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# AQUIFER ARCHITECTURE OF THE QUATERNARY ALLUVIAL SUCCESSION OF THE SOUTHERN LAMBRO BASIN (LOMBARDY - ITALY)

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ABSTRACT: Bersezio R. *et al*., *Aquifer architecture of the quaternary alluvial succession of the southern Lambro basin (Lombardy - Italy)*. (IT ISSN 0394-3356, 2004).
Aquifer stratigraphy of the sector of the Pleistocene – Holocene alluvial plain of Lombardy, run by the Lambro valley system south of Milan, has been reconstructed on the basis of geological mapping at 1:10.000 and subsurface interpretation and correlation of more than 150 among water wells, boreholes and deep excavations. The Middle (?) – Late Pleistocene sedimentary evolution of this sector includes four major progradation cycles of alluvial depositional systems that migrated from the alpine northern side towards the axial palaeo-Po depositional system. These cycles were governed by Pleistocene glacial cycles, in combination with ramp-folding of the San Colombano – Salerano apenninic anticlines and minor uplift of the alpine side. Every major cycle is soled by an erosion surface, and is shaped by minor fining upward sequences. Both major and minor sequences record at first the advance of coarse-grained units (distal braided alluvial fan or sandy braid plain) which fringe-out south-eastwards into meandering fluvial systems, and are replaced upwards by alluvial plain fines, which close the sequences. Physical stratigraphy and geomorphology, analysis of facies associations, characterisation of gravel composition, radiocarbon dating on 4 peat and plant relic samples and findings of transported artefacts allowed the correlation of the four cycles with the regional evolution. The Post Glacial meandering depositional systems of the deeply entrenched Lambro valley system (Unit 4, Holocene; Unit 5, historical), are cut into the braided stream to meandering depositional systems that developed during L.G.M. times, at present outside the Lambro valley (Unit 3, Late Pleistocene). These represent the uppermost aquifer unit, i.e. the phreatic – non saturated zone. The underlying Unit 2 (Late Pleistocene) can be correlated with the Besnate Allogroup, and therefore developed during the corresponding glaciations. It is formed by three stacked sequences, controlled by glacial cycles, which are deeply scoured into the lowermost succession that could be studied (Unit 1 Middle ? – Late Pleistocene ?). It represents the most important and permeable intermediate aquifer unit, that is only partly confined by the flood-plain fines of the uppermost sub-unit 2C.

*RIASSUNTO: Bersezio R.* et al., Architettura degli acquiferi nella successione alluvionale quaternaria del bacino del fiume Lambro (Lombardia, Italia). *(IT ISSN 0394-3356, 2004).*
*Nella Pianura Padana la conoscenza della geologia delle successioni continentali quaternarie, costituisce la base per la realizzazione dei modelli idrostratigrafici, di gestione delle acque sotterranee e per la programmazione della tutela e del risanamento ambientale. A questi fini è critica la comprensione dell'architettura deposizionale a scale diverse, sia per l'elaborazione di schemi idrostratigrafici regionali, sia per la modellazione del flusso e del trasporto degli inquinanti. In questa prospettiva la valle del Lambro, a sud di Milano, offre un caso di interesse generale per: 1) le relazioni tra acque superficiali fortemente compromesse ed acque sotterranee, 2) l'architettura deposizionale alluvionale altamente eterogenea, 3) la buona disponibilità di dati di sottosuolo. Si è pertanto avviato un progetto di studio stratigrafico-sedimentologico e geofisico, cui farà seguito la modellazione dell'eterogeneità degli acquiferi a diverse scale. Vengono qui presentati i risultati della ricostruzione geologica ed idrostratigrafica relativa al settore compreso tra Melegnano (a nord) e S.Angelo Lodigiano (a sud), sulla base del rilevamento in scala 1:10.000 e dello studio stratigrafico e petrografico di affioramenti, sondaggi e pozzi per acqua (173 punti di osservazione su un'area di circa 60 Km$^2$, con profondità di indagine di 100 m).*
*L'area in studio si sviluppa nella pianura lombarda meridionale, caratterizzata da pendenze medie della topografia minori di 1.5‰, dall'approfondimento degli alvei fluviali attuali, che decorrono entro scarpate di terrazzo di altezza decametrica e dalla presenza di un rilievo collinare di origine tettonica, con sollevamento attivo durante il Pleistocene (Colle di San Colombano), poco a nord del livello di base del Po. Le tracce meandriformi dell'idrografia attuale e dei paleoalvei sono scolpite nella superficie del cosiddetto "Livello fondamentale della pianura". Sono state suddivise cinque unità deposizionali informali, caratterizzate su basi stratigrafiche, petrografiche e di facies, che comprendono, dal basso:* Unità 1, sistemi deposizionali sabbioso–argillosi, *con caratteri indicativi di ambiente fluviale meandriforme, con tetto individuato tra 50 e 70 m di profondità, da nord verso sud. Essa comprende sequenze di facies* fining-upwards*, costituite da sabbie medie e fini, raramente ghiaiose, passanti a sedimenti fini, argilloso-limosi, con paleosuoli organici bruni. L'*Unità 2, sistemi deposizionali ghiaioso – sabbiosi, *comprende due sub-unità ghiaioso–sabbiose (2A e 2B), incontrate dalle perforazioni a profondità di 20-25 m, interpretabili come tipiche di un ambiente di conoide alluvionale distale a canali intrecciati. Esse passano a tetto ad una terza sub-unità (2C), sabbioso–limoso–argillosa, organizzata in sequenze di facies* fining-upwards *chiuse a tetto da argille organiche e paleosuoli bruni mal drenati, interpretabile come il prodotto della transizione tra un sistema di deposizione a canali intrecciati (settentrionale) ed un sistema di deposizione meandriforme (meridionale). Le datazioni $^{14}$C relative alla base dell'unità 2C hanno fornito età (non calibrate) comprese tra 23.145± 340 a BP e 24.145±160 a BP; il tetto della stessa unità è stato datato a 22.035±300 a BP. Le ghiaie che appartengono a questo gruppo di unità hanno composizione caratterizzata dall'abbondanza dei clasti metamorfici e magmatici, ampiamente prevalenti sui clasti sedimentari di provenienza sudalpina locale. L'*Unità 3, sistemi deposizionali sabbiosi, *è costituita da sedimenti localmente affioranti, organizzati in due sub-unità (3A e 3B) formate da lenti sabbioso-ghiaiose e/o sabbiose, sviluppate tra il piano campagna e la profondità di 10-15 metri. A queste si associano sedimenti fini limoso-argillosi bruni, con paleosuoli organici intercalati. Questi corpi, talora delimitati da orli relitti di terrazzi di altezza metrica, comprendono i depositi dei corsi d'acqua meandriformi delle paleovalli del Sillaro (ad est del Lambro) e del paleoalveo Carpiano-Bescapè (ad ovest del Lambro). Questi sedimenti vengono a contatto, per mezzo di una superficie erosionale inferiore, sia con i sedimenti fini a tetto dell'unità 2C, sia con le sabbie e ghiaie ad essi sottostanti (unità 2C inferiore e 2B). Il tetto dell'unità 3A è stato datato in un punto di misura compreso tra il dominio del Lambro e quello del Sillaro, a 18.785±230 a BP, calibrabile ad età comprese tra 19.909 e 20.785 cal BC. Le* unità 4 e 5, sistemi deposizionali antichi e post-glaciali della valle del Lambro*, sono costituite da sedimenti di ambiente fluviale meandriforme, organizzati in unità minori, contenute all'interno delle scarpate che delimitano questo sistema vallivo. Si tratta di depositi sabbiosi e ghiaioso-sabbiosi (barre di meandro e ventagli di rotta) associati a subordinate successioni di sedimenti fini, limosi ed argillosi, di argine, piana di esondazione e di abbandono di canale. Questi sedimenti si distribuiscono su tre ordini di terrazzo, sopraelevati più di 10 m rispetto alla quota dell'alveo di massima piena attuale del Lambro. Il terrazzo più recente, ancora sopraelevato fino ad oltre 6 metri sulla piana attuale, rappresenta le fasi di deposizione avve-*

*nute con certezza in tempi storici, databili per il sistematico ritrovamento di frammenti di laterizi e manufatti, da romani a rinascimentali, embricati nelle forme di fondo ghiaiose (sub-unità 5B).*
*La composizione delle ghiaie delle unità 3, 4 e 5 differisce fortemente dalle sottostanti, per la minima quantità di litici metamorfici e cristallini in genere, per il grado di alterazione di questi ultimi, che ne suggerisce il riciclo, e per la dominanza dei clasti sedimentari provenienti dalle unità mesozoiche sudalpine delle Prealpi Lombarde.*
*Sulla base della ricostruzione stratigrafica e deposizionale è stato realizzato un primo modello geometrico della successione pleistocenica superiore, che consente di prevedere e quantificare l'estensione e la localizzazione delle unità limoso-argillose (acquitardi) e dei principali corpi ghiaioso-sabbiosi (acquiferi). Il modello consente una stima del grado di connettività verticale ed orizzontale tra unità acquifere diverse, fornendo una prima approssimazione relativa alle relazioni tra acque superficiali e prima falda (o "Gruppo degli Acquiferi A", ENI-Regione Lombardia 2002).*
*L'evoluzione geologica ricostruita tra il Pleistocene superiore e l'attuale, evidenzia due cicli di progradazione della parte distale di un sistema deposizionale di conoide alluvionale settentrionale (unità 2A-2C), su un sottostante sistema fluviale a canali stabili e trasporto misto, verosimilmente di tipo meandriforme (unità 1A-B). L'insieme di questi sistemi deposizionali era alimentato da valli in grado di drenare la catena alpina fino allo spartiacque. Il sistema deposizionale dell'unità 3 appartiene verosimilmente all'ultimo massimo glaciale (L.G.M.), mentre le unità 4 e 5 rappresentano le unità post-glaciali, sviluppatesi durante l'Olocene, quando la presenza dei laghi pedealpini ed il mutato quadro morfo-climatico, determinarono la prevalenza dell'alimentazione locale dalle Prealpi, l'ampliamento verso nord dei sistemi deposizionali meandriformi, l'avulsione (Sillaro, paleoalveo Carpiano Bescapé) e/o il rapido approfondimento (Lambro, Lambro meridionale) delle valli fluviali.*

Key-words: alluvial sediments, aquifer sedimentology, hydrostratigraphy, Quaternary, Lombardy.

*Parole chiave: idrostratigrafia, Lombardia, Quaternario, sedimenti alluvionali, sedimentologia degli acquiferi.*

## 1 - INTRODUCTION

Modelling groundwater flow in alluvial aquifers requires the preliminary elaboration of conceptual models of subsurface geology, including hydrostratigraphic properties of the sediments. The hydrostratigraphic models must take into account the geometry of aquifer/aquitard/aquiclude units, their hydrodispersive properties, their connectivity and must include the evaluation of incertitude on the parameters (see for instance Anderson, 1997 or Huggenberger & Aigner, 1999, with references therein). A multidisciplinary approach is therefore necessary, by the integration of geological, sedimentological, geostatistical and numerical methods, with emphasis on the geological reconstruction. We apply such an approach to the study of aquifer dynamics of the southern Lambro valley, south of the Milan conurbation, close to the confluence with the main axial fluvial system of the present day Lombardy plain, the Po river (Fig. 1). The final goal is that of elaborating the hydrostratigraphic model of the main Aquifer Groups (Regione Lombardia-ENI, 2002), with attention to the shallowest hydrostratigraphic units of Middle p.p. - Upper Pleistocene age, in the alluvial plain between Ticino and Adda rivers, south of Milan (Figs. 2 and 3) and of the Holocene to recent units above them. This will provide the basis for modelling groundwater flow through these Aquifer Groups and their confining layers.

