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Late Quaternary Fluvial Sediment Architecture and Aquifer Systems of the Southern Margin of the Po River Plain

Sedimentazione fluviale tardo-quaternaria e sistemi acquiferi del margine sud-padano

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ABSTRACT - The study area, extending over 560km^2, is located in the southern portion of the Po River alluvial plain. The area is the internal side of a classical foreland basin and is affected by active thrust tectonics. The tectonic deformation and the general sedimentation pattern of the area are representative of the entire southern margin of the Po River plain and similar perisutural settings. The study area has been selected specifically to include a rapidly subsiding portion of the alluvial plain juxtaposed to a slowly subsiding portion, represented by the plain west of Torrente Enza and west of the Taro River, respectively.

Sediment deposition in the area is the result of the activity of tributaries of the Po River, i.e., the transversal drainage of the foreland basin, namely, Torrente Enza, Torrente Parma and especially the Taro River. The study is confined to a 5-20km wide portion of the plain where the topographic slope is relatively high (generally >4‰) and is aimed to define existing hydrostratigraphic units to depths of 50-200m and correlate them across the investigated plain. Stratigraphic reconstruction indicates that Late Quaternary sedimentation is controlled by tectonics modulated by 100ka astro-climatic cycles the physical expression of which are the so called high-frequency sedimentary cycles. These alluvial cycles are allostratigraphic units that we interpret as hydrostratigraphic units (HsU) consisting of elements such as aquifers (AQ) and associated confining layers (CL). Two hydrostratigraphic units developed in the last 180ka. From the surface they are: HsU1, comprising confining layer 1 (CL1) and underlying aquifer 1 (AQ1), and HsU2, comprising confining layer 2 (CL2) and underlying aquifer 2 (AQ2).

CL1 extends from ground surface up to 35m depth and is an essentially fine-grained body with a 12ka old base representing the mud-draping of the area during latest Pleistocene-Holocene times. Its depositional style is that of an alluvial plain in which active elements are braided and meandering perched rivers. CL1 attains its maximum and minimum thicknesses in the western and eastern portions of the plain, respectively. This indicates that during Holocene times the subsidence rate ranged from ca 2.0mm/a to ca 0.2mm/a. AQ1 is dominated by coarse-grained materials, up to 50m thick, which were deposited in an alluvial-fan channelbelt. AQ1, the base of which is dated at 75ka BP, is actually a composite aquifer. It comprises sediments of the stadial ice-periods characteristic of Late Pleistocene times amongst which deposits of the last glacial maximum are prominent. CL2 represents the fine-grained draping of the alluvial plain during the last interglacial (Eemian; Marine Isotope Stage 5), and has a 120ka old base. Its lateral continuity is locally interrupted due to erosion at the base of mayor bodies of alluvial fans. Similarly to CL1, internal structure of CL2 is the result of the activity of braided and meandering perched rivers. AQ2, attaining thicknesses up to 40m, consists of alluvial-fan channelbelt coarse-grained deposits the base of which is assumed to be 180ka BP.

In the study area as well as in the rest of the southern margin of the Po River plain, volumetrically most relevant water resources are contained in the huge alluvial fan bodies of AQ1 and AQ2. Recharge of such aquifers depends on their tectonically-controlled northeastward dip as well as on the amalgamation of AQ1 and AQ2 deposits in the southern portion of the plain. Northward these coarse-grained deposits are confined by increasingly thick and continuous confining layers. The volumetrically most important recharge is from the Taro River, a markedly loosing stream, sourcing the phreatic aquifer (coarse-grained deposits) of the southern elevated portion of the plain. This phreatic aquifer is hydraulically connected to the confined aquifers of the northern portion of the plain. Thus, in general, a remote phreatic aquifer supplies water to the confined aquifers to the north. Several minor perched aquifers occur in the essentially fine-grained CL1; their recharge is both from infiltration and surface-channels.

KEY WORDS: Southern Po River Plain, Thrust Fault, Alluvial Cycles, Alluvial Fan, Hydrostratigraphy, Groundwater Recharge.

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RIASSUNTO - L'area di studio è ubicata al margine sud della Pianura Padana ed occupa una superficie di 560km^2. Geologicamente essa è posta sul fronte deformato della catena appenninica, ovvero sul margine interno del bacino d'avampaese, un assetto strutturale che può essere ritenuto rappresentativo di gran parte del margine sud-padano e di altri simili contesti perisuturali. Il settore di margine è stato scelto in modo da investigare due condizioni caratteristiche di deformazione tettonica e corrispondente sedimentazione, vale a dire un tratto di fronte poco subsidente adiacente ad uno altamente subsidente, rispettivamente rappresentati dal settore in sinistra Fiume Taro ed in sinistra Torrente Enza.

La fascia di pianura studiata è ampia 5-20km e sviluppa una pendenza perlopiù >4‰. La sedimentazione è governata dall'attività dei corsi d'acqua che provvedono al drenaggio trasversale del bacino padano, specificamente i Torrenti Enza, Parma e Stirone e soprattutto il Fiume Taro. La recente acquisizione di molti nuovi dati stratigrafici ha creato le condizioni per sviluppare questa ricerca in cui si dettagliano i primi 50-200m di sottosuolo per identificare e definire l'andamento del Basamento Idrogeologico e delle unità idrostratigrafiche più superficiali che racchiudono le età degli ultimi 180ka circa. La rappresentazione di unità idrostratigrafiche e Basamento Idrogeologico è stata fatta su due sezioni rappresentative dei suddetti fronti a bassa ed alta subsidenza e su due sezioni chiave, trasversali agli assi deposizionali, che corrono lungo la Via Emilia e lungo l'autostrada A1 ove i corpi di sedimenti grossolani assumono i loro massimi spessori.

Nel tardo Quaternario la sedimentazione è notoriamente controllata dalla tettonica e modulata dai cicli astro-climatici fra i quali ben espresso è il ciclo con periodo 100ka che sviluppa unità allostratigrafiche, separate da superfici erosionali, qui interpretate come unità idrostratigrafiche. Negli ultimi 180ka sono riconosciute due unità idrostratigrafiche (HsU) entrambe costituite dalla coppia di elementi: acquifero (AQ) e soprastante barriera di permeabilita (CL). Dal punto di vista volumetrico le più rilevanti risorse idriche sono contenute negli apparati di conoide ciclicamente sviluppati nel Pleistocene medio-superiore. La ricerca mette in chiaro che attualmente le conoidi alluvionali del margine sud-padano non hanno un'espressione morfologica superficiale; in realtà si tratta di corpi sviluppati nel sottosuolo il cui tetto è rappresentato dall'andamento dell'isocrona 12ka BP circa. L'architettura interna del corpo olocenico indica invece che durante l'attuale stazionamento alto del l.m. i corsi d'acqua appenninici hanno costruito canali pensili e colmato la pianura con sedimenti fini tramite processi di avulsione e di alluvionamento.

La barriera di permeabilità CL1, con base datata a circa 12ka, rappresenta il drappeggio della pianura durante il tardo Pleistocene superiore-Olocene e si estende dalla superficie fino a profondità dell'ordine dei 35m. Questi spessori sono tuttavia molto diversi nel settore occidentale (Fidentino) ed orientale (Parmense) della pianura. Sulla base dell'accumulo sedimentario registrato in questo ultimo settore a massima subsidenza si calcolano tassi di sedimentazione medi fino a 2mm/a. L'acquifero AQ1, con base tentativamente posta a 75ka BP, è di natura composita comprendendo i diversi stadiali del Pleistocene superiore fra cui risaltano quelli dell'ultimo massimo glaciale. La barriera di permeabilità CL2 è stata deposta durante l'ultimo interglaciale, corrispondente al MIS 5, con base datata 120ka BP circa. La sua continuità laterale è localmente interrotta per erosione da parte dei soprastanti corpi grossolani dell'elemento AQ1. L'elemento AQ2, con base tentativamente posta a 180ka, è costituito in prevalenza da corpi grossolani spessi fino a 40m.

