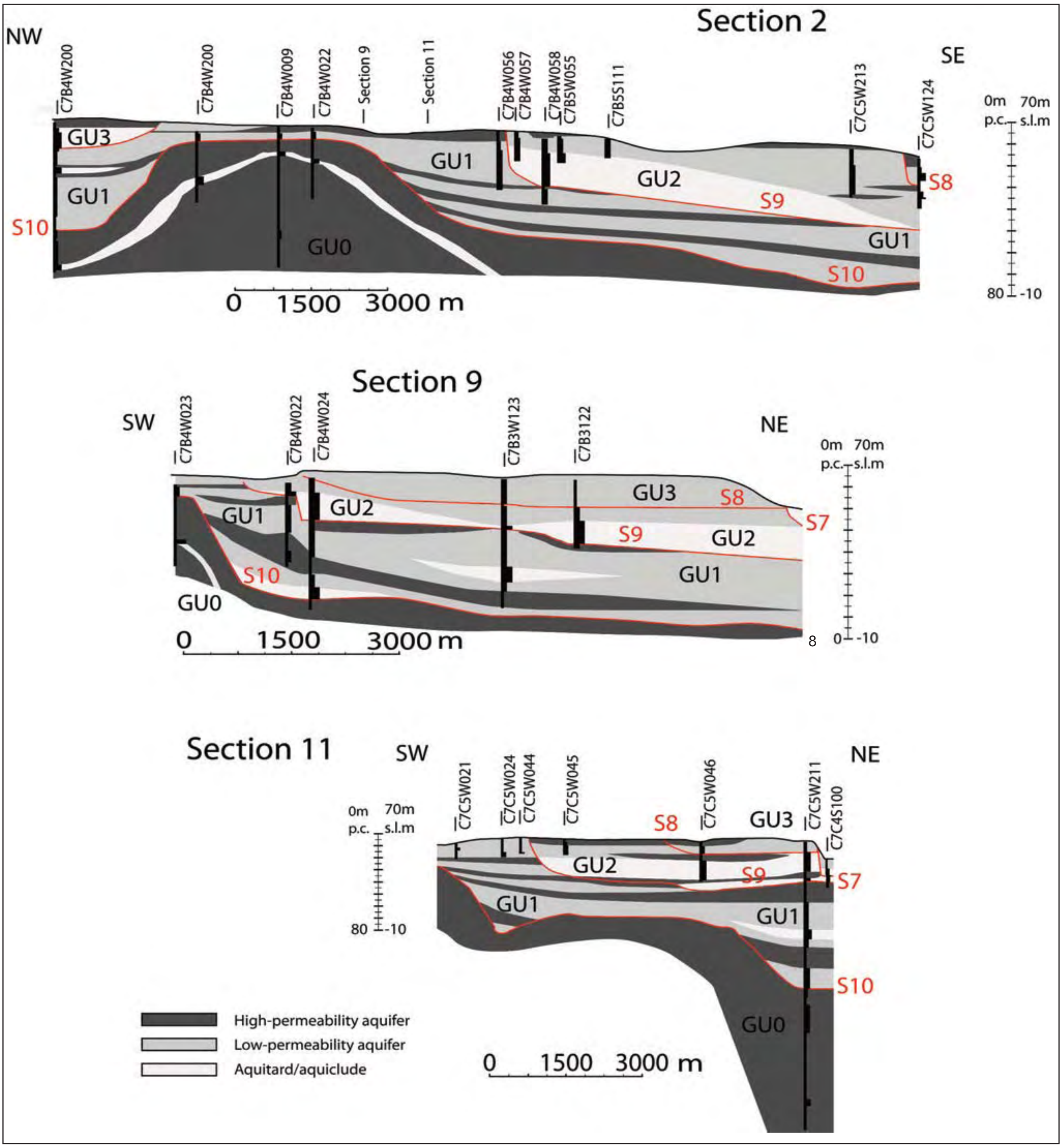

Fig. 5 – Three selected geological and hydrostratigraphic cross-sections in the Southern Lodi plain (location in fig. 4). S: bounding surfaces of maximum hierarchic order; GU informal subsurface geological units of maximum rank. The boundaries of the very thin topmost surface units, just below the ground surface, have been omitted for clarity.

– Tre sezioni geologiche ed idrostratigrafiche selezionate nella pianura lodigiana meridionale (ubicazione in fig. 4). S: limiti stratigrafici di ordine gerarchico massimo; GU: unità geologiche informali di sottosuolo, di ordine massimo. I limiti delle unità superficiali, molto sottili, sono stati omessi per chiarezza.