The research is in progress, following three steps: a) survey and elaboration of the geological model, incorporating geometrical, stratigraphic, petrographic and facies information at several scales (i.e. from surface mapping to outcrop sedimentology, boreholes, well and log analyses); b) elaboration of the hydrostratigraphic model, which will be inclusive of the semiquantitative geological model and of the geostistical 3D reconstruction, after which the evaluation of incertitude on estimates of distribution of hydrodispersive properties of the individual units will be possible; c) numerical modelling of flow, starting with the attempts to upscale local properties to the wider regional scales. Here we present the semiquantitative geological and hydrostratigraphic model. The results of numerical modelling of groundwater flow will be addressed elsewhere.

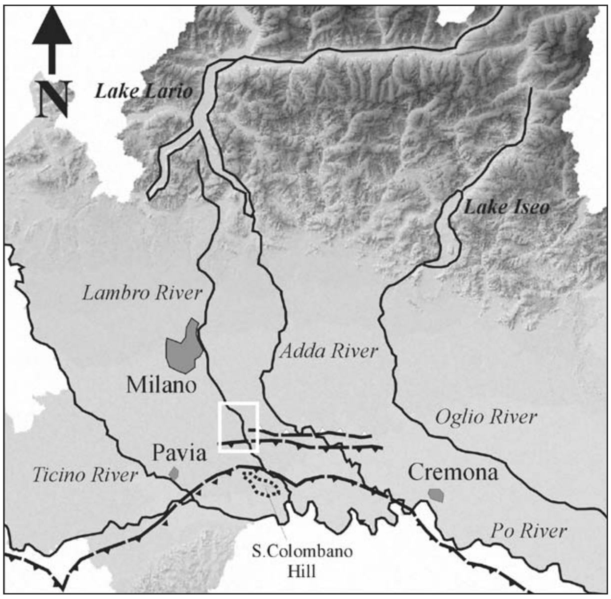



Fig.1 - Location map of the Lambro valley system and study area. The external thrust fronts of the Apennines are indicated with bold ornamented triangles; the most external thrust front of Southern Alps is ornamented with empty triangles. The study area is framed in white.

*Ubicazione del sistema vallivo del Lambro e dell'area in studio. I fronti esterni dei sovrascorrimenti appenninici sono indicati con triangoli neri; i fronti esterni Sudalpini sono indicati con i triangoli bianchi. L'area in studio è riquadrata in bianco.*

## 2 - REGIONAL GEOLOGY OF THE LAMBRO AREA

The Lambro valley is entrenched into the alluvial plain of southern Lombardy (Fig.1), which is characterised by a very low slope gradient (less than 1.5‰) towards the Po base - level. The present-day fluviatile network, south of Milan, is confined within narrow terraced valleys, bounded by scarps which are 5 - 30 m in height. At present the Lambro valley runs across the area between the major valleys of Ticino (west) and Adda (east). The catchment areas of these two rivers reach the core of the Alps, crossing the sedimentary South-Alpine nappes, their Variscan metamorphic basement units and the metamorphic Alpine nappes of the Central Alps, just north of the Insubric Line. Downstream their mountain course, two large alpine lakes (Verbano and Como lakes) started to sieve detritus fed from the internal Alps, since post-glacial times. On the contrary, the Lambro catchment is much smaller (similar to the Olona and Seveso basins west of it), reaching at present only the southernmost reliefs of the South-Alpine edifice, where only Meso- and Cenozoic rocks are exhumed.

Outside and above the Holocene valleys, south of Milan, an abandoned fluviatile network is sculptured into the so-called "Livello Fondamentale della Pianura" (see Castiglioni & Pellegrini, 2001; Marchetti, 2001 with references therein). This consists of several groups of NW – SE meandering traces bounded by low height scarps (always less than 5 m in height), which show a marked change in strike downstream (i.e. southward), to a WNW – ESE average direction (Bersezio, 1986). These relics of abandoned rivers are sometimes run by underfit streams with 2nd order meanders (e.g. Roggia Barona and Colatore Lissone, west of the Lambro river, Sillaro underfit stream, east of the same; Veggiani, 1982; Bersezio, 1986).

The San Colombano hill rises at the southern end of the Lambro valley (Fig. 1). It developed as a consequence of tectonic uplift of an Apenninic anticline, which deformed at least the lower Pleistocene and probably also the Middle Pleistocene sediments (Desio, 1965; Ariati *et al*., 1988; Alfano & Mancuso, 1996; Tellini & Pellegrini, 2001; Fantoni *et al.*, 2003 with references).

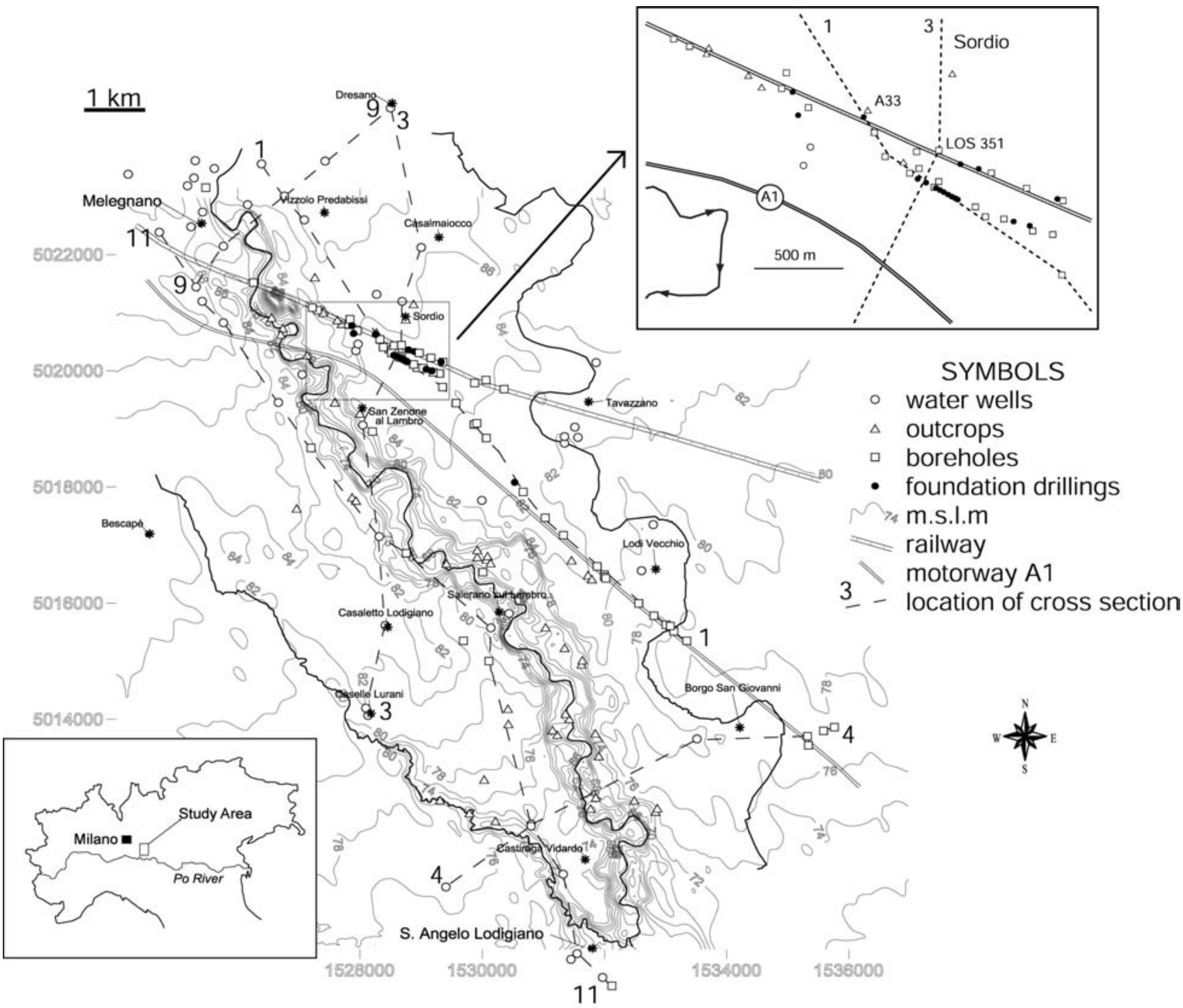



Fig.2 - Topography of the study area and index map of the data points. Equidistance among isohypse is 2 m.

*Schema topografico dell'area in studio ed ubicazione dei sondaggi, pozzi, affioramenti e sezioni stratigrafiche. L' equidistanza è di 2 m.*

The SE-verging fluviatile network of Southern Lombardy is tributary of the axial fluvial system, about E-W trending, i.e. the present-day and palaeo-Po, which drains the nappe systems of the Western Alps and North-Western Apennines, up-current in respect to the Lambro confluence.

The deep subsurface geology of the Po plain of Lombardy is portrayed mostly by the seismic and well data, which are property of the oil companies. The tectonic substratum of the Plio-Pleistocene succession is formed by the external south-verging fronts of the South-Alpine fold and thrust belt, involving the Meso - Cenozoic formations (Milan Belt of Laubscher, 1985; see also Pieri & Groppi, 1981; Cassano *et al*., 1986). In the central Po Plain, at the tip of the South-Alpine thrusts, gentle anticlines are shaped within the Tertiary clastic wedges, ("Southernmost Po Plain Structures", i.e. Corneliano, Caviaga, Soresina structures; Bersezio *et al*., 2001; Fantoni *et al.*, 2003). These folds, which are offset by the Northward propagation of the youngest external front of the North-verging Apenninic thrusts, were deformed after deposition of the syntectonic Lower Messinian units and were sealed by the Uppermost Messinian - Lower Pliocene sediments (Fantoni *et al.*, 2001). Since the latest Messinian, the evolution of the Southalpine front was therefore controlled mostly by flexuration of the Po Plain foreland, due to emplacement of the Apenninic tectonic load, which resulted in a 5 - 6° southward dip (Pedealpine Homocline; Pieri & Groppi, 1981). Tectonic activity on the Apenninic side lasted until Pleistocene, as it is documented by uplift of the San Colombano al Lambro and Salerano structures, which involve the Lower (and Middle?) Pleistocene sediments (Alfano & Mancuso, 1996; Fantoni *et al.*, 2003).

The Quaternary terrigenous succession developed above the Pliocene, deep marine units. It is formed by a clastic succession, at places more than 700 m thick, which shows a large-scale regressive trend, from the top of the Pliocene deep water units, to the Pliocene – Middle Pleistocene shelf and deltaic sediments and finally to alternating coarse and fine-grained alluvial units (Middle – Upper Pleistocene) (Dondi & D'Andrea, 1986; Regione Lombardia - ENI, 2002, with references therein). Based on seismic and well data of ENI's property, this large-scale stratigraphic architecture has been correlated to the northwards propagation of Apenninic thrusts, which forced the fan-delta of the palaeo-Ticino, Adda, and Apenninic rivers and the central palaeo-Po deltaic apparatus, to prograde, filling the former marine basin. At the site of the present-day Lambro valley system, the latest shallow shelf and delta sediments should be of early Middle Pleistocene age (older than 0.87 Ma; Muttoni *et al*., 2003). Since that time, fluviatile and glacio-fluvial sediments, mostly controlled by climatic/eustatic cycles and subsidence rates, spread over the study area, building a sand – gravel succession up to 100 m thick. Its lower part has been described by Regione Lombardia – ENI (2002) as arranged in two main fining upward sequences, which are covered by an upper, coarse - grained, non – cyclic unit of Late Pleistocene age. In the recently proposed hydrostratigraphic classification of Regione Lombardia – ENI (2002), the latter coarse grained unit represents the shallowest Aquifer Group A, which overlays the cyclical sequences of Aquifer Group B. Both these groups correspond to the Traditional Aquifer of Martinis & Mazzarella (1971), and include the three aquifers ("lithozones") recognised by Avanzini *et al.* (1995) and Francani (2001). At present no other modern stratigraphic classification, in terms of Allostratigraphic units or UBSU (NACSN, 1983; ISSC - Salvador, 1987), based on basin-scale correlations with glacial and glacio-fluvial units, is available.

