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figg. 8

Aquifer stratigraphy from the middle-late Pleistocene succession of the Po Basin

Stratigrafia di sistemi acquiferi nella successione medio - e tardo pleistocenica del Bacino Padano

AMOROSI A. (*), PAVESI M. (**)

ABSTRACT - Detailed stratigraphic correlations based upon a large borehole data base, coupled with a multi-proxy investigation of cores and its framing into a sequence-stratigraphic context, enable for the first time the reconstruction of a high-resolution, unitary scheme of (hydro)stratigraphic architecture for a large portion of the Po Basin (Emilia-Romagna and SE Lombardy) over the last million years, including specific facies connotation of the aquifer systems. Two stratigraphic unconformities of tectonic origin, identified on a seismic basis and dated to about 450 and 870 ka, respectively, represent the lower bounding surfaces of two stratigraphic units (Lower Po Synthem and Upper Po Synthem) that can be tracked and mapped throughout the basin.

A striking cyclic architecture is identified within the the Upper Po Synthem. Each cycle, which is about 50-90 m thick and represents an interval of approximately 100 kyr (4th-order sequence), includes basal, silt-clay overbank deposits with thin and lenticular fluvial-channel sands, showing upward transition to increasingly amalgamated and more laterally extensive fluvial-channel sand bodies. Four aquifer systems (I to IV) in the upper portions of cycles, corresponding to alluvial-fan and fluvial channel-belt deposits, can be correlated from the basin margins to the Adriatic Sea. Shallow aquifer systems I and II display an impressive lateral continuity and are affected by local tectonic deformation only in the Ferrara area and close to the basin margins, whereas syn-depositional tectonics appears to have exerted a marked influence on facies and reservoir distribution of the relatively deeper aquifer systems (III and IV).

On the basis of the overall stratigraphic architecture and diagnostic pollen signature, the laterally extensive mud-prone intervals acting as permeability barriers between the aquifer systems are interpreted to represent the landward equivalents of the transgressive nearshore deposits recognized at more distal locations. This allows subdivision of the fluvial succession into vertically stacked, transgressive-regressive sequences. The transgressive surfaces and their landward equivalents are readily identifiable stratigraphic markers that may be used to frame aquifer geometry within a sequence-stratigraphic context of fluvial architecture. The application of a hierarchy to subsurface stratigraphy in the Po Basin may thus represent the first step toward the interpretation and prediction of alluvial reservoir geometry and connectivity on a basin scale.

KEY WORDS: Aquifer stratigraphy, Alluvial deposits, Po Plain, Quaternary, Sequence stratigraphy

RIASSUNTO - Lo studio di dettaglio di un vasto database stratigrafico, integrato dall'analisi multidisciplinare di carote e dall'inquadramento di esse su base stratigrafico-sequenziale, consente per la prima volta la ricostruzione di un quadro (idro)stratigrafico unitario per i depositi medio- e tardopleistocenici di una vasta porzione del Bacino Padano (pianura emiliano-romagnola e mantovana). Due superfici di discontinuità, identificate su base sismica e datate rispettivamente a 450 e 870 ka, costituiscono i limiti di altrettante unità stratigrafiche (Sintema Padano Inferiore e Sintema Padano Superiore), riconoscibili e mappabili a scala bacinale.

Il Sintema Padano Superiore presenta una caratteristica architettura ciclica. I cicli deposizionali riconoscibili al suo interno hanno uno spessore di 50-90 m e rappresentano intervalli temporali di circa 100.000 anni (sequenze di quarto ordine). Ogni ciclo è dominato inferiormente da depositi sil-