La ricarica degli acquiferi è condizionata dall'inclinazione tettonica verso nordest dei corpi sedimentari che compongono le unità idrostratigrafiche e dall'amalgamazione degli elementi AQ1 e AQ2 sul dorso e sul fronte della struttura sepolta di Monticelli Terme. L'alimentazione primaria av-viene giusto in questa fascia, sostanzialmente posta a sud della Via Emilia, ad opera degli alvei disperdenti dei corsi d'acqua. In questa posizione i serbatoi acquiferi esprimono una falda freatica che verso settentrione viene progressivamente compartimentata da barriere di permeabilità di vario ordine. Questi acquiferi in pressione, sviluppati a nord della Via Emilia, sono ricaricati dall'acquifero freatico con flussi lungostrato orientati trasversalmente al fronte della struttura sepolta di Monticelli Terme.

PAROLE CHIAVE: Pianura sud-padana, Fronte di accavallamento, Cicli alluvionali, Conoide alluvionale; Idrostratigrafia, Alimentazione della falda.

1. - INTRODUCTION

The study area, located in the Province of Parma, extends in the east-west direction from Torrente Enza to Torrente Stirone and in the north-south direction from the A1 highway to the front of the Apenninic chain, covering a surface area of 560km^2. The area is part of the alluvial plain of the Po River, a classical foreland basin, the southern margin of which represents its internal side affected by active thrust tectonics. The fluvial sedimentary architecture of the study area resulting from interplay of tectonics and sedimentation style is characteristically expressed on the entire southern margin of the Po River alluvial plain and may be considered representative of many other similar perisutural settings (e.g. ANTOLINI *et alii*, 1999).

The alluvial sediments discussed here originate from the activity of the Po River tributaries, the transversal drainage of the southern portion of the foreland basin, namely Torrente Enza and Torrente Parma and especially the Taro River. The work is confined to the 5-20km wide margin of the plain where the topographic slope is commonly >4‰ (MURST - C.C. SCIENZE DELLA TERRA, 1995), and is aimed to present the big picture of both the depositional architecture and the related distribution of aquifer systems.

Regionally, it is now well documented that Late Quaternary sedimentation is controlled by tectonics, modulated by 100ka astro-climatic cycles the physical expression of which are the so called high-frequency sedimentary cycles (REGIONE LOMBARDIA & ENI-AGIP, 2002). These alluvial cycles are allostratigraphic units here interpreted as hydrostratigraphic units consisting of aquifers and associated confining layers. New acquisition of many stratigraphic data has provided the opportunity to define sedimentary architecture and hydrostratigraphic units back to ca 180ka BP up to depths in the range of 50-200m.

The portion of the alluvial plain presented here has been chosen in order to investigate two characteristic conditions of tectonic deformation and corresponding sedimentation, specifically, an area with little subsidence adjacent to a highly subsiding one; these are represented by the areas west of the Taro River and of Torrente Enza, respectively. Hydrostratigraphic units and Hydrogeologic Basement have been identified in two key cross-sections located in these two differently subsiding areas and on two other cross-sections transversal to the depositional axes, located along the Via Emilia and the A1 highway, where the hydrostratigraphic units reach their maximum thicknesses.

2. - TECTONICS, CLIMATE AND SEDIMENTATION

In the southern margin of the Po River plain, Quaternary continental sedimentation has been controlled by an active thrust belt located in front of the Apenninic chain. The study area presents a northwest-southeast oriented buried thrust front discussed by BERNINI & PAPANI (1987) and SAGNE (1998). This system of faults defined on the base of the deformation of Mio-Pliocene beds is indicated in figure 1 together with the position of the crest line of the positive structures. A significant example is provided by a north-south seismic section presented in figure 2 (RER & ENI-AGIP, 1998). The crest of the most prominent buried positive structures determines a northwest-southeast oriented front connecting

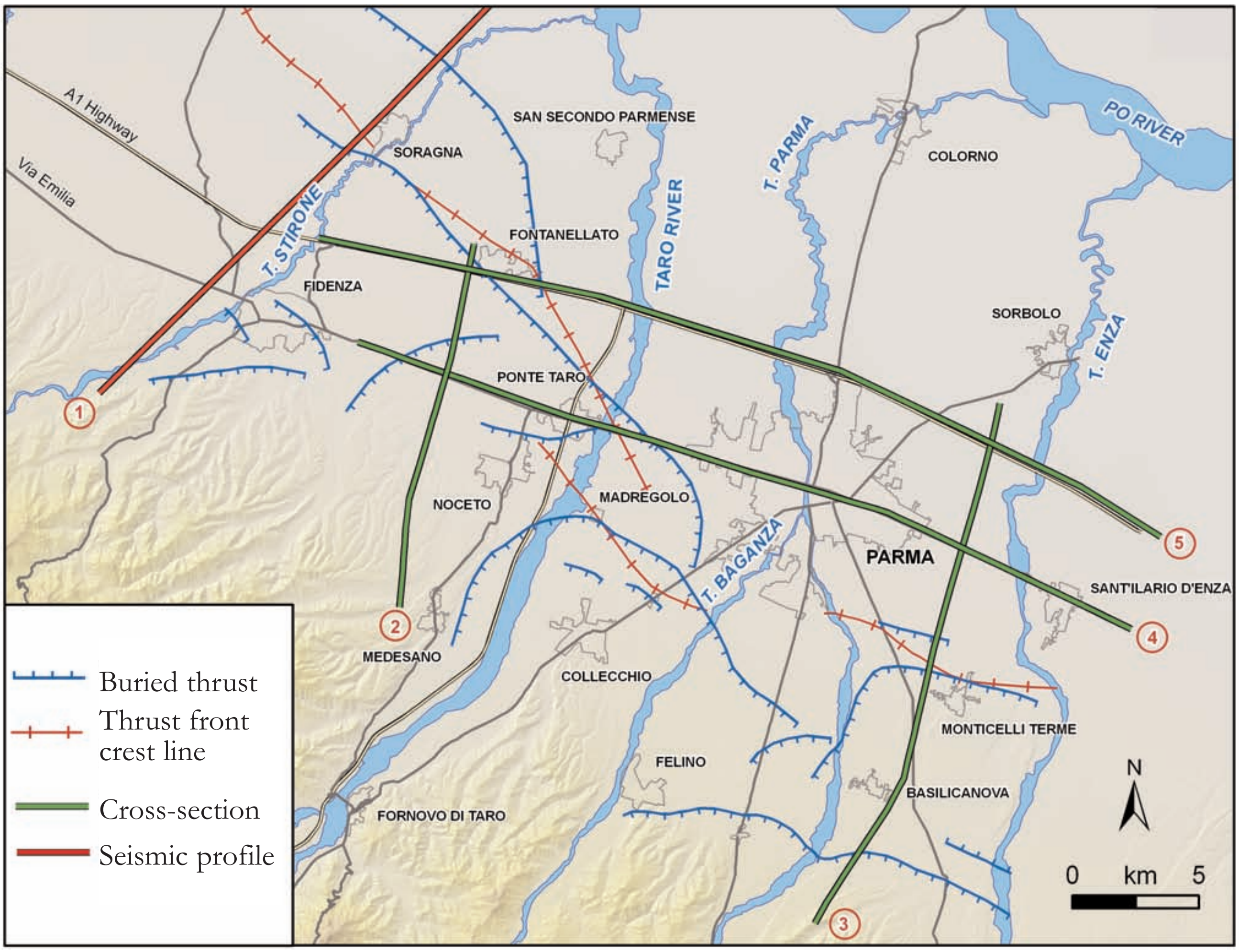

Fig. 1 - The study area, located in the southern elevated portion of the alluvial plain; its western (Torrente Stirone) and eastern (Torrente Enza) limit essentially coincide with the borders of the territory of the Parma Province. In red the trace of the seismic profile in figure 2. In green the trace of the geological cross-sections parallel (number 2 and 3) and normal (number 4 and 5) to the depositional axes. Thrust elements are from BERNINI & PAPANI (1987) and DI DIO *et alii* (1997).