## 3 - METHODS

The geological model of the Middle (*p.p.*) - Upper Pleistocene sediments of the Lambro valley has been obtained after 1:10.000 geological mapping of an area of about 120 $km^2$ (only a part, as large as about 50 $km^2$ is represented in Fig. 3), and subsurface analysis based on 173 points among excavations, natural outcrops, water wells and boreholes (Fig. 2). Some wells attain a depth of about 100 m below the topographic surface, but the majority of boreholes reach a maximum depth of some 50 m. This holds also for the closely spaced borehole transect, drilled for the TAV project (high capacity railway). These subsurface data allow a more detailed study for the stratigraphic units which form Aquifer Group A than for the underlying Group B, which is not the prime objective of this work.

Stratigraphic analysis was based on identification, hierarchization and correlation of the discontinuities which frame the different rank depositional units (*sensu* Miall, 1996). In order to integrate surface and subsurface data we adopted a simplified classification for ranking discontinuity surfaces and depositional lithosomes: 1$^{st}$ order surfaces frame 1$^{st}$ order units of the rank of the depositional systems (i.e. associations of major valley/channel fills and correlated levee, crevasse splay and flood plain areas where present); these surfaces are represented in the field by the major terrace scarps and in cross-section (outcrops or subsurface correlation grid and borehole stratigraphy) by surfaces that intersect and/or collect all the other stratigraphic boundaries, framing several stacked minor sequences or bedsets; 2$^{nd}$ order surfaces frame units of the rank of depositional elements (for instance, fining upwards sequences of point bar accretion within meandering channels); these are recognised in outcrops and boreholes; in the latter case they are represented by gravel - sand bedsets with a lower sharp boundary above finer grained units and/or silt - mud intervals; in the cross-sections their lower boundaries do not cut across the 1$^{st}$ order surfaces; 3$^{rd}$ order surfaces frame units of the rank of architectural elements (e.g. macroforms or minor channel fills); they are easily recognised in outcrops and correspond to the individual bedsets in boreholes, framed by boundaries which are cut by, or merge with, the 2$^{nd}$ order surfaces.

Thorough facies identification and coding could be applied only at outcrop observations. In this case we adopted Miall's (1996) classification, slightly modified to specify the grain size mixtures (Tab. 1). The study of wells and boreholes was based on a purely textural classification and encoding of sediments (Tab.1), when only disturbed samples were available. A more complete coding, including also sediment structure, could be adopted in the cases of undisturbed borehole samples

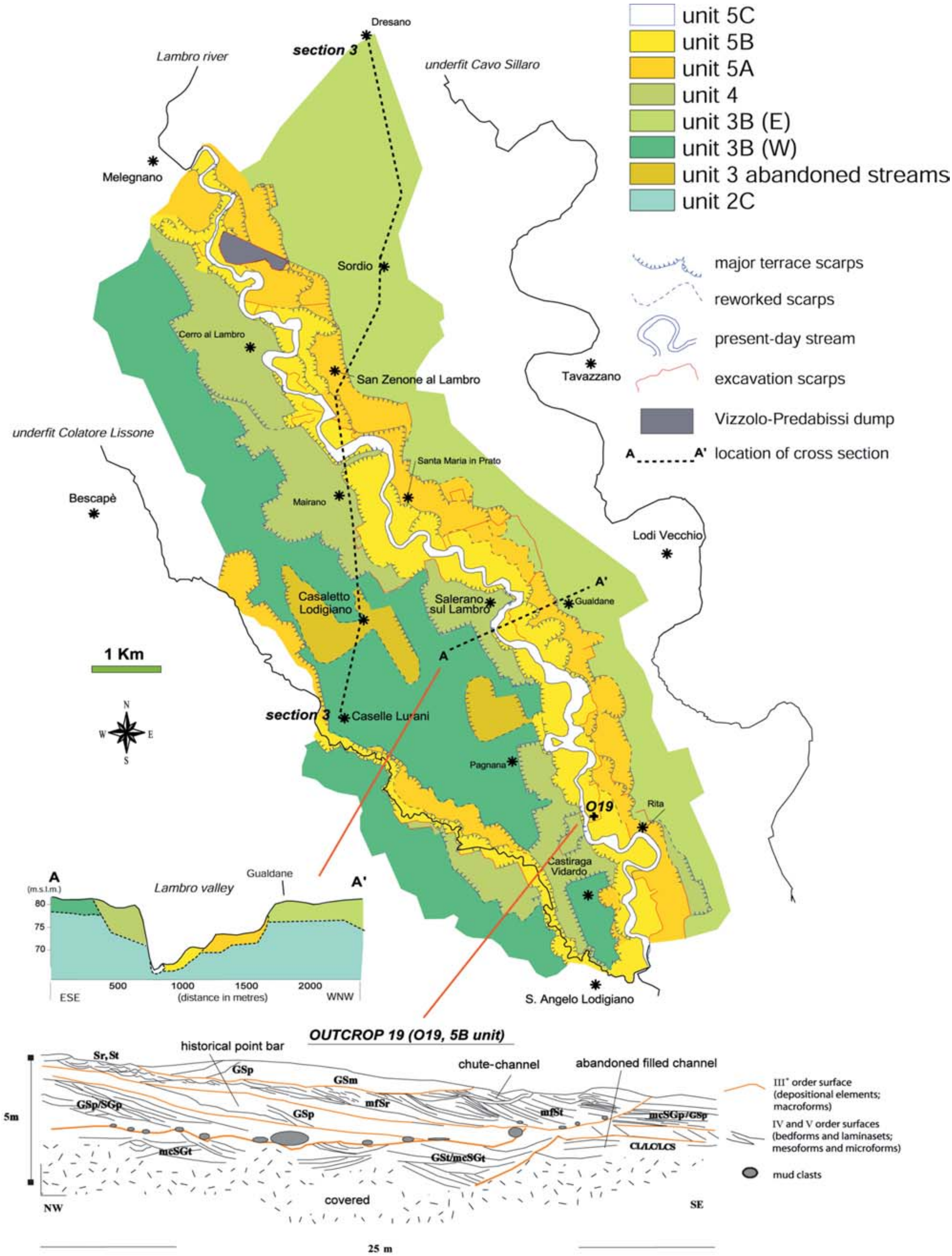



Fig.3 - Geological map of the study area. The two sketches represent 1) a general stratigraphic cross – section located along the A-A' trace; 2) line drawing of pit exposure of sub-unit 5B.

*Carta geologica dell'area in studio. I due schemi rappresentano: 1) schema dei rapporti stratigrafici ricostruito attraverso la sezione A-A'; 2) rappresentazione in affioramento dei caratteri della sub-unità 5B.*

(cohesive sediments and rare cores).

Compositional analysis of gravels was used to support correlations and to separate provenance of clasts from regional or local sources. Some 70 samples of gravel were collected, both in outcrops and boreholes, in the size range of $-3\Phi$ to $-5\Phi$, for classification and counting of at least 100 pebbles for sample. We used these data as a qualitative tool to characterise the different depositional units and to assist correlations.

Radiocarbon age determinations on 4 samples of peat, organic soils and plant relics provided dating of the bases of the youngest Upper Pleistocene units. Artefact fragments, which were deposited like clasts in fluvial bedforms, added age information on the Holocene, historical units.

Subsurface mapping of $1^{st}$ order boundaries between the major stratigraphic units was obtained after ordinary kriging, assisted by variogram structural analysis (Matheron, 1969).

## 4 - DEPOSITIONAL ARCHITECTURE OF THE SOUTHERN LAMBRO BASIN

Five $1^{st}$ order depositional units, bounded by $1^{st}$ order surfaces, build the alluvial architecture of the Middle Pleistocene (*p.p.*) - Holocene succession, down to about 100 m below the topographic surface, corresponding to Aquifer Groups A, B and probably uppermost C (Regione Lombardia – ENI, 2002). We numbered them starting from the deepest (Unit 1) and in this order they are described in the subsequent paragraphs. The top surfaces of Units 3, 4 and 5 are assembled to build the present-day topography (Figs. 3 and 4). Units 1 and 2 are subsurface units with no relations with the present day geomorphology. Only the top of unit 2 is rarely exposed by the Lambro terrace scarps or by the deepest quarry excavations.

### 4.1 - Subsurface Units

***Unit 1 – Sandy – clayey depositional system***

Unit 1 (Fig. 4) is the lowermost subsurface unit which was crossed by the available boreholes and wells, and consists of sand, silt and clay facies, arranged in fining upward sequences. Unit 1 gets progressively more sand-rich from the base upwards. It develops between a maximum top elevation of 45 m and a minimum base elevation of -20 m above sea level (Figs. 5 and 6). Its lower boundary is a $1^{st}$ order discontinuity surface, represented by the sharp contact of sandy layers above thick, grey, silty-clay deposits, which deepens southwards from –10 to –20 m a.s.l. The top boundary deepens from North to South (i.e. from Melegnano to S.Angelo Lodigiano; Fig. 2 and Fig. 5, sections 3 and 11), from 45 m a.s.l. to about 10 m a.s.l., being dissected by an erosion surface.

Unit 1 is formed by two subunits (1A and 1B; Figs. 4, 5, 6), separated by a silt-clay interval. They are both formed by stacked $2^{nd}$ order sequences, up to 10 m thick, with fining upward trends. Each minor sequence develops above silts and clays, with a lower sharp boundary and includes a lower grey to yellowish sand unit, sometimes with gravel divisions (cSG, mS and fS facies associations; Tab. 1 and Tab. 2); it is progressively covered by very fine sands and silty clays (vfS, SL, CL, C facies), sometimes cemented, with intervening dark organic soils and some peat. The sand facies associations form flat lens-shaped bodies, with longitudinal (about N-S) length of hundreds of meters and transversal width (about E-W) of tens of meters. A thinning of these bodies corresponds to a facies transition towards sand/silt-clay, thin bedded alternation. The fine-grained sequence which separates sub-units 1A and 1B has an average thickness of about 10 m and is present throughout the entire area except for the Casalmaiocco zone (Fig. 2; Fig. 5, section 3), where it is eroded and replaced by the lowermost sand-body of sub-unit 1B. It is characterised by thin-bedded alternating fS, LS and LC facies, with peat layers and grey-green palaeosoils. Differently, at the top of sub-unit 1B only discontinuous lenses of fines are present, also due to truncation at the top.

Geometry of sedimentary bodies and sediment assemblage of Unit 1 point to a mixed – load fluviatile depositional system, with stable channel-fill depositional elements (lens-shaped sand-bodies forming $2^{nd}$

Tab.1 - Sediment classification and facies encoding used to describe surface and subsurface units.