(*) Dipartimento di Scienze della Terra e Geologico-Ambientali, Università di Bologna, Via Zamboni 67, 40127 Bologna, Italy. E-mail: alessandro.amorosi@unibo.it
(**) Via Trifoglio 128, 46040 Ceresara, Mantova, Italy. E-mail: geolmart@gmail.com

toso-argillosi di piana inondabile, con isolate lenti sabbiose di canale fluviale; questi passano verso l'alto a corpi sedimentari grossolani a geometria tabulare, caratterizzati da un elevato grado di amalgamazione. In tutto sono riconoscibili quattro sistemi acquiferi (I-IV), che possono essere correlati dai margini del bacino al Mare Adriatico. Dal punto di vista sedimentologico i sistemi acquiferi sono impostati all'interno di depositi di conoide alluvionale e di channel belt fluviale. Gli acquiferi più superficiali (I e II) mostrano una rilevante continuità stratigrafica e sono deformati unicamente ai margini del bacino e in corrispondenza di alti strutturali quali, ad esempio, le pieghe ferraresi. E' evidente, al contrario, un forte controllo da parte della tettonica sindeposizionale sulle facies e sulla geometria dei sistemi acquiferi relativamente più profondi (III e IV).

Sulla base dell'architettura deposizionale e dei caratteri paleoclimatici (pollini) riscontrati in carota, i depositi prevalentemente fini, lateralmente continui, che formano le maggiori barriere di permeabilità tra sistemi acquiferi sono interpretati come gli equivalenti laterali dei depositi trasgressivi di ambiente costiero riconosciuti nel sottosuolo dell'attuale piana costiera, ponendo così le basi per la suddivisione della successione fluviale in sequenze trasgressivo-regressive. Le superfici di trasgressione ed il loro prolungamento verso terra costituiscono i principali marker stratigrafici alla scala dell'intero bacino, consentendo l'inquadramento degli acquiferi in un contesto stratigrafico-sequenziale. Questo studio dimostra come l'individuazione di una gerarchia di superfici all'interno del Bacino Padano costituisca un elemento imprescindibile per una ricostruzione realistica della geometria degli acquiferi a scala bacinale.

PAROLE CHIAVE: Acquiferi, Depositi alluvionali, Pianura Padana, Quaternario, Stratigrafia sequenziale

1. – INTRODUCTION

The Po Plain, a rapidly subsiding foreland basin bounded by the Alps to the North and the Apennines to the South, is one of the largest alluvial plains in Europe and makes up an appealing target for water research. For this reason, after the early studies mostly focused on basin formation and evolution (PIERI & GROPPI, 1981; PIERI, 1983; DONDI & D'ANDREA, 1986; DALLA *et alii*, 1992; ORI, 1993; MUTTONI *et alii*, 2003), extensive subsurface investigations have been performed in the Po Basin with the aims of defining a general framework of aquifer distribution within the middle-late Pleistocene alluvial succession, and of evaluating the volume and characteristics of the groundwater resource (REGIONE EMILIA-ROMAGNA & ENI-AGIP, 1998; REGIONE LOMBARDIA & ENI-DIVISIONE AGIP, 2002; BERSEZIO *et alii*, 2004). Through multiple-scale input data (from seismic mapping to well-log interpretation), these studies enabled the reconstruction of large-scale stratigraphic architecture, leading to internal subdivision of the Pliocene-Quaternary basin fill into six depositional sequences South of Po River (REGIONE EMILIA-ROMAGNA & ENI-AGIP, 1998), and four depositional sequences North of Po River (REGIONE LOMBARDIA & ENI-DIVISIONE AGIP, 2002). Each sequence, corresponding from a hydrostratigraphic viewpoint to an aquifer group, is bounded at its base by a tectonic unconformity, which is interpreted to have formed during a phase of significant basin reorganization.

A key issue featured in early stratigraphic studies was the concept of cyclic architecture on a variety of scales (AMOROSI & FARINA, 1995; REGIONE EMILIA-ROMAGNA & ENI-AGIP, 1998; REGIONE LOMBARDIA & ENI-DIVISIONE AGIP, 2002; AMOROSI *et alii*, 2008). Due to poor availability of continuous core data, however, facies received relatively little attention in these studies. As a consequence, most stratigraphic reconstructions did not incorporate information on the sedimentology of the aquifers, nor carried out a consistent analysis of the genetic relationships between alluvial and coastal depositional systems.