- Ubicazione dell'area di studio, estesa dal Torrente Stirone a ovest al Torrente Enza ad est, posta nella porzione medio-alta della pianura alluvionale. In rosso la traccia della sezione sismica di figura 2. In verde le tracce delle sezioni geologiche parallele (numero 2 e 3) e trasversali (numero 4 e 5) agli assi deposizionali. Accavallamenti sepolti da BERNINI & PAPANI *(1987) e* DI DIO *et alii (1997).*

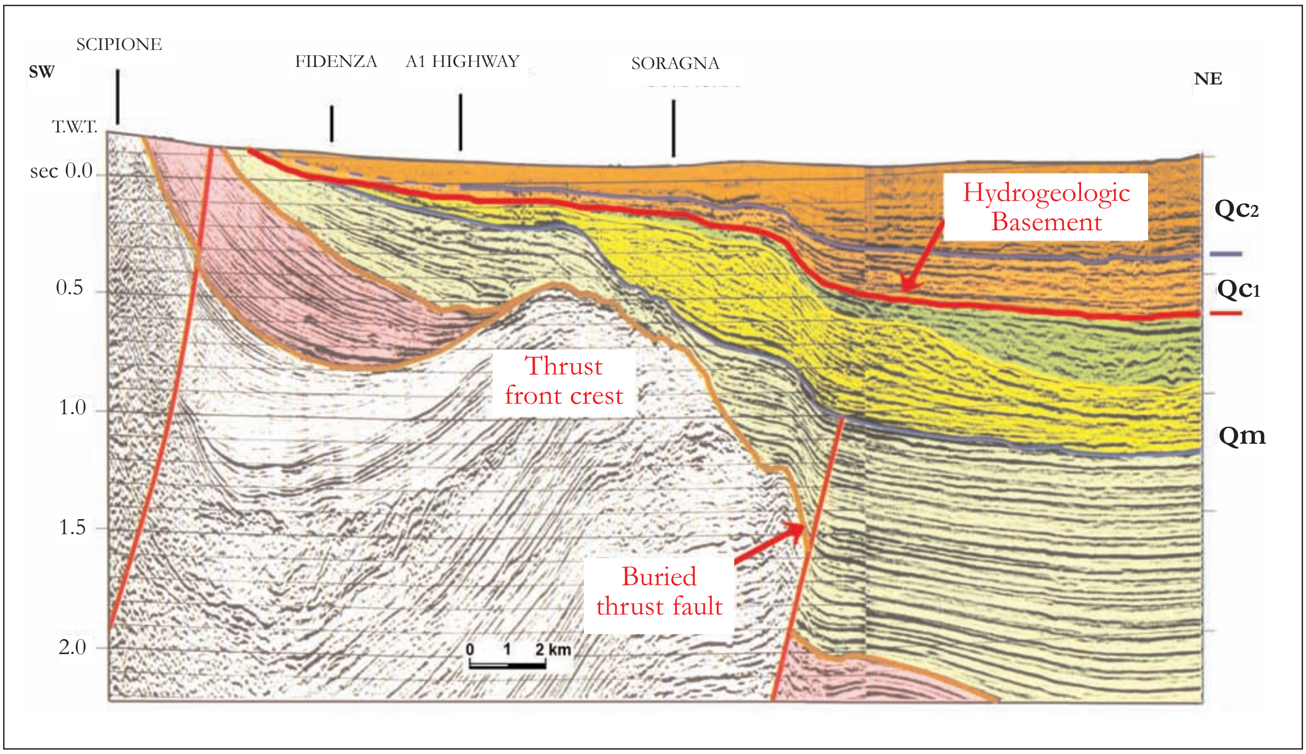

Fig. 2 - Seismic profile transversal to the orientation of the buried thrust front (trace 1 in figure 1). In pink the Middle-Late Pliocene marine strata; the red line indicates the Quaternary Marine Sequence/Continental Sequence unconformity (Hydrogeologic Basement) dated at about 800ka. Qm = Quaternary Marine Sequence; Qc_1 and Qc_2 = Quaternary Continental Sequence (modified after RER & ENI-AGIP, 1998).

- Profilo sismico interpretato orientato trasversalmente agli assi strutturali ubicato all'altezza del T. Stirone (traccia n°1 di figura 1). In rosa il Pliocene medio superiore; la linea rossa indica il limite inconforme Quaternario marino/continentale (basamento idrogeologico) datato circa 800ka BP. Qm = Quaternario Marino; Qc_1 e Qc_2 = Sintema Emiliano-Romagnolo Inferiore e Superiore (da RER & ENI-AGIP, 1998, modificato).

the towns of Fontanellato, Madregolo and Monticelli Terme (fig. 1). On the exact vertical of Monticelli Terme the Quaternary continental sediments are 10m thick, a value which gradually increases towards northwest, modulated by the crest line culminations and depressions, up to more than 100 metres (PETRUCCI *et alii*, 1975).

Besides the strongly uplifted Marine substrate, figure 2 shows several unconformities affecting Middle-Late Pliocene and Quaternary marine sediments; in particular, the red line marking the unconformity between the Quaternary marine (Qm) and Continental (Qc) sequence is of basinal significance and the corresponding surface, dated at 800ka (DI DIO *et alii*, 1997), is here named Hydrogeologic Basement. Also of basinal significance is the erosional unconformity, dated at 450ka BP, subdividing the Quaternary Continental Sequence (Qc) into Continental Sequences Qc_1 and Qc_2 (CALDA *et alii*, this volume). The sediment thicknesses of Qc_1 and Qc_2 is strongly controlled by the active buried thrust (BEDULLI & VALLONI, 2004). The thickness of the Quaternary Continental Sequence (Qc) increases from the crest of the positive structure in the north-east direction and reaches 340m vertically below the downtown of Parma; further north, below the route of the A1 highway, Qc thickness reaches its maximum of 510m at the crossing with the Parma-Sorbolo motor-road (fig. 1).

The main controls on rates of sediment production in different natural conditions have been discussed by LEEDER *et alii* (1998) who demonstrated enhanced water and sediment supply from Mediterranean catchments during glacial times. KUKLA & CILEK (1996) have identified Plio-Pleistocene sedimentary megacycles at the continental scale initiating with thick units interpreted as a deposit of severe glaciation and terminating with a cluster of soils indicative of warm humid climate. BLUM & TÖRNQVIST (2000) have investigated the cyclicity shown by alluvial sedimentation as a function of sea-level fluctuations; their sedimentation cycle is composed by forestepping coarse-grained deposits (lowstand) at the base and aggradation fines (highstand) at the top. In a stratigraphic borehole located in the northern Po plain MUTTONI *et alii* (2003) have shown a major unconformity at ca -80m a.s.l., abruptly overlain by coarse-grained braidplain sediments corresponding to the onset of the first major Pleistocene glaciation in the Alps dated at 870ka, corresponding to Marine Isotopic Stage 22.