GU1. In the subsurface, within GU1, four sub-units have been recognised (fig. 5), each formed by a fining upwards trend from gravelly-sands to sands and sandy-silty clays. The uppermost sub-unit is exposed in the Casalpusterlengo relief (fig. 4). The lower three sub-units of GU1 wedge-out and lap onto both sides of the Casalpusterlengo anticline, showing decreasing upwards mild deformation towards the limbs of the fold. The uppermost sub-unit smoothes the fold hinge, resting above a flat erosion segment of surface S10 (fig. 5 and 6). Based on outcrop and subsurface sedimentary features, we interpret GU1 as the alluvial succession that unconformably overlays the ma-

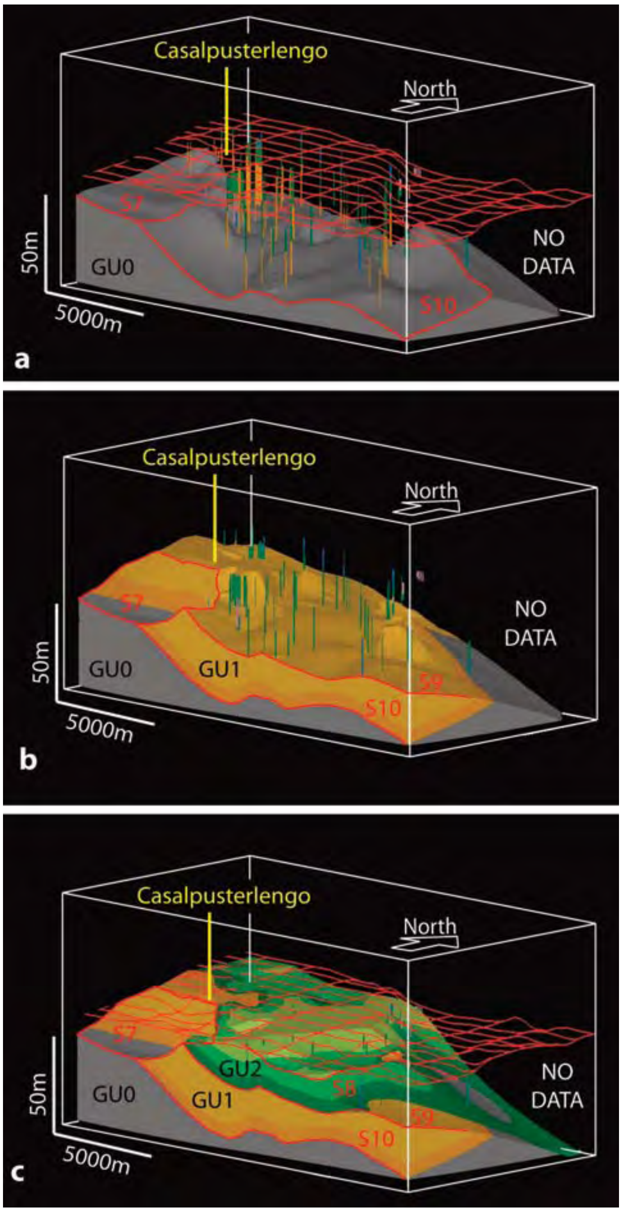

Fig. 6 – Three-dimensional models of subsurface geology of the Southern Lodi plain. Labels as in figure 5. Vertical dashes: well and borehole logs (location in figure 2). A recomputed DTM (based on 1:10.000 CTR *Regione Lombardia* topography, with dm vertical accuracy) is reported as a red grid in models (a) and (c).

– Modelli tridimensionali della geologia di sottosuolo della pianura lodigiana meridionale, corrispondente all'area di studio. Sigle come in figure 5. Barre verticali: dati stratigrafici di sottosuolo (ubicazione in figura 2). Un DTM ricalcolato con precisione verticale 1 dm, sulla base della carta topografica CTR Regione Lombardia in scala 1:10.000, è riportato in rosso come griglia nei modelli (a) e (c).

rine Lower Pleistocene succession. Down-tracing of stratigraphy from outcrops of the San Colombano area permits to correlate parts of this unit to the Invernino and Cascina Parina units (Middle Pleistocene; PELLEGRINI *et alii*, 2003, with references therein). Palynological data from a well in the neighbourhoods of Lodi suggest to attribute the equivalent sandy gravel succession of the Lodi synformal depocentre to the Middle Pleistocene (RIGATO, 2007). These data help to attribute GU1 to the regional glacio-fluvial cycles of the Middle Pleistocene (MUTTONI *et alii*, 2003), plausibly equivalent to the Specola and/or Binago alloformations, following the classification of Pleistocene glacial and glacio-fluvial sediments proposed by BINI *et alii* (2004).