The widespread drilling campaign carried out by the Emilia-Romagna and Lombardy Geological Surveys in the Po Plain during the past 15 years has made it possible to focus recent stratigraphic work more specifically on facies characterization and multi-proxy investigation of continuous cores, up to 200 m long. After the pioneer work of AMOROSI *et alii* (1999a) on the 173 m-long Core S17 in the Romagna coastal plain, several studies have depicted stratigraphic and sedimentological characteristics of long cores in Emilia-Romagna (AMOROSI *et alii*, 2001, 2004, 2007) and Lombardy (MUTTONI *et alii*, 2003; SCARDIA *et alii*, 2006; AMOROSI *et alii*, 2008). A complete data set is offered by the Emilia-Romagna and Lombardy sheets of the 1:50,000 Geological Map. For a sequence-stratigraphic review, the reader is referred to AMOROSI & COLALONGO (2005) and AMOROSI (2008).

The aim of this paper is to provide for the first time a unitary scheme of aquifer architecture for the middle-late Pleistocene record of the Po Basin on a regional scale (fig. 1). Specific objectives are: i) the geometric characterization and facies connotation of the major aquifer bodies on the basis of a wide dataset, encompassing Emilia-Romagna and southern Lombardy, and ii) the construction of a framework of aquifer distribution into a sedimentological and sequence-stratigraphic context.

2. – REGIONAL STRATIGRAPHY

The recent mapping projects carried out by the geological surveys of Regione Emilia-Romagna and Lombardy have provided a wealth of infor-