The grain-size curve of sediments cored from boreholes within 20km distance from the Po River studied by VITTORI & VENTURA (1995) matches the oxygen isotope curve of paleotemperatures for the Late Quaternary. In the southern margin of the Po River plain BEDULLI (2004) tentatively matched the stages of the oxygen isotope curve of MARTINSON *et alii* (1987) to the coarse-grained (glacial and stadial phase) and fine-grained (interglacial and interstadial phase) units of the late Middle Pleistocene-Holocene alluvium.

Since Middle Pleistocene the continental deposits of the Po River plain record the sedimentary effects of glacial phases, with extensive development of alluvial fans, and of interglacial phases, where the alluvial plain is subjected to mud draping. Hydraulically this change corresponds to the shift from bedload to suspended load rivers (SCHUMM, 1977). STARKEL (2002) has documented the onset of the Holocene interglacial phase in the Vistula and Varta river systems by the widespread occurrence of organic layers dated at about 10ka BP. Holocene sedimentation in the Po River plain is also dominated by a fine-grained unit draping and levelling ground surface in coastal (AMOROSI *et alii*, 1999) and in internal (SEVERI *et alii*, 2002) areas as well. The repeated deposition of such fine-grained sediment drapes of basinal significance during Middle Pleistocene-Holocene times gave rise to relatively thick and laterally continuous permeability barriers.

3. - SEDIMENTATION AND HYDROSTRATIGRAPHIC UNITS

The sedimentary expression of climatically controlled Quaternary sedimentary cycles at different time scales has been studied extensively. The work of VANDENBERGHE (1995) on the Late Middle Pleistocene continental deposits of The Netherlands indicates that in terms of fluvial depositional style the response to the 100ka climatic cycles is particularly well pronounced, with aggradation and soil production during glacial phases and incision and coarse-grained sedimentation during interglacials. In the Quaternary Continental Sequence (Qc) of the southern portion of the Po River plain, CALABRESE & MOLINARI (2003) recognized four 100ka sedimentary cycles (their Medium Scale Depositional Sequences) and other internal astronomically-driven sequences at a lower scale.

We have explained that during Middle-Late Pleistocene times alluvial sedimentation in the Po River plain is controlled by both tectonics and astronomically driven climatic cycles. In the key paper by RER & ENI-AGIP (1998) it is shown that the 100ka climatic cycles are so clearly expressed that the corresponding sedimentary sequences are actually distinct aquifer complexes (SEVERI, 2001). Such aquifer complexes are consistent with the definition of hydrostratigraphic units and have been so indicated in figure 3 together with the Superficial Aquifer, of latest Late Pleistocene-Holocene age, defined in the follow-up paper by DI DIO (2001). Also the hydrostratigraphic units formally presented here are tied to the 100ka climatically-driven cycles and their corresponding depositional sequences confined by surfaces of basinal unconformity. Summarizing, the DOMENICO & SCHWARTZ (1998) definition of hydrostratigraphic unit is here adapted to indicate a continental depositional sequence formed in a 100ka climatic cycle composed of a basal aquifer and an overlying confining layer (fig. 3).

In the southern margin of the Po River plain water reservoirs are thus tied to the coarse-grained basal element of the hydrostratigraphic units (fig. 3). In paleoenvironmental terms, they represent Pleistocene alluvial fans (DI DIO & VALLONI, 1997) that have no modern counterpart in the area; in other words, due to the compensation of topography provided by the Holocene fine-grained cover, alluvial fans of the last glacial maximum have no morphological expression. The physical reconstruction of Pleistocene alluvial fans was accomplished by the correlation of the closely-spaced stratigraphic logs shown in figure 6 and other literature data (e.g., BORTOLAMI *et alii*, 1979). An idealized reconstruction of an alluvial fan presumed to be active during the Pleistocene in the study area is presented in figure 4. In the

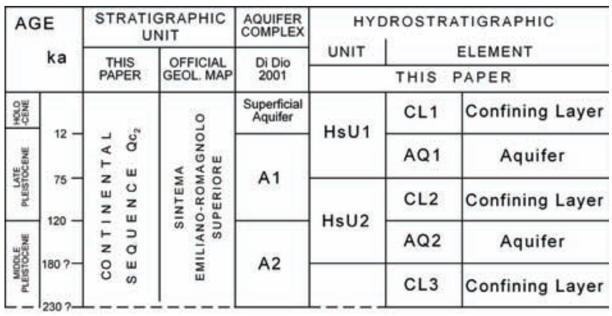

Fig. 3 - Late Quaternary stratigraphic units and corresponding Hydrostratigraphic Units/Elements. Late Pleistocene dates are approximated, Middle Pleistocene dates are tentative. HsU = Hydrostratigraphic Unit; AQ = Aquifer; CL = Confining Layer.

- Quadro delle unità stratigrafiche dei deposti tardo-quaternari del margine sud della pianura e corrispondenti elementi/unità idrostratigrafiche. Le datazioni all'interno del Pleistocene medio sono ipotetiche, quelle all'interno del Pleistocene superiore sono approssimate. HsU = Unità Idrostratigrafica; AQ = Acquifero; CL = Barriera di Permeabilità.