Geological Unit 2 (GU2) partly fills a composite erosional depression, marked by surface S9 (fig. 5 and 6), that surrounds the San Colombano and Casalpusterlengo gentle anticlines. In the most complete successions, the stepped (*i.e.* terraced) S9 surface is covered by three gravel-to-sand, to silty clay with peat, fining upwards sub-units of alluvial environment. The uppermost one is exposed at the ground surface close to the Adda and Po terrace scarps, in the Maleo–Meleti area (Cascina Chiesiolo relic relief; fig. 2). Physical correlation in the subsurface permits to correlate GU2 with the homonymous succession of the northern Lodi plain that was attributed to the Besnate Allogroup and dated as Middle p.p. - Late Pleistocene, by radiocarbon age determinations of the topmost sediments, palynology and stratigraphic position (BERSEZIO *et alii*, 2004). GU2 terminates against the terraced flanks of the mentioned anticlines, thickens away from them and attains its maximum thickness in the erosional depocentres that are located some kilometres eastward of these positive structures (fig. 6). Surface geology and subsurface correlations suggest that GU2 did not suffer active folding stages, representing the seal of the Pleistocene Apennine structures, eventually involved by differential uplift/subsidence after the end of active tectonic deformation.

Geological Unit 3 (GU3) is soled by erosion surface S8 that truncates GU2 and GU1, carving some terraced valleys, the latest and most evident of which is at the southern end of the Sillaro palaeo-river (fig. 5 and 6). GU3 is characterized by different local successions in the different river valleys; as a general rule it is formed by at least two fining upwards sub-units, sandy gravel to sandy silt, interpreted as meandering river sediments and attributed to latest Pleistocene (LGM to initial post-Glacial) based on radiocarbon datings (BERSEZIO *et alii*, 2004; BERSEZIO *et alii*, 2007). GU3, that is exposed widely in the study area, has been correlated to the Cantù Alloformation (LGM) following the classification of BINI *et alii* (2004).

2.3. - SUMMARY OF GEOLOGICAL CONSTRAINTS TO HYDROSTRATIGRAPHY

The geological reconstruction indicates how Apennine active thrusting contributed to shape the shallow and subsurface geometry of sedimentary bodies. 1) Early p.p. to Middle p.p. Pleistocene folding of the San Colombano and Casalpusterlengo very gentle thrust-related anticlines, raised the Lower Pleistocene marine succession (GU0), before and during deposition of the first alluvial units of the region (GU1). This evolution shaped the alluvial depocentres in the eastern sector of the study area and determined the lateral termination of the alluvial units against the uplifted marine substratum (fig. 6). 2) Middle p.p. to Late Pleistocene entrenchment of hydrography (terraced GU2 above S9, terraced GU3 above S8) occurred during differential uplift of positive structures vs. depocentral areas. This is testified also by the flat erosion surfaces carved at different elevations above the hinges and flanks of the folds (fig. 6). One exposed example is the erosion surface at the top of the relic relief of Casalpusterlengo, the origin of which can be constrained to the Late Pleistocene by superposition of an LGM loess profile (CREMASCHI, 1987) above the truncated topmost sub-unit of GU1. The Late Pleistocene sediments (GU2 and GU3) seal the previous deformation structures at different stratigraphic levels and elevations. 3) During the Post-glacial to recent entrenchment of the major river valleys (Adda, Lambro, Po) the existing stratigraphy was truncated. The relationship between the inherited structures and the location and trends of the terraced river valleys, and of the river courses within them, is apparent (fig. 1 and 2). During the same time span, a veneer of fine-grained alluvial deposits blanketed the Adda – Lambro interfluve, corresponding to the LFP surface.