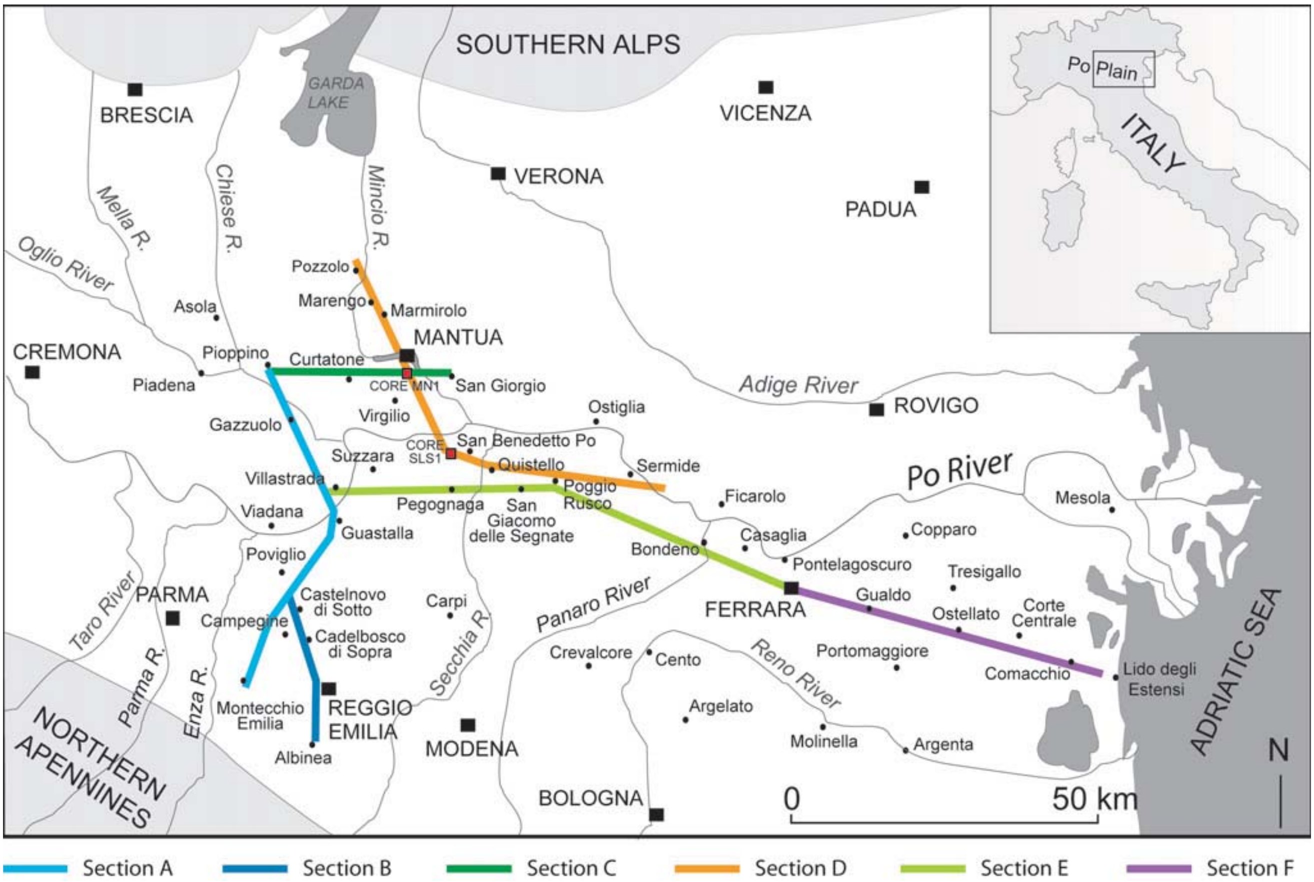

Fig. 1 - Study area, with indication of the section traces of figures 4-9.
- *Area di studio con indicazione delle tracce di sezione relative alle figure 4-9.*

mation, which has considerably improved previous knowledge on the Quaternary subsurface stratigraphy of the Po Basin. However, pragmatic use of the 1:50,000 geological maps beyond regional boundaries may be a difficult task, owing to i) mixed use of different types of stratigraphic units (depositional sequences, alloformations, unconformity-bounded stratigraphic units, hydrostratigraphic and lithostratigraphic units), ii) changes through time in age attribution of the bounding unconformities, and iii) use of locally inconsistent stratigraphic criteria across Po River (see below).

South of Po River, in Emilia-Romagna, the third-order depositional sequences (*sensu* Mitchum *et alii*, 1977) recognized on a seismic basis have been mapped as unconformity-bounded stratigraphic units (UBSU) by Regione Emilia-Romagna & ENI-AGIP (1998) and by Molinari et al. (2007), but are labelled as alloformations (see “AES” or “AEI”) on the geological maps. The youngest UBSU, which coincides in outcrop with the well-known Cycle Qc of Ricci Lucchi *et alii* (1982), is termed the “Emilia-Romagna Supersynthem” (fig. 2). A stratigraphic unconformity of tectonic origin allows subdivision of the Emilia-Romagna Supersynthem into two lower-rank units, namely “Lower Emilia-Romagna Synthem” and “Upper Emilia-Romagna Synthem”. This latter, in turn, is subdivided into a number of subsynthems (AES1 to AES8 in Molinari *et alii*, 2007 and in the Emilia-Romagna geological maps). From a hydrostratigraphic viewpoint, the Upper Emilia-Romagna Synthem coincides with Aquifer Group A, the Lower Emilia-Romagna Synthem with Aquifer Group B, while the underlying deposits, corresponding in outcrop to Cycle Qm of Ricci Lucchi *et alii* (1982), to Aquifer Group C (fig. 2). Aquifer group A is subdivided into four aquifer systems (A1 to A4) according to Regione Emilia-Romagna & ENI-AGIP (1998), but five aquifer systems (A0 to A4) according to Molinari *et alii* (2007). Although event stratigraphy is advocated as the conceptual basis for all of these stratigraphic subdivisions, no one-to-one correlation is readily available between aquifer systems A0 to A4 and subsynthems AES1 to AES8 (fig. 2).