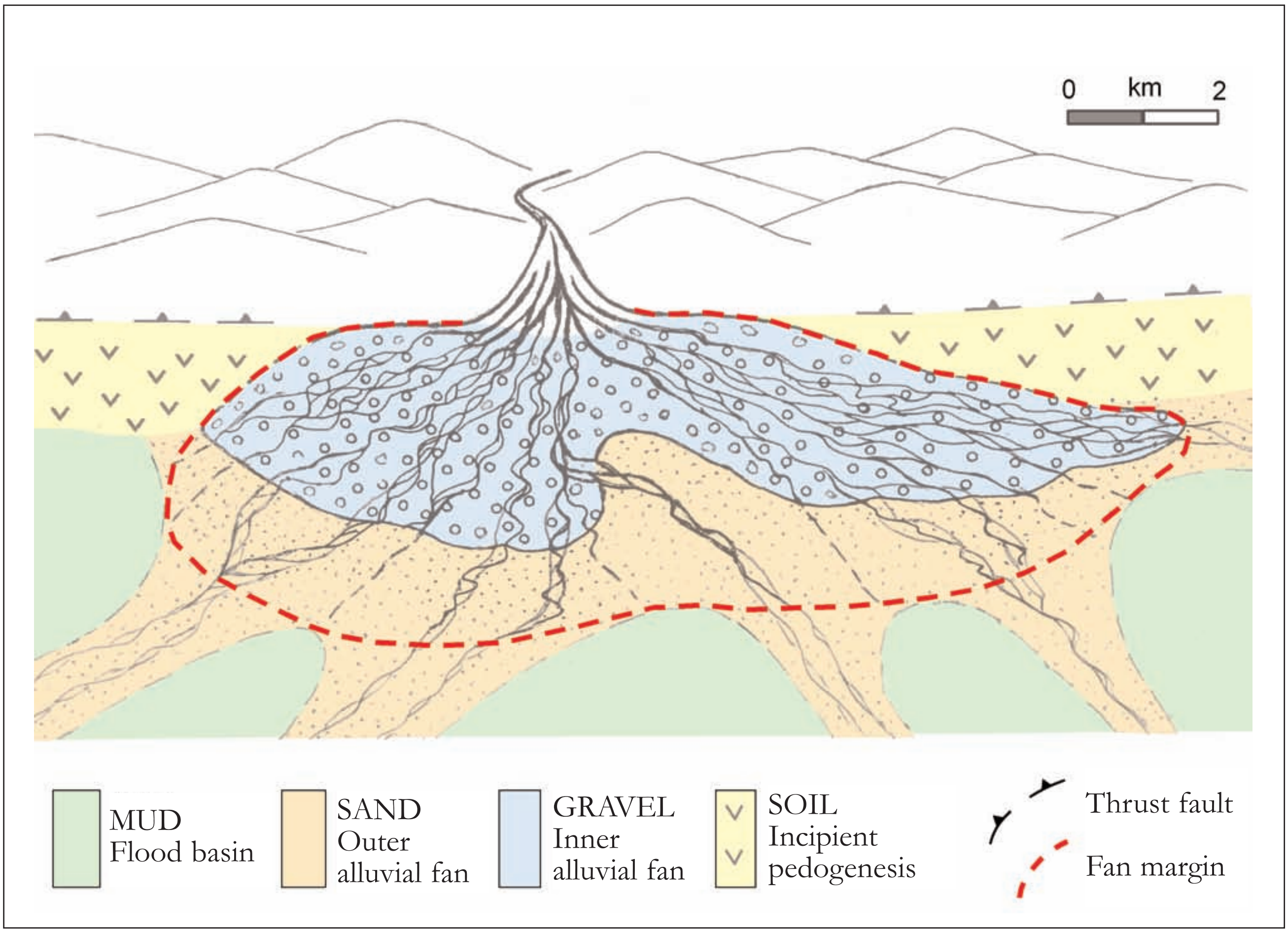

Fig. 4 - Conceptual scheme of an alluvial fan depositional system presumed to be active during the last glacial maximum in the southern margin of the alluvial plain (cf. fig. 5). The thrust fault separates the areas of prevailing erosion (Apennines, in white) and deposition. Bar scale is approximate.
- Schema concettuale di un sistema deposizionale conoide alluvionale attiva (es. ultimo massimo glaciale) del margine sud della pianura (cf. fig. 5). La linea di faglia delimita i domini ad erosione prevalente (area bianca, Appennino) ed a deposizione prevalente (area colorata, pianura). La scala grafica è approssimativa.

case of the Taro River, the alluvial fan representing the hydrostratigraphic elements AQ1 and AQ2 discussed here has giant dimensions extending radially up to 15km and transversely up to 20km (BEDULLI & VALLONI, 2004). In this giant system, the sands at the fringe of the fan interfinger with the sands of the Po River (axial drainage).

In the subsurface of the southern margin of the Po River plain the architectural features critical to the aquifer systems' hydrology are to be found at the very margin of the alluvial plain as exemplified in figure 5. In the elevated margin of the alluvial plain, the bodies of coarse-grained alluvial fans amalgamate. This implies that aquifers AQ1 and AQ2 are welded with the erosion of interposed confining layer CL2. Such amalgamation is not limited to the southernmost portion of the plain shown in figure 5 but also occurs about 7km northward on top of the positive structure of Monticelli Terme (fig. 2 and 7B). The hydrologic consequence is that the aquifer is phreatic and highly vulnerable to pollution (BEDULLI *et alii*, 2004); several kilometers north of the Monticelli Terme positive structure the aquifer becomes confined (FERRAZZO *et alii*, 1997) by progressively frequent and thick permeability barriers (e.g., CL2).

The sedimentation pattern during warm humid (interglacial) climatic phases is generally assumed to have an analogue in Holocene and modern sediment facies architecture; this is spotlighted in figure 5 where (1) coarse-grained sediment transport is confined to the river channel areas, (2) fine-grained alluvium fills interchannel areas, and (3) pedogenesis due to continuing exposure affects elevated areas of non-deposition at the innermost margin. River channels are nested on topographically elevated alluvial ridges (perched rivers) and are prone to avulsion (MURST - C.C. SCIENZE DELLA TERRA, 1997). Channel deposits occur as ribbons and crevasse sheet gravels and sands, embedded in overbank muds, and commonly host perched aquifers (superficial aquifers of the local workers).

4. - SEDIMENT ARCHITECTURE AND AQUIFER SYSTEMS

Several hydrostratigraphic cross-sections have been drawn (e.g. CONTI *et alii*, 1999) on the basis of the stratigraphic database created during many years of research in the area. The depositional facies recognized in the numerous stratigraphic boreholes have been grouped in Hydrostratigraphic Units (HsU), i.e., aquifers (AQ) and overlying confining layers (CL). Specifically, the aquifer is composed of gravels and sands of the proximal alluvial-fan channelbelt, and the distal braided-channel, crevasse splay and levee deposits, whereas the associated confining layer is composed of floodplain mud deposits, minor coarse-grained alluvial ridge channel deposits, and occasional clay and peat deposits in swamps and ponds.

4.1. - HYDROSTRATIGRAPHIC CROSS-SECTIONS

The construction of hydrostratigraphic cross-sections relies on numerous stratigraphic logs from water wells and borehole sediment cores (e.g. GUADAGNINI *et alii*, 2002) the locations of which are shown in figure 6. The cross-sections presented here are traced parallel and transverse to the depositional axes (fig. 1). The former illustrates the poorly and the strongly subsiding portions of the alluvial plain, west of the Taro River (fig. 7A) and of the Torrente Enza (fig. 7B) respectively, and the latter (fig. 8) follows two key alignments represented by the Via Emilia and the A1 highway where the coarse-grained sediment bodies attain their maximum thickness.

The hydrostratigraphic elements of figure 3 are identified by physical correlations of chronostratigraphic significance, their validation being provided by radiocarbon dates (limited to the last 50ka) and earlier stratigraphic work (e.g. SAGNE, 1998). In the cross sections of figures 7 and 8 the Hydrogeologic Basement coincides with the conventional top of the Quaternary Marine Sequence dated at about 800ka BP. In the overlying thick Quaternary Continental Sequence, the definition of hydrostratigraphic units is limited to the deposits of latest Middle Pleistocene and Late Pleistocene-Holocene age where imposing allu-