*Classificazione dei sedimenti e codifica di facies utilizzata per descrivere le unità in superficie e nel sottosuolo.*

| Sediment Textures (all observations) | Code | Sediment Structures (outcrops, excavations, pits) | Codes |
|---|---|---|---|
| Gravel | G | Normal graded | n |
| Sandy Gravel | GS | Inverse graded | i |
| Gravelly Sand | SG | Horizontal parallel laminated | h |
| Sand | S | Low-angle laminaled | l |
| Silty Sand | SL | Planar cross laminated | p |
| Clayey Sand | SC | Trough cross laminated | t |
| Sandy Silt | LS | Small scale trough cross lam. | r |
| Silt | L | | |
| Clayey Silt | LC | **Additional textural codes** | |
| Clayey-Sandy Silt | LCS | Very fine | vf |
| Silty Clay | CL | Fine | f |
| Sandy Clay | CS | Medium | m |
| Gravelly Clay | CG | Coarse | c |
| Clay | C | Very coarse | vc |
| Peat | P | | |

order sand-silt fining-upwards sequences, soled by low-rank erosion surfaces and capped by organic-rich sediments), crevasse splay (and possibly levee?) depositional elements (isolated thin bedded sand-silt lenses, thin-bedded clay-silt-sand alternations) associated with humid flood plain deposits (organic-rich silt-clay facies with alluvial-type palaeosoils). In addition to these features, the horizontal and vertical cross-cut relations among sand-bodies suggest a deposition dynamics governed by lateral migration, channel truncation/abandonment and channel avulsion. It is therefore suggested that sub-units 1A and 1B represent two stages of evolution of a meandering river depositional system, even if well data do not allow the recognition of the lateral accretion units. Sediment load was medium sand and fines, with minor fine gravel in the lower stage, coarse sand with gravel and fines in the upper one.

The first migration of a meandering channel system (1A) was followed by the establishment of a wide flood plain, where soil could form over flat and stable surfaces, due to either major avulsion or back-stepping of the fluvial system as a consequence of rising base-level. After the scouring of an erosion surface, a new south-eastward migration of the depositional system, with coarser sediments, occurred (sub-unit 1B). The N-S sections of Fig. 5 show the facies transition that occurs in less than 15 km towards the SE, within both the sub-units, from sand-dominated and thick-bedded towards fine-dominated and thin-bedded facies associations.

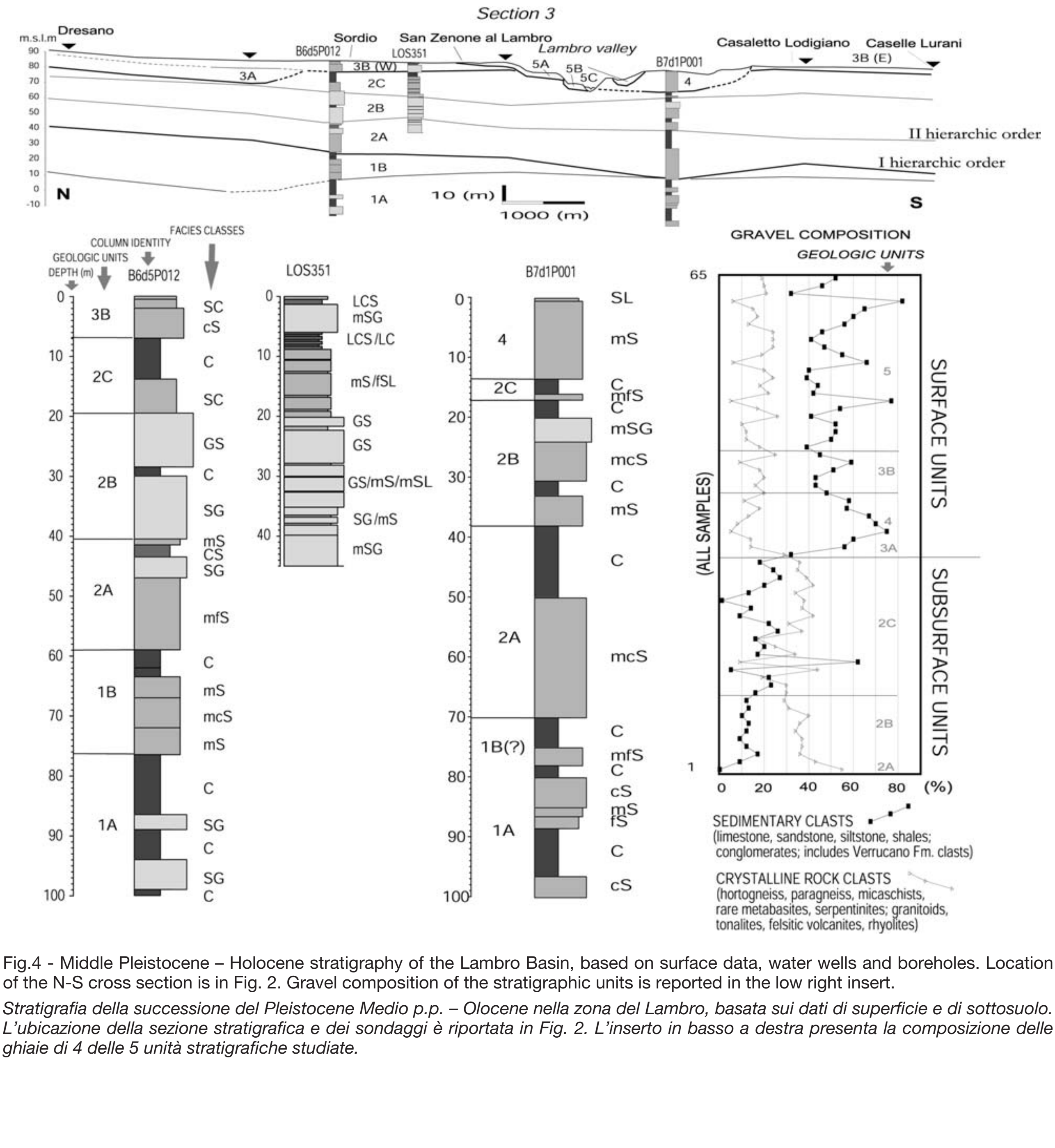



Fig.4 - Middle Pleistocene – Holocene stratigraphy of the Lambro Basin, based on surface data, water wells and boreholes. Location of the N-S cross section is in Fig. 2. Gravel composition of the stratigraphic units is reported in the low right insert.

*Stratigrafia della successione del Pleistocene Medio p.p. – Olocene nella zona del Lambro, basata sui dati di superficie e di sottosuolo. L'ubicazione della sezione stratigrafica e dei sondaggi è riportata in Fig. 2. L'inserto in basso a destra presenta la composizione delle ghiaie di 4 delle 5 unità stratigrafiche studiate.*

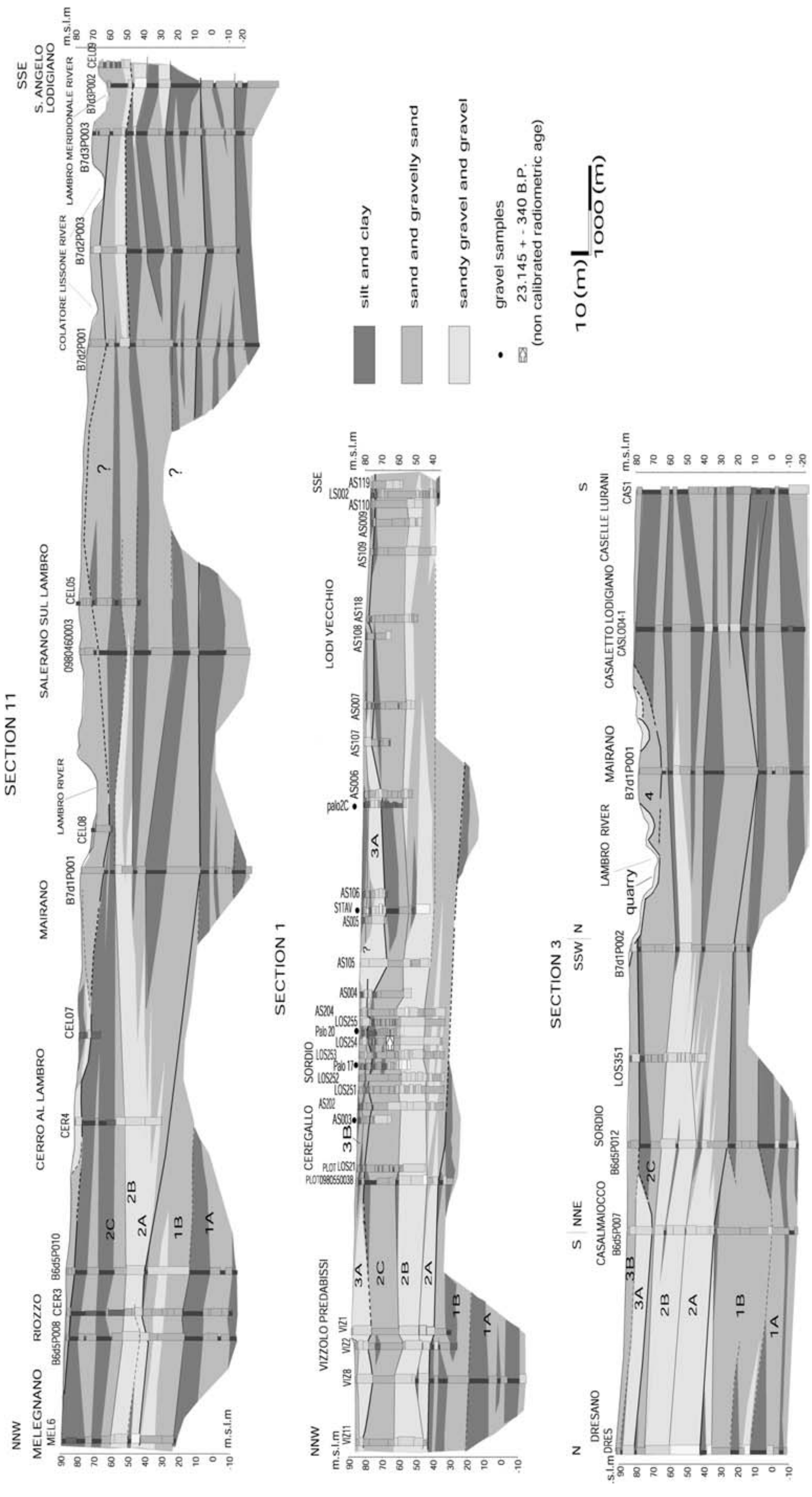



Fig.5 - Longitudinal cross sections (about N-S) across the Lambro area (location in Figs.2 and 3).
*Sezioni stratigrafiche longitudinali (circa N-S) nella zona del Lambro. L'ubicazione è riportata nelle Fig. 2 e 3.*

***Unit 2 – Gravel - sand depositional system***

Unit 2 (Fig. 4) is a subsurface unit, whose top develops between 85 m and 45 m a.s.l (North) and base between 62 – 10 m a.s.l. (South), with a thickness ranging 13 – 52 m. It consists of gravel and sand bodies, with minor fine grained layers (mostly silt, rare or no clay), which form three sub-units (from bottom to top 2A, 2B and 2C). Only the uppermost one (2C) crops out locally in the deepest scours of the Lambro valley; it presumably corresponds to the sand-gravel units which are exposed at the topographic surface of the "Livello Fondamentale della Pianura" just North of the study area (Strini, 2001; Bini *et al*., this volume). The stacking of sub-units 2A and 2B determines a clear coarsening upwards trend, which is followed by two fining upwards minor sequences, corresponding to sub-unit 2C).

The lowermost sub-unit 2A develops above a lower discontinuity which deepens southwards, deeply dissecting Unit 1. In the northern sector of the study area the sub-unit consists of sands and gravelly sands (facies association is presented inTab. 2) stacked in non-cyclical bedsets, up to 10 m thick, which alternate with thin and discontinuous fine sand-silt layers. South of the Salerano – Lodi Vecchio area (Fig. 2, and Fig. 5) a transition to stacked fining upwards sequences, up to 10 m thick with sand - silt facies association occurs (Tab. 2; Fig. 5).