Unlike Regione Emilia-Romagna & ENI-AGIP (1998), Regione Lombardia & Eni-Divi-

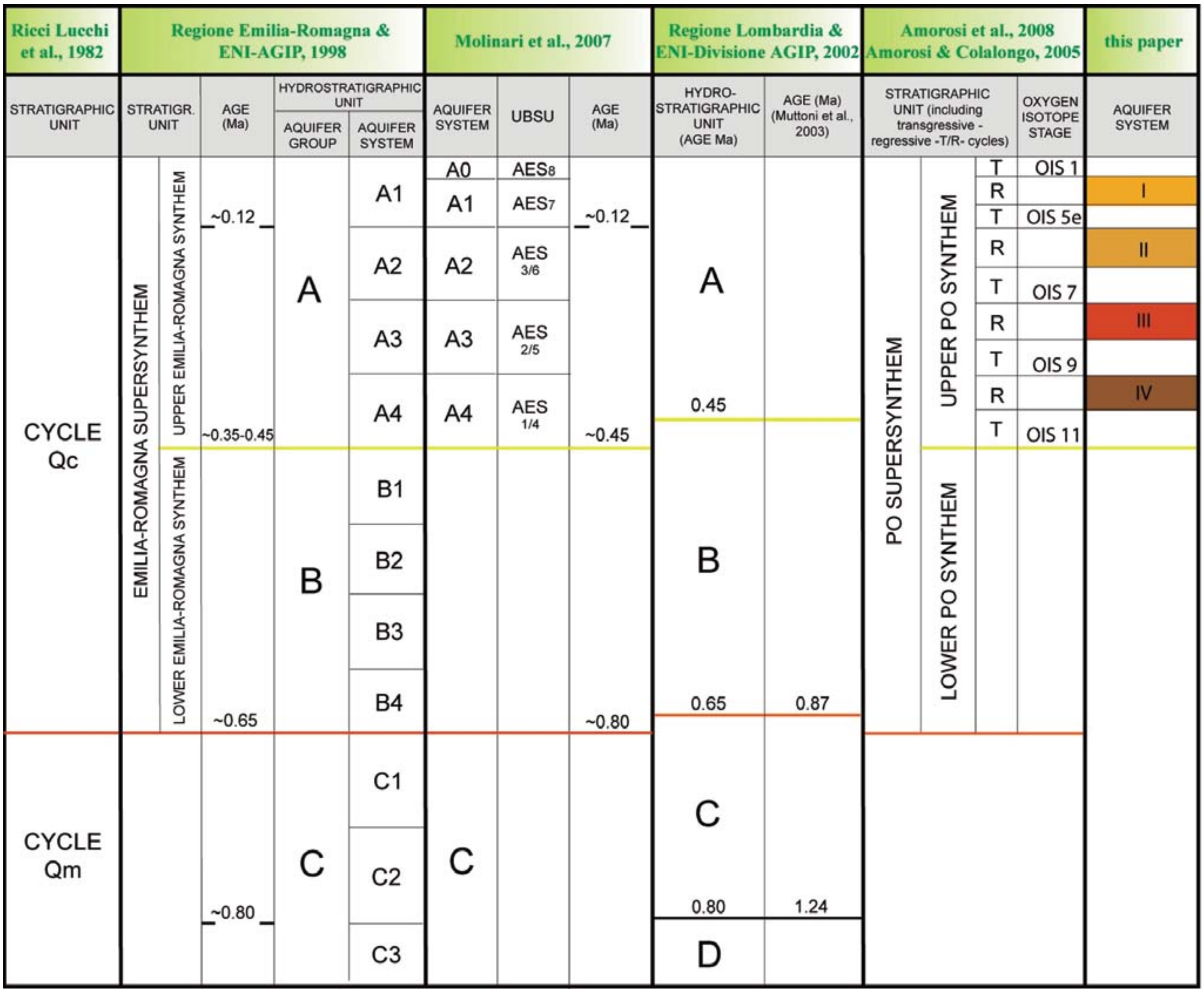

Fig. 2 - Generalized stratigraphic framework for the Quaternary deposits of the Po Basin.
- *Quadro stratigrafico sintetico dei depositi quaternari del Bacino Padano.*

sione Agip (2002) did not carry out a stratigraphic subdivision of the coeval deposits North of Po River into unconformity-bounded stratigraphic units, but just performed a hydrostratigraphic subdivision into aquifer groups (fig. 2). Although the aquifer groups identified in Lombardy are supposed to represent the lateral equivalents of those identified by Regione Emilia-Romagna & ENI-AGIP (1998), careful examination of the hydrostratigraphic sections South and North of Po River reveals obvious inconsistencies between these two studies. Specifically, while Regione Emilia-Romagna & ENI-AGIP (1998) used the tops of laterally extensive aquifers as bounding surfaces for their aquifer groups, Regione Lombardia & Eni-Divisione Agip (2002) used their bases, thus making stratigraphic correlations across Po River very difficult (see figs. 2 and 3).