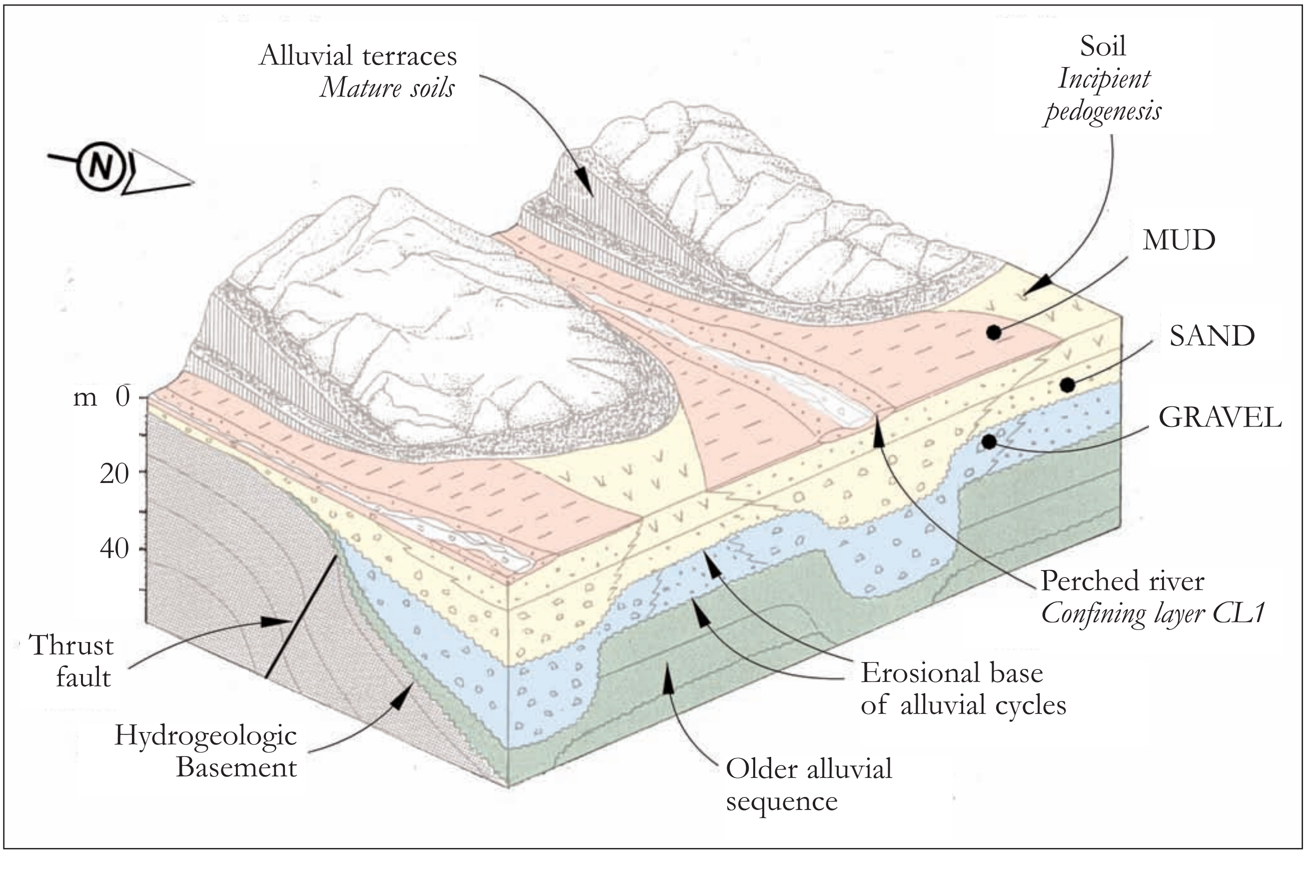

Fig. 5 - Conceptual scheme of sediment architecture in the southern margin of the alluvial plain. Confining Layer CL1 (cf. fig. 3) is the fine-grained superficial cover of latest Late Pleistocene-Holocene age (modified after DI DIO & VALLONI, 1997).
- Schema concettuale dell'architettura sedimentaria del margine sud della pianura. La barriera di permeabilità CL1 (cf. fig. 3) rappresenta il corpo di sedimenti fini di età alto pleistocenica-olocenica che drappeggia la pianura (da DI DIO & VALLONI, 1997, modificato).

vial fan systems occur.

The 180ka and 75ka BP time lines represent the erosive base of sedimentary allocycles deposited in cold climatic phases (Marine Isotopic Stages 6 and 4) that developed alluvial fan systems along the margin of the plain in front of all major river channels (ARPA-RER, 2005). The 180ka BP surface also represents the incised top of a permeability barrier of particularly high lateral continuity described by CALDA *et alii* (this volume). The time-line dated at 12ka BP indicates the deactivation of alluvial fans of the last glacial maximum; the corresponding physical surface represents the physiography of the alluvial plain at the beginning of the "Holocene" eustatic sea-level rise. The overlying essentially fine-grained body that drapes the alluvial plain records the activity of perched river channels subjected to avulsion (VALLONI *et alii*, 2003). Comprehensive evidence of the change from alluvial fan to perched river sedimentation is provided by the current position of the Torrente Enza flowing several kilometers west of the corresponding Late Pleistocene alluvial fan shown in figure 8A in the subsurface of Caprara.

4.2. - HYDROSTRATIGRAPHIC UNITS

Hydrostratigraphic Unit 1 is composed of confining layer CL1, base of which is dated at 12ka BP, and underlying aquifer AQ1, base of which is dated at about 75ka BP. CL1 is an essentially fine-grained member top of which coincides with the ground surface; in the western portion of the study area, characterized by poorly developed bodies of alluvial fans the position of its base is either not recognized (fig. 7A) or is only tentative (fig. 8). The thickness of CL1 is variable and, in limited areas of the southernmost elevated portion of the alluvial plain, even nil (e.g. fig. 7B); its thicker portions, exceeding 20m, commonly host perched aquifers (superficial aquifers of DI DIO, 2001).

In the two cross-sections transverse to depositional axes (fig. 8), the position of the CL1 base, represented by the isochron 12ka BP, highlights differences in subsidence rates. In the area west of the Taro River the ground surface is topographically elevated and subject to pedogenesis; this is a tectonically uplifting area, as demonstrated by the

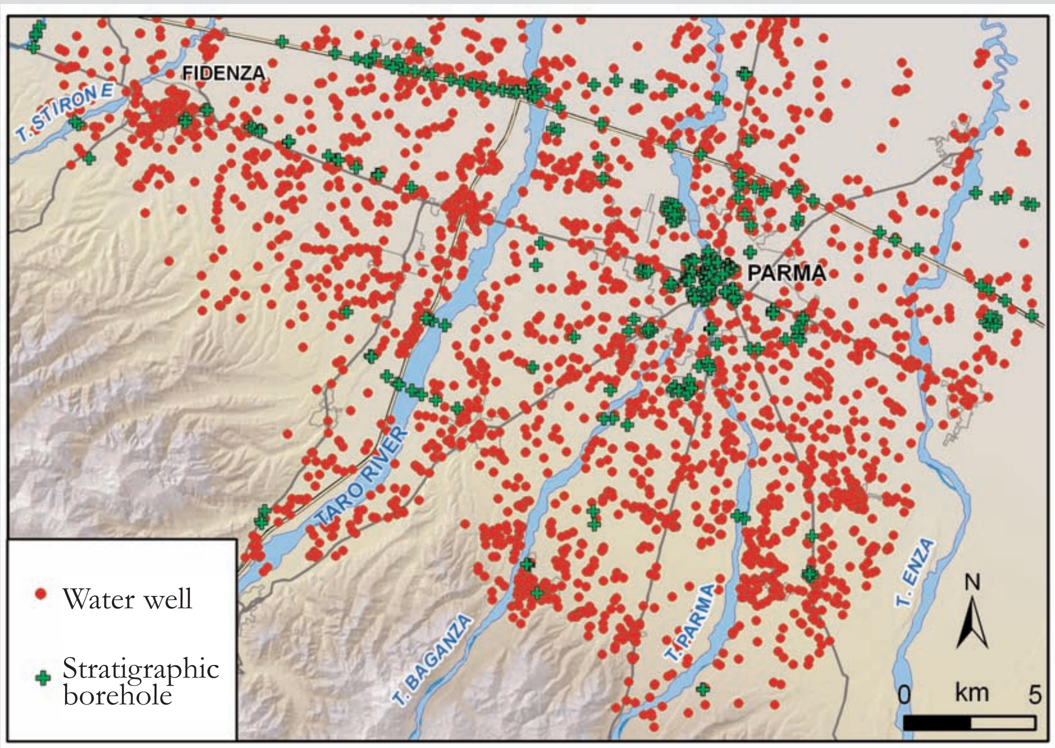

Fig. 6 - Location of water well stratigraphies and of stratigraphic boreholes suitable for the hydrostratigraphic cross-sections of figures 7 and 8.
- Ubicazione dei pozzi per acqua con stratigrafia nota e dei sondaggi a carotaggio continuo utilizzabili per la realizzazione delle sezioni idrostratigrafiche delle figure 7 ed 8.