3. - HYDROSTRATIGRAPHY

The regional hydrostratigraphic framework of entire Lombardy has been recently sketched by ENI – REGIONE LOMBARDIA (2002). Four Aquifer Groups have been identified, named D to A in ascending order. Groups A and B are hosted by the Middle – Upper Pleistocene alluvial succession, groups C and D roughly correspond to the transgressive-regressive cycles (from open marine to coastal and alluvial) of the lower part of the Middle Pleistocene and Lower Pleistocene succession (including the "*Villafranchiano*" *Auct.*). The salt/freshwater interface occurs within the mostly marine and deepest Group D, rarely raising into the lowest part of transitional Group C.

The study area shows how complex might be the hydrostratigraphic reconstruction in the region subjected to the strong local control of active Apennine thrusts, combined with variable sediment supply from the northern sources during the Middle – Late Pleistocene cycles of glacial advance and retreat. A qualitative attempt to classify the stratigraphic architecture in terms of hydrostratigraphy has been made, after textural parametrization of the sedimentary bodies, at their lowest hierarchic rank (minimum genetic sequences within sub-units). The result is displayed in figure 5, in which a rough threefold subdivision into high-permeability aquifers (mostly gravel), low permeability aquifers (mostly sand) and aquitards/aquicludes (mostly clays and silts with scattered sand-gravel lenses) has been adopted. In the study area, the unsaturated zone occupies the uppermost 5 – 10 m below ground surface, all the other aquifer units being saturated with freshwater. High concentrations of salt solutes have been detected in those parts of the aquifers that are adjacent to the San Colombano and Casalpusterlengo anticlines (ARIATI *et alii*, 1988; ALFANO & MANCUSO, 1996)

Dealing with the architectural component of hydrostratigraphy, that is the aim of this paper, we can observe that: i) the basal aquiclude (GU0, marine Lower Pleistocene) is uplifted by folding, forming hydrogeological divides between depocentres that collected the alluvial aquifers (fig. 5); ii) aquitard layers subdivide the deepest low-permeability aquifer hosted by GU1 into several aquifer systems (fig. 5), some of which host groundwater bearing a strong hydrochemical signature of mixing with marine connate waters (ARIATI *et alii*, 1988); iii) the depocentral areas, far-away from the uplifted structures, host the thickest and coarsest aquifers (uppermost GU1 and GU2; fig. 5), within wide and deeply entrenched palaeo-valleys, that contour the positive structures and wedge-out above erosion surfaces (S10 and S9); iv) in the LFP area (Adda – Lambro interfluve) the vadose zone and the shallow phreatic surface are almost everywhere hosted by GU3 (LGM) and Post-glacial to Recent fine-grained and sandy sediments, but in the local exposure areas of GU2 (Besnate Allogroup) and GU1. Within the major river valleys, the unsaturated zone corresponds to the gravelly and/or sandy Post-glacial to recent deposits, mostly derived after recycling of the Pleistocene alluvial units.

4. - CONCLUSIONS

Surface geology and geomorphology, subsurface stratigraphy, age constraints from radiocarbon data and palinology, permitted to sketch the architecture and evolution of hydrostratigraphy, above the Lower Pleistocene marine shales (GU0) that form the regional aquiclude in the Southern Lodi plain. Subsurface mapping of the aquiclude (GU0) and of its top boundary (S10) shows that they are gently folded and progressively lowered from SW to NE, in a sequence of en-echelon thrust-related folds (San Colombano, Casalpusterlengo). The growth of these northernmost and youngest WNW-ESE striking Apennine folds was accompanied by erosion at their flanks and hinges and regressive deposition in alluvial plain to alluvial environments. As a result, Middle Pleistocene alluvial sands and shales filled the depocentres hosted by the intervening gentle synclines, during the decline of folding rates, forming a group of at least partly confined aquifer systems (GU1). The resulting aquifer bodies are gently folded wedges that pinch-out towards the uplifted marine aquicludes and fill incised valleys in their depocentres. During the syn-glacial entrenchment of the river network (late Middle Pleistocene – Late Pleistocene), the major group of aquifer systems was built within deeply terraced valleys (GU2, Besnate Allogroup), under control of glacial pulses and differential uplift/subsidence of the depocentres vs. folded areas. The latest glacial cycle (LGM; GU3 and Postglacial units) shaped the present-day geomorphology, building the vadose zone above terraced erosion surfaces (S8 and S7).

In summary, the Early-Middle Pleistocene Apennine tectonics acted to: 1) confine the aquifer systems into different depocentres, 2) raise buried hydrogeological divides, 3) force the erosion of hydrogeologic windows, shaping the lateral contacts between pervious alluvial bodies of different ages and 4) constrain aquitard/aquiclude building during the recovery stages of the river network.

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