Subunit 2B is the coarsest lithosome, formed by coarse and massive gravel bodies, up to 10 m thick, with minor sand layers (see facies association in Tab. 2). The gravel bodies are rarely separated by grey – brown silt and mud layers and possibly palaeosoils. In the same northern sector, as referred to just above, sub-unit 2B merges with sub-unit 2A, forming a unique gravel body, up to 30 m thick. The two subunits deepen and get progressively separated southwards, owing to the facies transition towards sand – silt fining upwards sequences, which is observed also for sub-unit 2B. The top of the gravel body is sharp and locally shows weathering profiles, which develop on some metres in thickness (Munsell colours 7.5YR5/6, 5YR5/6).

Sub-unit 2C is formed by one (South) or two (North) fining upwards sequences (up to 15 m thick) of dark grey, coarse - middle sand, silt to mud facies (Tab. 2; Figs. 5 and 6), frequently capped by organic-rich palaeosoils and some peat layers, with a total thickness ranging from 30 m to 3 m, the latter case due to top truncation at the base of units 3 to 5. The exposed sections of this sub-unit show that these sequences are formed by large-scale, trough cross-laminated sands in

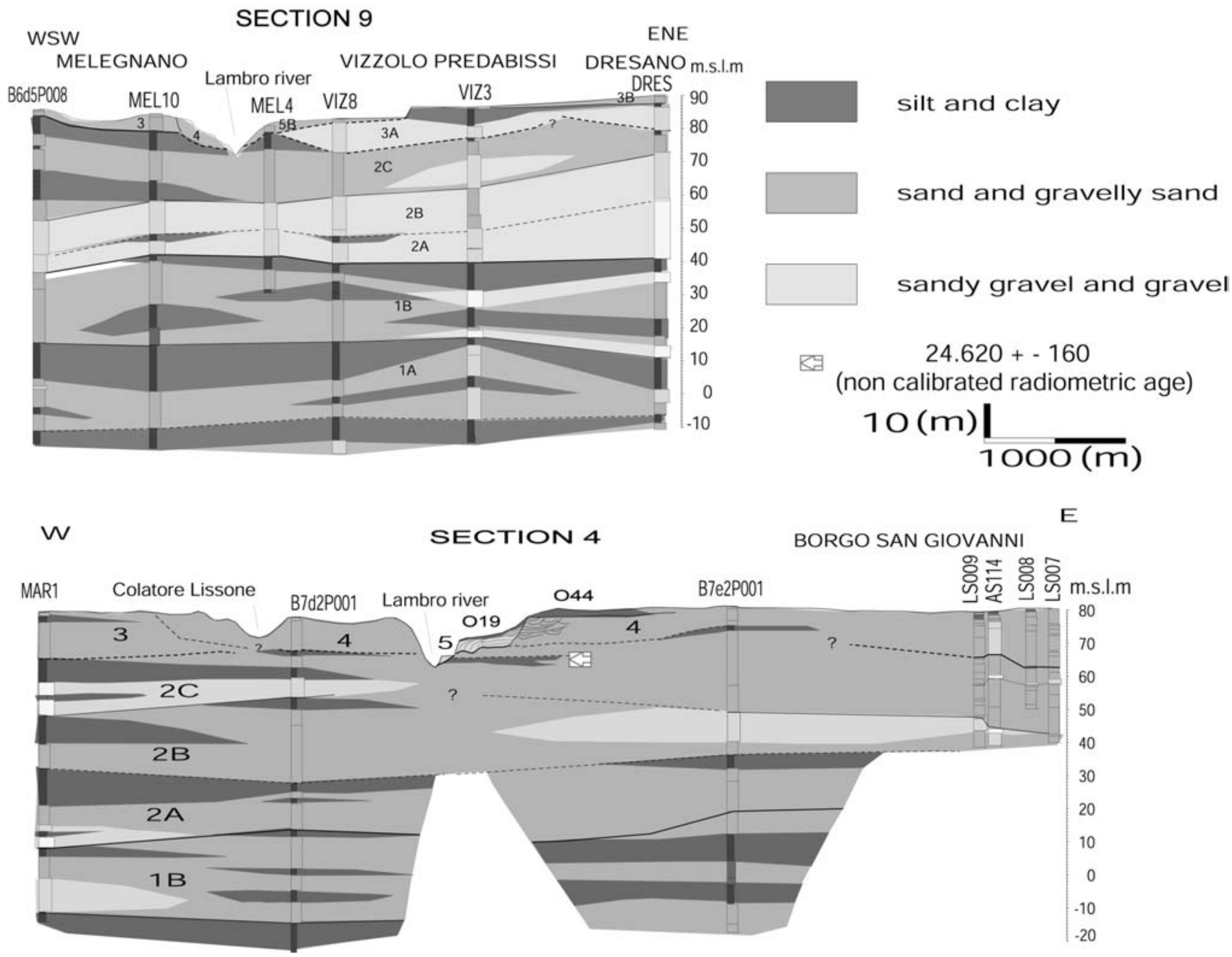



Fig.6 – Transversal cross sections (about E-W) across the Lambro area (location in Figs. 2 and 3).
*Sezioni stratigrafiche trasversali (circa E-W) nella zona del Lambro. L'ubicazione è riportata nelle Fig. 2 e 3.*

Tab.2 - Facies association and interpretation of the five depositional units. Codes as in Tab. 1
*Associazione di facies e relativa interpretazione delle 5 unità individuate. Codifica come in Tab. 1.*

| UNIT | SUB - UNIT | FACIES ASSOCIATION | INTERPRETATION |
|---|---|---|---|
| 5 | **5C** (river exposures) | VfSL, LCS, P<br>GSh, SGt, mSp, mSt, fSr | Flood plain, oxbow lake<br>Point bar, transverse bar |
| | **5A - 5B** (exposures) | Sn, Si, fSr, vfSLn, LS, LCS, P<br>SG, SGp, Sr, LCS, CL, P<br>SGn, mSGp, SGt, mfSr, LCS | Flood plain, oxbow lake, crevasse<br>Chute channel, abandoned channel<br>Point bar |
| 4 | (boreholes - exposures) | LCS, fSh, fSr, SLm, P<br>cSn, mSp, mSt, fSr, fSL, LCS | Flood plain, oxbow lake, crevasse<br>Sand bar, point bar, chute channel |
| 3 | **3B** (boreholes - rare exposures) | vfSL, LCS, CLS, P<br>mSGl, mSG, Sp, St, fSr, LCS | Flood plain, oxbow lake<br>Point bar, channel fill |
| | **3A** (boreholes) | CfS, Sn, mfS vfS LCS, LC | Sand bars, flood plain |
| 2 | **2C** (°) subsurface (*) exposures | (*) mSt, mSp, mSh, mSr, fSL, LC)<br>(°) mS, vfSL, LCS, L, LC, CL, P<br>(°) SG, S, L, LC, P<br>(°) cSG, cS, mS, fS, fSL | Point bars, abandoned channel fills<br>Flood plain, crevasse splays, soils<br>Abandoned channel fills<br>Sand bars – point bars |
| | **2B** subsurface | SG, cS, mS, fS, L<br>G, GS, SG, cS | Sand bars, braid plain<br>Gravel bars |
| | **2A** subsurface | fS, fSL, CL, C<br>SG, cS, mS | Flood plain, alluvial soils<br>Sand/gravel bars, channel fills |
| 1 | **1B** subsurface | mS, fS, CL, P<br>cSG, cS, fS, CL | Abandoned channel fills<br>Lateral accretion bars |
| | **1A** subsurface | fs, vfS, SL, C, P<br>mS, fS, CL | Flood plain, crevasse splays, soils<br>Channel fills – point bars |

association with planar, high-angle, cross-laminated sands and low-angle to sub-horizontal laminated sands (Tab. 2). This association is frequently covered by alternating, thin-bedded, rippled fine sands and laminated to massive silt and silty mud (Tab. 2). A facies transition occurs southwards, towards more mud-rich and thin-bedded successions (Fig. 5, Sections 3 and 11).

The upper part of sub-unit 2C (Figs. 5 and 6) is represented by a widely distributed and continuous succession of laminated to massive, fine grained facies (silty and sandy mud, muddy silt), frequently interbedded with organic-rich palaeosoils and some peat. Lenses of grey, laminated to massive mud occur recurrently; they contain plant relics, sometimes metre-sized, continental gastropods and other molluscs. Within these fine grained facies association, decimetre-thick sand lenses are present.

Gravel composition of sub-units 2 A, B, C is quite homogeneous, with rare exceptions, as it is shown in Fig.4. Excluding the ubiquitous and uniformly distributed quartz pebbles, crystalline rock fragments are almost invariably dominant on sedimentary rock pebbles, with some fluctuations of the relative proportions. The most abundant rock clasts are gneisses and micaschists, with some phyllites and slates (up to 50 % in some samples), invariably associated with igneous rocks (up to 15 %), which include granitoids, granodiorites, rhyolites and intermediate to basic porphyritic volcanites. Rare green metabasite fragment and serpentinite complete the crystalline rock composition. Sedimentary rock pebbles are never more abundant than 20%; they are mostly represented by limestones, cherts, sandstone-siltstones (among which the Collio – Verrucano, the Cretaceous Flysch and the Gonfolite sources are easily recognised), rare marlstones. They can be generally correlated with the SouthAlpine sedimentary cover, with no clear indications of Apenninic or other Alpine provenance.

Some samples of plant fragments, collected in one temporary exposure due to excavations and in two boreholes, yielded radiocarbon ages relative to sub-unit 2C. Its lower sandy succession has been dated between 23.145+/- 340 a BP. (Fig. 6, Section 1) and 24.620+/- 160 a BP. (Fig. 5, Section 4); these non-calibrated ages are realistically close to the age of the 2B – 2C boundary. The fine-grained top interval of sub-unit 2C has been dated to 22.035+/-300 a BP, by a sample collected in an excavation just south of Melegnano (Fig. 2).

The architecture of unit 2 can be interpreted on the basis of grain size distribution, stacking patterns, exposed facies associations and gravel composition. Its development marks a sudden change of depositional style, that occurs after truncation at the top of the deposits of the meandering fluviatile depositional system of Unit 1. Sub-units 2A and 2B can be interpreted as the result of sudden invasion of the former alluvial plain by bedload and debris flow – dominated, depositional systems, during at least two different increments of southwards progradation of a distal alluvial fan with braided stream alluvial style. A southward transition to a sandy braid-plain, characterised by channel sequences flanked by flood plain sub-environments, is documented by fringing-out of the gravel units and facies change to a sandy silty succession. A generalised back-step of this depositional system is recorded by sub-unit 2C, which is characterised by sandy facies associations, with abundant fines at the top and within minor sequences. It testifies the transition from a sandy braid plain (North) to a mixed-load depositional style (South), with development of point bars, which is typical of meandering fluvial systems. The fine-grained interval at the top of sub-unit 2C documents the wide diffusion of a flood plain across the entire study area, due either to another back-step of the sand dispersion system, or to an avulsion, capture, or inactivation of the depositional system. Compositional uniformity suggests that no major change of the source areas occurred during the different progradation-retrocession steps recorded by Unit 2, whose gravels show a mixed North-Alpine – South-Alpine provenance.

**4.2 - Surface Units**

The upper boundary of units 3, 4 and 5 is the present-day topography. In particular the top of Unit 3 forms the largest part of the "*Livello Fondamentale della Pianura*", an almost flat surface, SSE dipping on average by 1.125‰, which is cut by the terrace scarps of the Lambro valley system. The *Livello Fondamentale* is run by the meandering traces of the abandoned river network, the most continuous of which are the Carpiano – Bescapè abandoned stream (West of the Lambro valley; Bersezio, 1986) and the Sillaro meandering trace, to the East (Veggiani, 1982; Bersezio, 1986). At present these traces are bounded by 1 – 5 m scarps; the average radius of bends is comparable in length with that of the meanders of Adda or Ticino rivers, i.e. one order of magnitude larger than the present-day and abandoned Lambro, Olona and Seveso river bends.