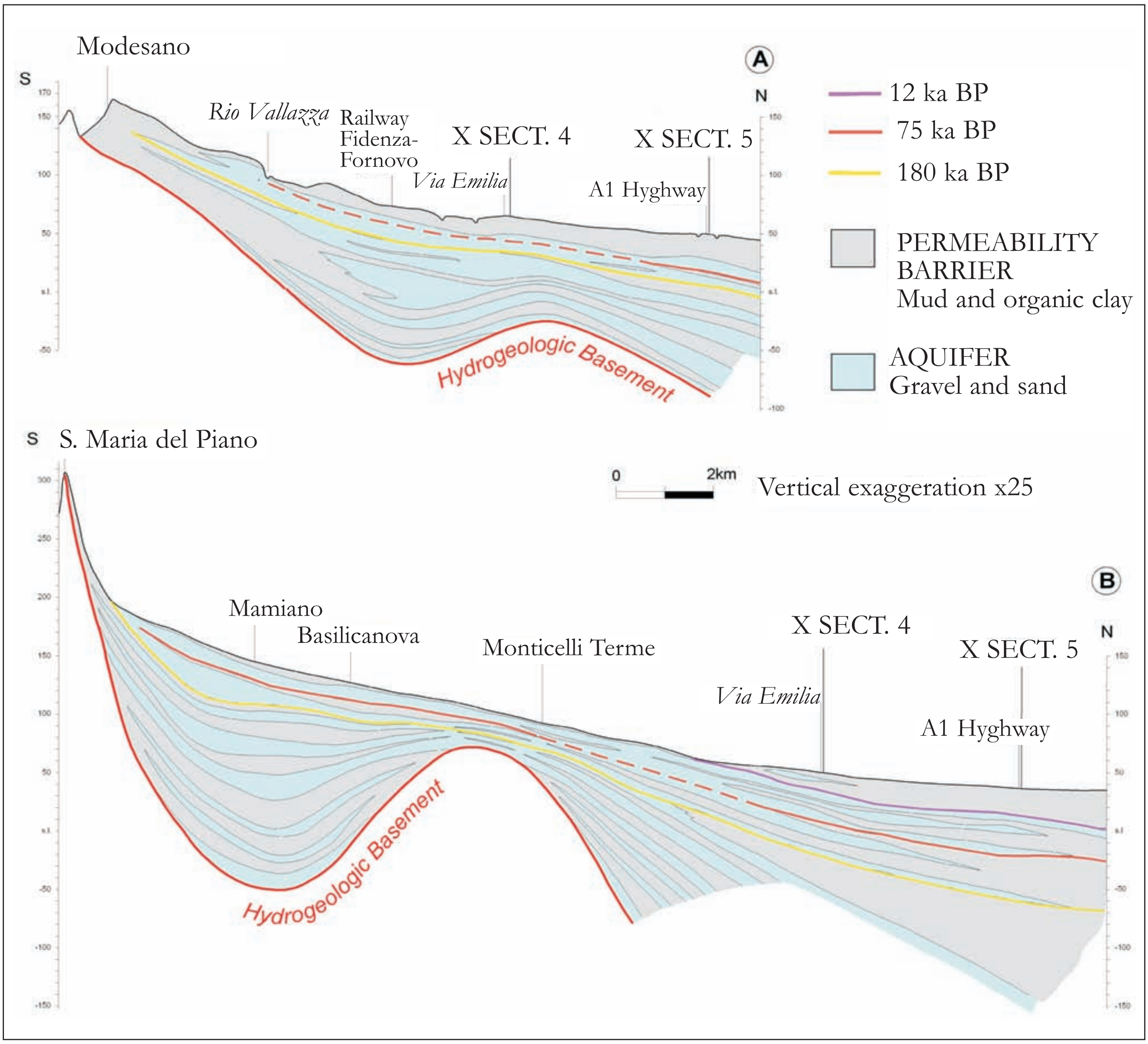

Fig. 7 - Hydrostratigraphic cross-sections parallel to the depositional axes (modified after Bedulli 2004). (A) Western portion of the study area (section 2 in fig. 1); (B) Eastern portion of the study area (section 3 in fig. 1). The crossing with sections 4 (Via Emilia) and 5 (A1 highway) of figure 8 is indicated.
- *Sezioni idrostratigrafiche lungo gli assi deposizionali (da Bedulli, 2004, modificato). (A) Sezione in sinistra Fiume Taro (traccia n°2 in fig. 1); (B) Sezione in sinistra Torrente Enza (traccia n° 3 in fig. 1).*

presence of active thrust faults (Di Dio *et alii*, 1997). On the contrary, in the area west of Torrente Enza CL1 is thick and contains, especially in proximity of its base, widespread organic clay deposits indicating 10-12ka old grounds with stagnant-water. Along the alignment of the A1 highway (fig. 8A) the measured thickness of CL1 indicates an average subsidence rate up to 2mm/a during the last 12ka.

Aquifer AQ1 is actually a composite hydrostratigraphic element consisting of (probably) three coarse grained bodies of alluvial fans separated by laterally discontinuous fine-grained alluvial deposits. In figure 8A the alluvial fan deposited during the last glacial maximum is identified by the time-line 24ka BP at its base. Aquifer AQ1 is the thickest and laterally continuous hydrostratigraphic element of the Middle-Late Pleistocene Continental Sequence Qc_2; its maximum thickness, up to 50 metres, is shown in the alluvial fans of Taro River and Torrente Enza. The tectonic structure (Monticelli Terme high) created by the buried thrust front involving the Hydrogeologic Basement (fig. 1, 2 and 7) controls the geometry of HsU1. On top and front of the Monticelli Terme high, coarse-grained deposits of alluvial fans amalgamate. Northward, in the 5km distance stretching from Via Emilia to A1 highway, progres-