Age attributions also are ambiguous. Assignment of the uppermost two unconformities to 0.45 and 0.65 Ma, respectively (Regione Emilia-Romagna & ENI-AGIP, 1998; Regione Lombardia & Eni-Divisione Agip, 2002 – see fig. 2), has been recently questioned by Muttoni *et alii* (2003) who, on the basis of magnetostratigraphic data, documented that the latter (their "R-surface") should be placed close to the Matuyama-Brunhes reversal, at 0.87 Ma. This latter interpretation is fully consistent with the age around 0.80 Ma estimated in outcrop by Amorosi *et alii* (1998) for the Qm/Qc boundary (top of Imola Sands).

Recent identification, within the Upper Emilia-Romagna Synthem, of a depositional architecture controlled by a Milankovitch-scale (100 kyr) cyclicity (see pollen characterization in Amorosi *et alii*,

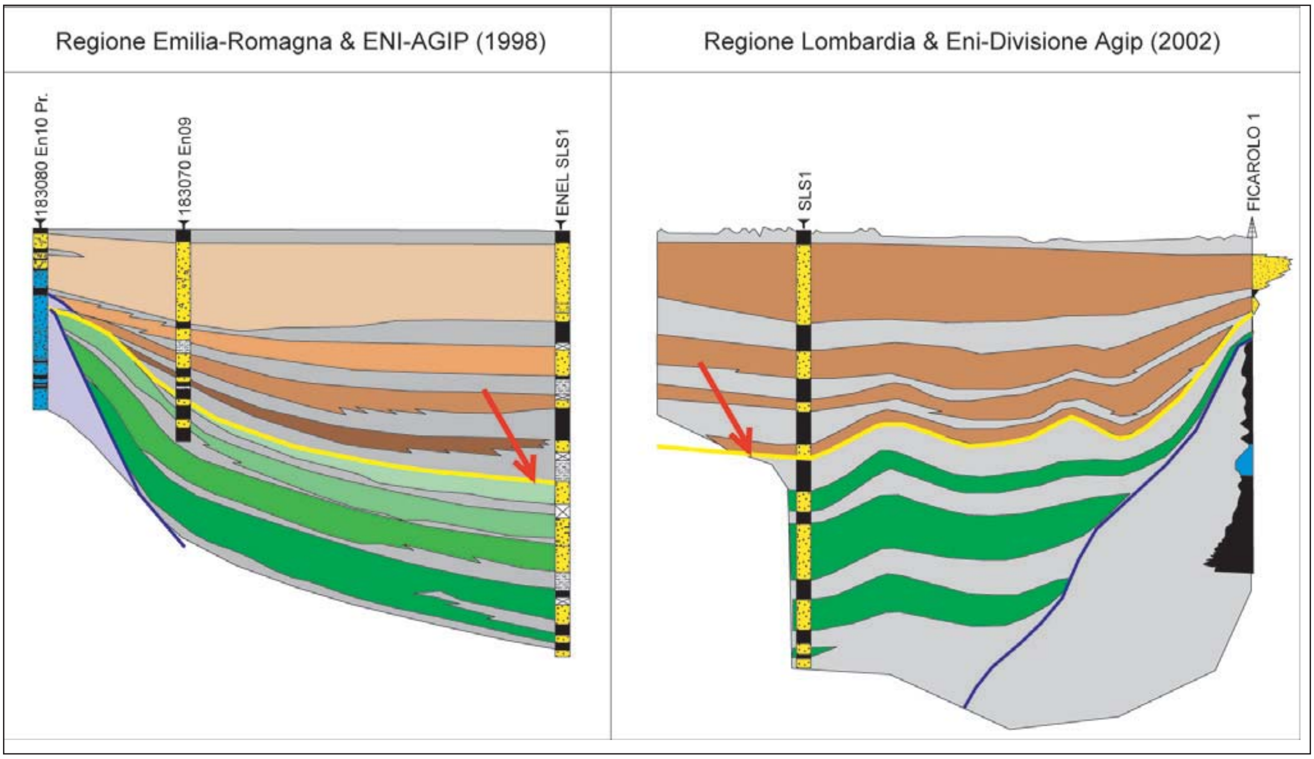

Fig. 3 - Inconsistent positioning, evidenced by arrow, of the lower boundary of Upper Po Synthem (yellow line) according to REGIONE EMILIA-ROMAGNA & ENI-AGIP (1998) and REGIONE LOMBARDIA & ENI-DIVISIONE AGIP (2002). Core SLS1 (see fig. 1), common to both sections, for reference.
- *Posizionamento incoerente, evidenziato dalla freccia, del limite basale del Sintema Padano Superiore (linea gialla) da parte di REGIONE EMILIA-ROMAGNA & ENI-AGIP (1998) e REGIONE LOMBARDIA & ENI-DIVISIONE AGIP (2002). Il sondaggio SLS1 (v. fig. 1), comune ad entrambe le sezioni, funge da riferimento.*

1999a, 2001, 2004, 2008) has allowed interpretation of the 4th-order depositional cycles (subsynthems) as transgressive-regressive (T-R) sequences, leading to the construction of a reliable chrono-stratigraphic framework. By placing age constraints on the key stratal surfaces, a linkage has been made between sedimentary cyclicity and climatic events, allowing correlation of the five basal transgressive surfaces (maximum regression surfaces of CATUNEANU *et alii*, 2009) on top of the aquifer systems with the onset of oxygen isotope stages 1, 5e, 7, 9 and 11 (AMOROSI & COLALONGO, 2005; AMOROSI, 2008) (fig. 2).