The width of the Lambro river valley, sculptured into the *Livello Fondamentale*, varies from about 2 km (North) to less than 1.5 Km (South; Fig. 3). The valley is formed by four orders of minor terraces bounded by different height scarps. The transversal profile of the valley is strongly asymmetrical. Three orders of minor terraces are generally observed at the eastern side; they link progressively the elevation of the *Livello Fondamentale* with the present day Lambro stream, which is lowered by about 15 m. Differently, only two terraces are present at the western side, where the difference in height with the *Livello Fondamentale* is almost totally achieved by one major scarp, on the right hand of the present-day valley (Fig. 3). Moreover, the elevation of this western terrace within the valley, is higher than the others on the opposite side, suggesting that no correlation is possible between them. The western and most elevated terrace bounds the top of depositional Unit 4; the other minor terraces represent the top surfaces of the different sub-units which form the most recent Unit 5 (sub-units 5A, 5B and 5C; Fig. 3).

***Unit 3 – Sandy depositional system***

Unit 3 is the uppermost stratigraphic unit outside the most external terrace scarp which bounds the Lambro valley system; it is poorly exposed and crossed by a few boreholes and wells. It includes two sub-units (3A and 3B in ascending stratigraphic order) which develop with a maximum total thickness of about 15 m. Sub-unit 3A is bounded at the base by an erosion surface, scoured into the uppermost fine-grained horizon of sub-unit 2C. To the west of the Lambro valley sub-unit 3B is difficult to separate from 3A; differently, to the east of the valley, it forms the uppermost unit between Lambro and Sillaro, just above sub-unit 3A, or can be deeply scoured into sub-unit 2C (Figs. 3, 5 and 6).

On the whole sub-unit 3A forms a sandy fining upwards sequence, with discontinuos fine-grained layers and palaeosoils at the top. It is formed by km-sized, coarse to middle sand lenses, dark brown to yellowish in colour, which are locally separated by thin silt-mud units (Tab. 2). Also sub-unit 3B is formed mostly by sand lenses, with a typical yellowish-brown colour and shows a general fining upwards trend, from coarse sand with rare gravel to sandy silt and mud. Rare outcrops show the association of graded, gravelly-sands with dm-thick beds of coarse to middle sand with trough cross lamination and low-angle oblique laminasets (Tab. 2). These lenses grade upwards to sandy-silt and silty-clay layers, with yellow - orange to reddish paleosoils (Munsell colours range from 10YR6/8 to 7.5YR5/8 and 2.5Y6/6). The meandering palaeo-streams which characterise the top boundary of sub-unit 3B (Sillaro and Carpiano – Bescapè among others) are characterised by the presence of gravel and sand deposits. These abandoned stream traces are cut 1-5 meters below the top of sub-unit 3B, with a top elevation which is in some cases comparable with that of the top of Unit 4, which is going to be introduced later on. At present these observations do not seem to be sufficient to correlate these deposits with those of Unit 4, but their stratigraphic attribution is still open. Therefore we included provisionally these sediments within Unit 3, with the specific definition of "Unit 3 – abandoned streams" (Fig. 3).

Gravel composition of Unit 3 has been obtained mostly for the different sub-units of the group 3B, as far as only a few samples could be collected within unit 3A. As shown in Fig.4, the deposition of Unit 3 marks an important compositional change, from crystalline-dominated to sedimentary-dominated. Sedimentary clasts of South-Alpine provenance (sandstones, limestones, siltstones, cherts, marlstones, rare conglomerates) are generally more abundant than 43%; sometimes their percentage is as high as 60%. The crystalline rock fragments are on the whole less than 30% (20% metamorphic, 10 % igneous, with the same composition already shown for Unit 2). The abundance of the ubiquitous quartz fragments fluctuates between 10 and 20%. Fig.4 shows that this sedimentary-dominated composition is also typical of units 4 and 5, with minor differences which can be hardly imputed to provenance variations rather than to hydraulic selection, differential alteration, mixing with recycled clasts from the older units and so on.

Radiocarbon dating of woody fragments from a peat sample, which was collected at the boundary between sub-units 3A and 3B, at one excavation site close to Sordio (Fig.2 and 3), allowed the determination of an age of 18.785+/-230 b.p for the top of sub-unit 3A. This date could be calibrated to 20.785 – 19909 cal BC (CALIB REV4.4.2; Stuiver & Reimer, 1993).

Additional information is provided by stratigraphic position and cross-cut relations with the other units. Sub-unit 3A is at least older than the quoted radiocarbon age; both sub-units 3A and 3B are cut by the terrace scarp that bounds Unit 4, therefore they are older than Unit 4 which is the most ancient unit within the Lambro valley system. Nevertheless, it cannot be excluded that flood deposits coeval with Unit 4 veneer the oldest sediments of sub-unit 3B, close to the external margin of the Lambro valley.

Unit 3 can be interpreted as the result of deposition within different palaeo-rivers, with moderate sinuosity and development of longitudinal sand bars (sub-unit 3A), or highly sinuous, meandering, with development of point bar - channel - abandonment sequences, with alluvial soils. Flood plain fine sediments are locally associated with these depositional elements, and veneer the top of both the sub-units. The gravel composition shows the highest abundance of sedimentary clasts, testifying to provenance from local sources located in the Southern Alps foothills; the geometry and distribution of sedimentary bodies and of their abandoned traces suggests dispersion of detritus either by multiple streams or by an unstable river with frequent abandonment and avulsions cycles, which could have reached the end-moraines of the Lecco - Brianza area to the North. Unit 3 marks the time of definitive disappearance of distal alluvial fan – braided stream depositional systems from the study area, thus documenting the definitive northwards shift of the braided – meandering hinge. It also marks the first appearance of a clearly recognizable network of meandering streams, whose organisation is very close to the present day shape of the fluviatile network.

***Unit 4 – Ancient Lambro depositional system***

Unit 4 is the most ancient depositional unit of the Lambro valley system, within which it is preserved only to the west of the present-day river. It is bounded to the west by the most external terrace scarp, which is less than 2 m in height, and to the east by the internal scarp, which is the highest (on average more than 12 m above the present day flood plain). The top boundary of Unit 4 is a terrace surface, whose elevation does not correlate with any other terrace within the valley system, being comparable with the elevation of the Sillaro and Carpiano – Bescapè abandoned streams. The lower boundary is observed locally and is interpreted in the subsurface cross-sections. It is a first order erosion surface cut into sub-unit 2C and 3.

Unit 4 shows a total maximum thickness of about 12 m. It consists of gravelly-sand and sand facies associations (Tab.2), with minor fine grained layers and peat, which form fining upwards sequences. Some exposures allow the observation of planar to trough, oblique-laminated sands and gravelly sands, associated upwards with rippled fine sands and mud or peat units. These correspond laterally to thin bedded and fine grained sand with small-scale trough cross-laminae which interbed with laminated silt and peat (Tab. 2). Some silt-mud laminated or massive units contain gastropod and bivalve tests and show some intense burrowing. In the subsurface of the Mairano area (Fig. 3) borehole correlations allowed the reconstruction of a km-sized sand lens, with minor fine-grained layers at the top (Fig. 5 and 6, section 11), which is truncated by a terrace scarp to the East.

Gravel composition of Unit 4 is comparable to that of sub-unit 3B, and very close to that of sub-unit 3A (Fig. 4): sedimentary lithoclasts are largely more abundant than crystalline rock fragments, which are often moderately to deeply weathered.

No direct age determinations are available for Unit 4. Stratigraphic relationships indicate that it should be at least younger than 20.785 – 19909 cal BC, but this is only an approximation of its maximum age, as the time-span represented by sub-unit 3B could not be estimated yet. In any case Unit 4 is cross-cut by the erosional lower boundary of sub-unit 5A.

Geometry of sedimentary bodies and facies association of Unit 4 allow the interpretation of its fining upward sequence as the result of lateral accretion and SSE migration of a channel - point bar system, typical of a mixed load, meandering fluvial style. This is quite obviously confirmed by the relationships with the geomorphological features of the surface boundaries of this unit. Unit 4 represents the oldest deposits of the Lambro valley meandering system. As it has been previously stated, a time correlation with the sediments deposited into the meandering abandoned streams which are cut into the Livello Fondamentale outside the Lambro terrace scarps, cannot be excluded. Local provenance of sediments is documented by prevalence of sedimentary clasts within the gravel-sized facies; obvious mixing with second cycle clasts, eroded from the older alluvial succession and/or from the glacial deposits of the northern end-moraines, is witnessed by the presence of weathered crystalline clasts, which originated in the internal Alps.

***Unit 5 – Post - glacial Lambro depositional system***

Unit 5 is formed by the sediments which were deposited within the Lambro valley system during its progressive entrenchment, to form three orders of terraced units, which are progressively lowered to the present day elevation of the Lambro stream (about 15 m below the *Livello Fondamentale*). These terraces bound the top of three sub-units, 2 - 6 m thick, whose lower boundaries merge to form the 1$^{st}$ order surface that delimitates the Lambro:valley system. As a rule this surface is marked by gravel lags or by a very typical concentration of mud clasts, sometimes as large as 80 cm. Sub-unit 5A is preserved only on the eastern side of the present-day Lambro; it is bounded by an erosion surface at the base, which truncates laterally and vertically Unit 4, 3 and sub-unit 2C. Sub-unit 5B, whose base truncates also sub-unit 5A (Fig. 7), is preserved on both sides of the river at an intermediate elevation. Sub-unit 5C is the present-day channel-bars-flood-plains system of the Lambro river.

Sub-units 5A and 5B are formed mostly by sands and gravels which are organised in flat lenses, tens to hundreds of meters in size, up to 6 m in height, with lateral accretion of fining upwards gravel-sand units (Fig. 8A). The typical facies association of these lateral accreted lenses (Tab. 2) includes a lower graded gravel bed, soled by a flat erosion surface and covered by coarse – middle, trough to planar, cross-laminated sand, which are followed by ripple cross-laminated fine sand and laminated to massive muddy silt. Sometimes,

Fig.7 - Gravel point bar (sub-unit 5A) laying over truncated , well-sorted grey sands of sub-unit 2C. Lambro valley, outcrop O19 (Fig. 3).

*Barra di meandro a granulometria ghiaioso – sabbiosa (sub-unità 5A), ricoprente le sabbie grigie, ben selezionate della sub-unità 2C. Affioramento O19 nella valle del Lambro (ubicazione in Fig. 3).*

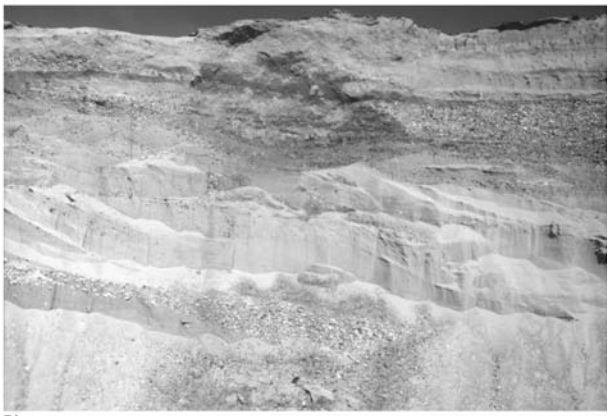
metres-thick, silty-clay and clay plugs are preserved at the top of the ε-cross stratified units. More frequently the same are cut by rounded scours, which are filled either by gravel-sand lags and bars, or plugged by sandy clay and peat (Tab. 2; Fig. 3; Fig. 8B). The lateral accreted lenses are laterally juxtaposed and vertically superimposed on one another, by means of almost flat erosion surfaces (Fig. 8A). Recurrently they are separated by metres-thick fine grained units, formed by the association of laminated to massive silty-mud, with thin sand beds which can be graded, horizontal laminated or rippled (Tab. 2).