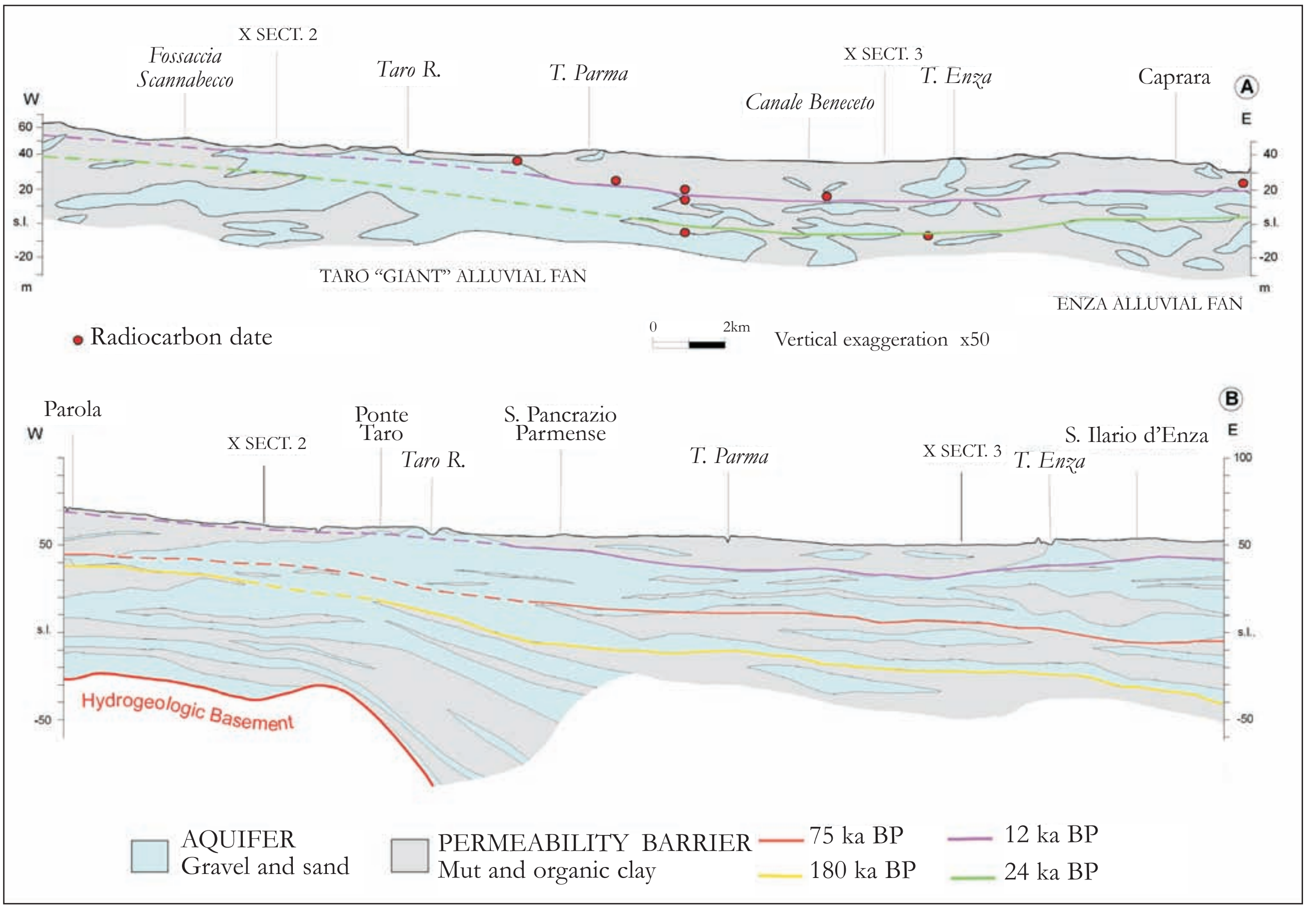

Fig. 8 - Hydrostratigraphic cross-sections transversal to the depositional axes (modified after BEDULLI, 2004 and VALLONI *et alii,* 2003). (A) route of the A1 highway (section 5 in fig. 1); (B) route of the Via Emilia (section 4 in fig. 1). The crossing with sections 2 and 3 of figure 7 is indicated. Cross-section A is limited to the depth of ca 50m in order to detail the base and top of the coarse-grained deposits of last glacial maximum.
- Sezioni idrostratigrafiche trasversali agli assi deposizionali (da BEDULLI, 2004 e VALLONI et alii, *2003, modificate). (A) Sezione lungo il tracciato dell'autostrada A1 (n° 5 in fig. 1); (B) Sezione lungo il tracciato della Via Emilia (n°4 in fig. 1). La sezione A mette a fuoco i primi 50 m di sottosuolo per dettagliare la base ed il tetto dei depositi dell'ultimo massimo glaciale.*

sively thicker and laterally continuous fine-grained alluvial deposits develop and confine the aquifer.

Hydrostratigraphic Unit 2 is composed of confining layer CL2, the fine-grained body deposited during the Eemian (MIS 5), and underlying aquifer AQ2 base of which is tentatively dated at 180ka BP (CALDA *et alii,* this volume). East of the present course of the Taro River, permeability barrier CL2 is continuously present from the front of the Monticelli Terme high northward, whereas CL2 is completely lacking west of the Taro River. Coarse-grained deposits of AQ2 and AQ1 amalgamate in the Taro alluvial fan. Aquifer AQ2 reaches its maximum thickness of about 40m west of the city of Parma and rests on a particularly large and continuous permeability barrier acting as an effective aquitard; only on top of the Monticelli Terme high (fig. 7) and in the Taro alluvial fan (fig. 8) the aquitard is eroded and the coarse-grained deposits of AQ2 are hydraulically connected to the underlying aquifer (cf. VIGNA, 1996).

5. - CONCLUSIONS

In the southern margin of the Po River plain Quaternary sedimentation is controlled by both thrust tectonics and climate forcing. Tectonic deformation is mostly due to the activity of a buried thrust-front causing variations in sediment thickness. The base of the Quaternary Continental Sequence, dated at about 800ka, is near-surface at Monticelli Terme and reaches depths of 340m and 510m vertically below the downtown of Parma and the A1 highway, respectively. Tectonic/sedimentary subsidence, calculated as sediment accumulation rates during the last 12ka, reaches a maximum of 2mm/a in the area between Torrente Enza and Torrente Parma.

With respect to climate, the sediments of the Middle-Late Pleistocene record several depositional sequences confined by surfaces of basinal unconformity responding to the 100ka astronomical cycles; accordingly the hydrostratigraphic units (HsU) are recognized using the same 100ka time intervals and defined as composites of a basal aquifer (AQ) and an overlying confining layer (CL) where AQ and CL are dominated respectively by alluvial-fan gravel and sand, and by floodplain mud deposits.

With the onset of the glacial phase corresponding to MIS 6 (ca 180ka BP), alluvial fan systems of particularly large dimensions filled the southern margin of the Po River plain. Two thick HsUs are deposited that contain the largest volume of water resource of the entire Continental Sequence Qc_2. They are, in descending stratigraphic order, HsU1, constituted by confining layer CL1 and underlying aquifer AQ1 and HsU2, constituted by confining layer CL2 and underlying aquifer AQ2.

Confining layer CL1 has variable thickness that may well exceed 30m or even be nil as commonly happens in the southernmost elevated portion of the alluvial plain. It consists of an essentially fine-grained body with a 12ka old base representing the mud-draping of the region during latest Late Pleistocene-Holocene time interval. Its depositional style is that of an alluvial plain active elements of which are braided and meandering channels flowing on alluvial ridges. CL1 characteristically hosts several minor perched aquifers that recharge from both infiltration and surface-channels.

Aquifer AQ1 is a composite element comprising deposits of the stadial ice periods of Late Pleistocene times, among which those of the last glacial maximum (base at 24ka) are prominent. AQ1, up to 50m thick, is dominated by alluvial fan channelbelt deposits and has a 75ka old erosive base. Confining layer CL2 represents the fine-grained draping of the alluvial plain that took place during the last interglacial, known as Eemian (MIS 5) and has a ca 120ka old base. CL2 is laterally continuous with a thickness exceeding 20m east of the Taro River and is almost completely eroded west of it. Consequently, AQ1 and AQ2 amalgamate to the west of Taro River (fig. 8B) allowing interaquifer flow. Aquifer AQ2 is essentially constituted by alluvial fan channelbelt deposits and attains its maximum thickness (up to 40m) between the Taro River and Torrente Parma.

Tectonic deformation plays a primary role in governing ground water circulation. First, in the tectonically elevated area west of the Taro River, the lack of accommodation space prevented the deposition of significant thicknesses of the coarse-grained sediments of AQ1 and AQ2. Second, along the front and on top of the thrust-generated structure of Monticelli Terme, because of river-channel incision during Late Pleistocene glaciations AQ1 and AQ2 are welded (fig. 2 and 7B). Thus, in such areas the aquifer becomes phreatic with the water flow directed northeast until, somewhere between Via Emilia and the A1 highway, the water flow becomes confined by CL1, CL2 and other minor permeability barriers.

Finally, the tectonically-driven orientation of the depositional axes pointing northeast (1) influences the attitude of CL1, CL2 and CL3 which dip northeast and (2) controls the facies and fabric anisotropy of the coarse-grained deposits of AQ1 and AQ2; as a consequence, the general flow of the aquifer is directed toward northeast as shown by the piezometric gradient of phreatic and confined aquifers. The recharge model is constrained by the natural hydraulic gradient of the aquifers, directed northeast, and by streams loosing water until they reach the area north of Monticelli Terme high. River beds recharge the welded AQ1 and AQ2 sediment-bodies that essentially develop into a single phreatic aquifer which in turn recharges via horizontal flow the hydraulically-connected confined aquifers distributed northward of the Via Emilia.

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