Sub-unit 5C is represented by the present-day sediments of the Lambro river, which are actively evolving. They include gravel-sand units, forming tens of meters long, 1 – 3 m high point bars, side bars, middle channel bars. Gravel material is mostly recycled from the older units, as well as for the abundant mud clasts, which slide into the channel from the erosional shores. The present-day narrow flood plain is covered by rippled fine sand and silt to mud layers. Some silty mud layers (spill-over deposits) are observed outside the "normal" flood plain (which is constrained within the terrace scarp between sub-unit 5B and 5C); these veneers are deposited above the terraces of sub-unit 5B and locally also above the terrace of Unit 4, marking the highest levels reached by the exceptional floods (one of which occurred during the fall of 2000) in the narrowest sectors of the valley system.

Gravel composition of Unit 5 is homogeneous and very similar to that of Unit 4. Sedimentary clasts are the most abundant (on average more than 50%); metamorphic (20% on average) and igneous (mostly granitoids; 10%) are subordinate; quartz fragments of different origin are, as usual, as abundant as about 20% of the total. Most of crystalline fragments are variably weathered; differently the sedimentary clasts show very low to absent alteration. Some peculiar lithologies, which occurred with very low abundances in the sediments of Unit 3 (intermediate to acidic porhyrites and rhyiolites) or of Unit 2 (green metabasites and serpentinites), are no longer observed within the gravel-size sediments of Unit 5. Among the gravel fraction of sub-unit 5B, brick fragments and other artefacts are recurrent. These fragments are imbricated with the other clasts, documenting that they were caught-up by fluvial transport.

Age determination of Unit 5 is based on several different evidences. The base of sub-unit 5A cross-cuts units 3 and 4, therefore it is at least younger than 20.785 – 19909 cal BC. The brick fragments that we found within 5B point bars indicate an historical age for sub-unit 5B. Based on the typology of the recovered artefacts (Cremaschi, pers. Comm., 2003) a time span between the Roman age and the Renaissance has been recognised. Sub-unit 5C is the recent – present-day depositional unit. Based on this evidence we suggest

A)



B)

Fig.8 - A) Sub-unit 5B (Domodossola, outcrop O19 of Fig. 3; see also line-drawing in the lower insert of the same picture). Lateral accretion of a sandy-gravelly point bar; note the flat surface at the top, covered by differently oriented sand mesoforms. Total height is about 5 m (hammer on the left for scale). B) Same location of picture (A): sub-unit 5B, historical point bar cut by chute channel; note the gravel lag and bar filling the chute channel, with an upwards fining sequence. Spill-over and flood plain fine grained deposits seal the bar-chute sequence.

*A) Sub-unità 5B (Domodossola, affioramento =19, Fig. 3; confrontare con lo schizzo di Fig.3). Accrezione laterale di una barra di meandro sabbioso-ghiaiosa, delimitata a tetto da una superficie planare, coperta da mesoforme di fondo sabbiose a differente orientazione (altezza totale dello spaccato, circa 5 m; martello di scala sulla sinistra). B) Stessa ubicazione di (A): sub-unità 5B, barra di meandro di età storica, troncata da canale di rotta con riempimento di ghiaie residuali e barre ghiaioso-sabbiose in sequenza fining-upwards. La successione è sigillata da sedimenti fini di esondazione.*

that Unit 5 represents the post-glacial (Holocene) deposits of the Lambro valley system.

The interpretation of the depositional elements which form sub-units 5A and B is based on their facies assemblage, geometry, surface morphology and relationships with the shape and fluvial style of the Lambro valley system. The lateral accreted units are directly recognised as point-bar deposits, with a partially preserved shape. Chute channels are cut into these point-bars. They are filled by gravelly-sand bars and silt-clay plugs. The fine grained sediment facies associations with sand lenses (Tab. 2) are interpreted as typical flood-plain crevasse splay deposits. Finally, the sand-mud lens-shaped units, with peat, are recognised as typical channel abandonment sequences, with deposition within oxbow lakes. These interpretations are confirmed by the depositional processes and facies which have been described for the present-day sub-unit 5C. Gravel petrography supports the interpretation of local provenance of detritus, both from the oldest alluvial and glacial sediments, and from the Mesozoic rocks which are at present under erosion in the South-Alpine foothills of the Brianza, which are the source areas of the Holocene Lambro river.

## 5 - DISCUSSION

### 5.1 - Stratigraphy

The five informal units defined above can be compared to the stratigraphic framework of the Po plain Quaternary succession, both based on physical stratigraphy and on time equivalences. For clarity they will be re-examined in descending stratigraphic order, from the youngest Unit 5 to the oldest Unit 1.

*Unit 5* represents the most recent depositional unit, confined within the Lambro valley system, which formed during its recent entrenchment below the *Livello Fondamentale*. Based on stratigraphic relationships, age determinations and fluvial style, it can be attributed to a post-glacial, Holocene age. Therefore, it is equivalent to the Post Glacial Unit of the northern sectors of the Po plain (Bini *et al*., in press).

The correlation with regional stratigraphy of *Unit 4* is affected by some incertitude. It is confined within the Lambro valley system, and its age is constrained by the minimum age of Unit 3A (20.785 – 19909 cal BC) and the maximum age of unit 5B (historical). It could therefore be attributed both to the latest Pleistocene and to the Holocene. In the latter case it should be included into the Post Glacial Unit together with Unit 5.

*Unit 3* represents the depositional systems which build the morphological surface of the *Livello Fondamentale*, outside the terraces of the Lambro valley system. It is constrained in age by the youngest age available for sub-unit 2C (22.035+/-300 a BP ) and the age of the boundary between sub-units 3A and 3B (20.785 – 19909 cal BC). In addition to these data, the stratigraphic position, gravel composition and depositional style suggest a correlation with the alluvial units which were deposited during the waning time of L.G.M. (Crowley & North, 1991; Bini et al., in press). In this case we could suggest a correlation with the deposits of the Alloformazione di Cantù, which have been recognised within the entrenched valleys to the North of the study area by Strini (2001). As no physical correlation is available yet between the two areas, we consider this interpretation as a working hypothesis for ongoing studies.

*Unit 2* represents the coarsest grained unit of the Lambro area; the composition of its gravels is dominated by alpine-sourced clasts, with a strong fingerprint of provenance from the metamorphic basements of Southern and Northern Alps. The age of the uppermost sub-unit 2C is constrained within 24.620+/-160 a BP and 22.035+/-300 a BP, but no constraints are available for the lowermost sub-unit 2A. These data indicate a minimum Late Pleistocene age for Unit 2. In addition we can also consider that, based on regional dip of stratigraphic units, Unit 2 should be at the surface to the North of the study area. In this area, a sand-gravel unit with a comparable gravel composition, represents the shallowest stratigraphic unit, bounded by the topographic surface. By physical correlations, Strini (2001) was able to include this unit into the Besnate Allogroup (Da Rold, 1990; Bini, 1997a; b). This Allogroup is formed by several glacial, glacio-fluvial and alluvial units, which form at least 5 alloformations related to different glaciations (Bini, 1997a). Therefore we suggest that the three sub-units which form Unit 2 can be correlated with the Besnate Allogroup of the pedealpine area. However, we cannot exclude alternative correlations for sub-unit 2A, which could also represent a glacio-fluvial succession , correlative to a pre-Besnate glaciation.

The stratigraphic correlation of Unit 1 is highly uncertain, because we have neither physical correlations, nor age determinations. Unit 1 has been deeply eroded by the lower boundary of Unit 2, and is characterised by a mostly fine-grained facies association, that we interpreted as a distal, meandering fluvial succession. This advises against interpreting this unit as a glacio-fluvial succession linked to a pre-Besnate glacial advance. Actually, in the most conservative hypothesis, it could represent an ancient post-glacial unit, of pre-Besnate age; otherwise it could also represent a pre-glacial unit. This second hypothesis would imply an age older than Middle Pleistocene (Penk & Bruckner, 1909; Kukla & Cilek, 1996), which is not supported, at present, by any circumstantial evidence.

### 5.2 - Sedimentary evolution

The Lambro area is a part of the alluvial plain which developed during Middle – Late Pleistocene between the South-Alpine and Apenninic thrust fronts. The depositional style of filling of this former Pliocene – Early Pleistocene marine area has been controlled principally by northwards propagation of the Apennine frontal thrusts (Salerano and San Colombano ramp anticlines; Pieri & Groppi, 1981; Bersezio *et al*., 2001; Fantoni *et al*. 2003, with references therein), uplift on the Alpine side (Arca & Beretta, 1985), onset and dynamics of glaciations (since the Middle Pleistocene; Penk & Bruckner, 1909; Bini, 1997a with references therein), dynamic of the regional base-level and erosion-deposition hinge.

The succession that we could investigate developed in an alluvial environment, built by the coalescent deltas of transversal alpine rivers and palaeo-Po axial system, when the coast-line was already far away, to the East of the study site (Dondi & D'Andrea, 1986, Regione Lombardia – ENI, 2002). In fact no indications of marine influence has been found in the deepest succession that we studied (Unit 1). This succession resulted from two steps of SE-wards migration of a meandering river depositional system (Tab. 2), which are separated by an avulsion or a marked retrogression step, documented by the widespread diffusion of flood-plain and palustrine fine-grained sediments. Whether this was due to tectonic control by uplift increments of the Salerano – San Colombano anticlines ("forced regression" concept of Regione Lombardia – ENI, 2002) or to the response to glacial pulses of a pre-Besnate glaciation, or to a combination of the two, cannot be stated with the presently available data.

A subsequent, Late Pleistocene, north-westwards shift of the erosion-deposition hinge, is witnessed by the development of the deep erosion surface that soles Unit 2, at the onset of the Besnate glaciations (Bini, 1997a, b). The kriged, plan and 3D view of this surface is portrayed in Fig. 9 (lower maps). This unit documents two major south-eastwards progradation increments of distal, braided alluvial fans, fed from South- and North-Alpine sources. During both steps, the transition to a southern fluvial plain is recorded in the centre of the studied area. The position of the south-eastern fan boundary is clearly recognised in Fig.9, by a marked downward step of the 2A – 1B boundary, together with the channel like shape of the same erosion surface more south-eastwards. The mildly erosional base of sub-unit 2C, which mimics the original shape of the top of the alluvial fan sub-unit 2B, is shown in the same picture, that allows the appreciation of the marked south-eastwards shift of the southern fan boundary, fringing to a fluvial plain system. A direct control from the major Late Pleistocene glaciations can be suggested for these dynamics, linking basal erosion and subsequent progradation of the three coarse-grained depositional systems with the onset and evolution of a glacial stage of the Besnate. The fine-grained deposits of the retrogression stage at the top of unit 2A was poorly developed or incompletely preserved. Differently sub-unit 2C, which is dated between the non-calibrated dates of 22.000 and 24.000 a BP, documents almost entirely the latest cycle of the Besnate, with a widely preserved fine-grained fluvial unit at the top.

A new regional erosion surface heralds the southwards migration of the sandy braid-plain - meandering river depositional system (Unit 3) that developed during the L.G.M. glaciation. The time bracket that is identified by radiocarbon dates (22.000 – 19.900 a BP) for deposition of sub-unit 3A, allows for correlation with the isotope stage 2 (Martinson *et al*., 1987). This is in good agreement with the gravel-sand depositional style of this unit, which differs from the overlaying meandering systems of sub-unit 3B, that could correlate with a glacial retreat. At this time the entire study area was located south of the braid-plain/meandering hinge, as it is portrayed by the map of the lower boundary of sub-unit 3B (Fig. 9), which shows several entrenched and sinuous scours, cross-cutting to one another.

The post-glacial evolution is recorded by the entrenched meandering depositional systems of the Lambro valley system (units 4 and 5). Their deepening was very fast, and high erosion rates lasted up to historical times, if we consider that the top of the "renaissance age" l.s. point bars of sub-unit 5B is about 6 m above the top of the present-day bars of the Lambro river. This is related to the dynamics of the local base-level (Po river), and could be triggered by the ongoing slow uplift of the Apennine structures.

### 5.3 - Hydrostratigraphy and Bearings on hydrogeologic modelling

The previous reconstruction of stratigraphic architecture provides the base for the definition of aquifer stratigraphy of the Lambro area, valid for a thickness of about 100 m. This can be visualised with the aid of the cross-sections in Figs. 5-6 and of the plan view of the kriged boundaries of the most relevant units (Fig. 9).

The distribution and connectivity of the gravel – sand intervals vs. thickness, complexity and continuity of the fine-grained units, defines the aquifer organisation of this succession. Taking into account the basic definition of hydrostratigraphic units (Maxey, 1964; Anderson, 1997 with references therein) it is possible to identify three aquifer units (in ascending order: lower sub-unit 1A; sub-units 1B-2A-2B-lower 2C; units 3-4-5), which are discontinuously separated by two aquitards (upper sub-unit 1A; upper sub-unit 2C). The separation between aquifers is very poor in the northern sector of the study area, where the sand: gravel units merge due to erosion and/or non-deposition of the fine grained layers at their base (Fig. 5 and Fig. 6).

We do not propose any label for these hydrostratigraphic units, because aquifer classification is already sufficiently confused in literature (Martinis & Mazzarella, 1971; Avanzini *et al*.,1995; Francani, 2001; Regione Lombardia – ENI, 2002). We shall refer to them respectively as "lowermost", "intermediate" and "uppermost" aquifer, being aware of their local significance, which is restricted to the study area.

The *lowermost aquifer* is mostly sandy and shows internal complexity, due to southwards fringing of the sand-bodies, which alternate with silt-mud, flood plain intervals. The aquitard at its top is represented by the widespread flood plain muddy unit that tops the fining-upwards sequence 1B. Although it is locally truncated northwards (Fig. 9, maps of base 2A), it seems to represent an efficient confining layer at the scale of the study area.

The *intermediate aquifer* is the coarsest and thickest one. It corresponds to the lower part of the "Aquifero Tradizionale" (*Auct*.), and possibly could belong to Aquifer Group A (?) of Regione Lombardia – ENI (2002). It is formed by gravel-sand bodies, which are interconnected to the North due to the development of the regional erosion surface that soles Unit 2 and of the sharp progradation surface of sub-unit 2B above 2A. Southwards these coarse-grained bodies fringe out, due to transition from braided alluvial style, to meandering fluvial deposition, with development of flood plain-oxbow lake-channel abandonment fine-grained deposits. Seemingly, the retrogradation of the 2B gravel-sand body determined the development of a general upwards fining succession, whose sand – mud alternations form the overlaying complex aquitard. The efficiency of the latter is strongly affected by erosion of sub-unit 2C to the North and East (Figs. 5, 6 and 9), that determines the connection with the uppermost aquifer, and locally with the topographic surface (Lambro valley system,

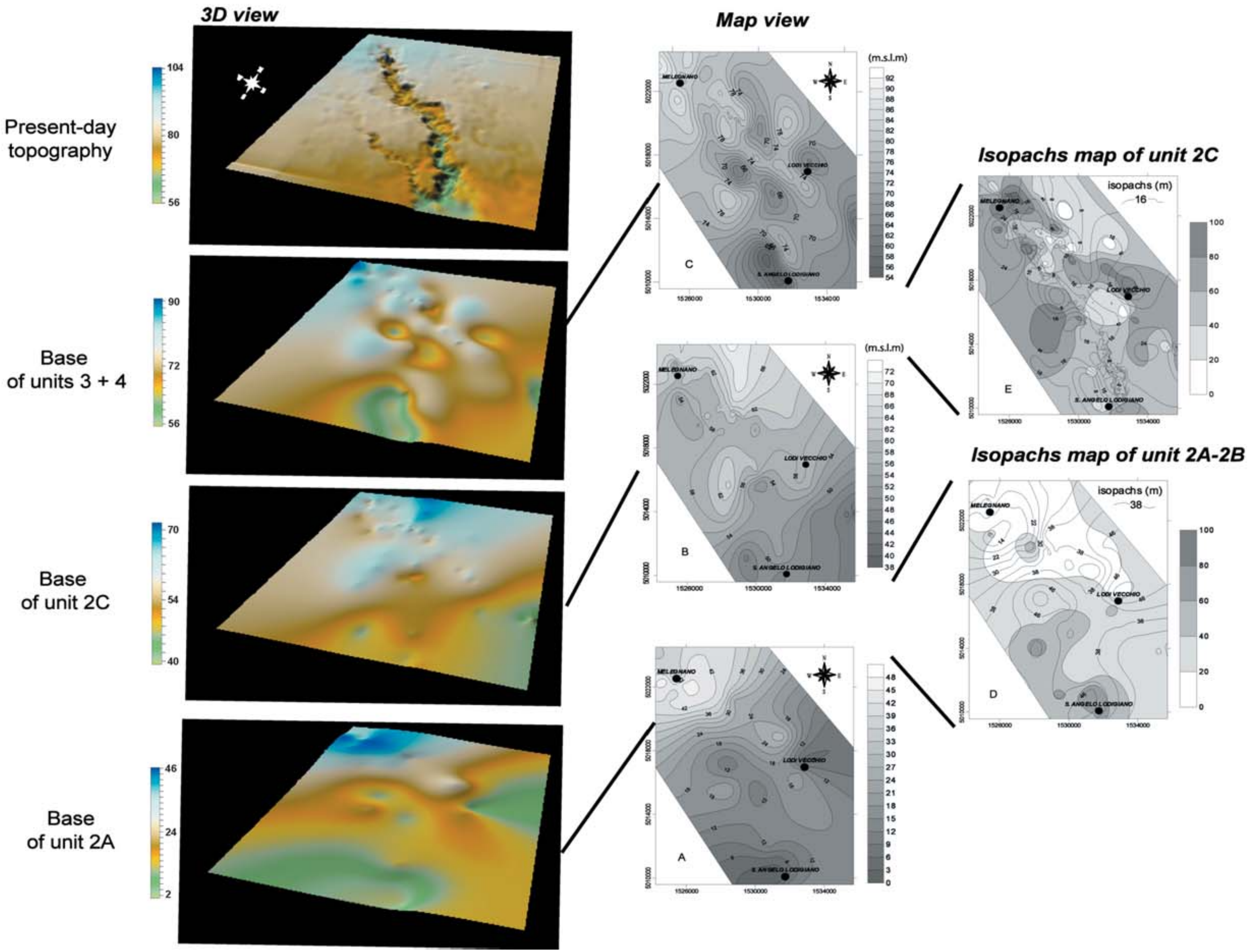



Fig.9 - Kriged isobaths (right) and 3D view (left) of the lower boundaries of sub-units 2A, 2C, 3 and of the present-day topography. At the extreme right, the isopach maps of sub-units 2A-B and 2C are represented. The maps show the basal scouring of the aquifer units into the fine-grained aquitards, cumulative thickness of the most important aquifer (sub-units 2A and B) and the post-glacial entrenchment of the Lambro valley system.

*Mappe delle isobate e visione 3D dei limiti inferiori delle sub-unità 2A, 2C e 3; in alto è riportata la ricostruzione della topografia. Le mappe sono ottenute per kriging delle superfici indicate. A destra sono rappresentate le mappe di isopache delle sub-unità 2A-2B e 2C. Le mappe illustrano l'erosione alla base degli acquiferi principali, approfonditi all'interno dei relativi acquitardi, lo spessore dell'acquifero intermedio (2A - B) e l'approfondimento post-glaciale del sistema vallivo del Lambro.*

Fig. 9 uppermost map). Therefore, the intermediate aquifer is a multi-pay, partly confined aquifer unit, whose separation from the surface waters is not completely ensured throughout the study area. However, its bulk recharge should be looked for also northwards of the same area, where the top of the Besnate Allogroup is close to the surface (Strini, 2001).

The *uppermost aquifer* is the phreatic one and includes the non-saturated zone at its top. The recent regional piezometric maps (Francani, 2001) indicate that the water table-top fluctuates between 5 and 10 m below the topographic surface. Field observations of excavations, quarries, borehole drillings and terrace scarps, indicate that temporary and local water nappes are contained at least up to a depth of 2 m below the surface. This is confirmed by semi-permanent historical water sources which are aligned on the scarps of the major terrace of the Lambro river. These ground waters are only intermittently and locally in contact with the Lambro river waters. These observations are clearly justified by the organisation in minor fining upwards sequences of sub-unit 3B, with flood plain fines which act to compartment ground waters within the phreatic nappe. Below the upper part of this unit, there is a good potential interconnection among the gravel-sand lenses of Units 3A and 4, as far as they are juxtaposed by deep erosion surfaces. This observation holds also for the relations with the intermediate aquifer, which is truncated at the top by the lower erosional boundary of the Lambro valley system (Fig. 6). In fact the uppermost aquifer is deeply dissected by the Lambro terrace scarps (Fig. 9, left). The top of the uppermost aquifer is only poorly protected by sandy soils (Brenna, 2002), therefore this unit acts like a vertical filtration zone recharging this shallow aquifer and contributing to the recharge of the intermediate one.

## 6 - CONCLUSIONS

Aquifer stratigraphy and architecture of the Upper Pleistocene succession of the Lambro valley area, south of Milan, has been built by the dynamics of alpine-fed, alluvial depositional systems. The hydrostratigraphic complexity is determined by:

- the Late Pleistocene, glacial controlled, erosion - progradation – retrogression cycles, that determined the repetitive stacking of gravel/sand, fining upwards sequences (most permeable aquifers), topped by widespread, fine-grained, least permeable units (aquitards);
- the erosional entrenchment of depositional systems, controlled by the dynamics of the erosion – aggradation hinge under the influence of climatic cycles and local uplift of the Salerano – San Colombano ramp anticlines, that shaped the connectivity of the most permeable bodies;
- the NW – SE transition from distal alluvial fan/braid plain to meandering fluvial/flood plain depositional systems, that occurs in the centre of the studied area.

The *lowermost aquifer* (sub-unit 1A) is a multi-pay, confined unit, presumably developed during an interglacial period of pre-Besnate age. It is partly sealed by alluvial plain fines (top of 1A).

The *intermediate aquifer* (sub-units 1B, 2A, 2B, lower 2C) corresponds to the traditional aquifer *Auct*. and to part of Aquifer Group A (Regione Lombardia – ENI, 2002), and includes a pre-Besnate sand – gravel unit and the alluvial depositional systems equivalent to the Besnate. It is a multi-pay unit, formed by stacked cycles of advancement and retreat of distal alluvial fan/braid plain, only partly confined at the top by the retrogradational fines of the upper part of sub-Unit 2C. It is recharged in the area of northern emergence of the Besnate Allogroup and locally by the surface waters, including the strongly compromised Lambro river waters.

The *uppermost aquifer* includes the phreatic/non saturated zone and is formed by the braid-plain to meandering depositional system (Unit 3) which correlates with the L.G.M. in the study area; it is in full contact with the Post Glacial to historical meandering depositional system of the Lambro valley (units 4 and 5). It is only poorly protected by discontinuous flood plain fines and by mostly sandy surface soils.

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