In order to avoid characterization of the Quaternary record of the Po Basin through stratigraphic units of local significance only, the "Emilia-Romagna Supersynthem" of REGIONE EMILIA-ROMAGNA & ENI-AGIP (1998) and Aquifer Groups A and B of REGIONE LOMBARDIA & ENI-DIVISIONE AGIP (2002) have been recently grouped into a new stratigraphic unit, provisionally referred to as "Po Supersynthem" (AMOROSI *et alii*, 2008; PAVESI, 2009), and subdivided into two lower-rank units ("Lower Po Synthem" and "Upper Po Synthem" - figure 2). This recent nomenclature is taken as a reference for this study.

3. – T-R SEQUENCES, AQUIFER SYSTEMS AND ALLUVIAL FACIES

As widely documented for selected portions of the Po Basin (AMOROSI & FARINA, 1995; REGIONE EMILIA-ROMAGNA & ENI-AGIP, 1998; REGIONE LOMBARDIA & ENI-DIVISIONE AGIP, 2002; AMOROSI & COLALONGO, 2005; AMOROSI *et alii*, 2008), stratigraphic architecture of the Upper Po Synthem reveals distinctive cyclic changes in lithofacies and channel stacking patterns of fluvial deposits, which allow their subdivision into five T-R sequences (fig. 2). Each sequence includes basal, silt-clay overbank deposits, with thin and lenticular fluvial-channel sands, showing upward transition to increasingly amalgamated and more laterally extensive fluvial-channel sand bodies. In hydrostratigraphic terms, the sheet-like fluvial bodies in the regressive portion of T-R sequences represent the major aquifer systems, termed here I to IV (fig. 2), while the overbank fines form the most important permeability barriers. The uppermost T-R sequence, of post-Last Glacial Maximum age (18 kyr-Present), is incomplete, and lacks almost entirely its upper, regressive portion. Despite this relatively simple picture of facies architecture, several heterogeneities are identified at both the lithofacies and facies association scale (see WEBER, 1986; DREYER *et alii*, 1990) on the basis of core data (AMOROSI *et alii*, 2008). Sedimentological characteristics of the two major alluvial facies associations (*i.e.*, aquifer systems *versus* permeability barriers) are summarized below.

Fluvial-channel bodies represent complex systems of laterally migrating, braided- and low-sinuosity rivers, consisting of moderately well-sorted, medium to coarse sands. These are progressively replaced by gravels toward the basin margin (alluvial fan deposits). Individual fluvial-channel units, generally 3-20 m thick, are characterized by an erosional lower boundary and a fining-upward internal trend, and are commonly amalgamated into thicker (> 50 m) sedimentary bodies. Unidirectional, high-angle cross bedding and sub-horizontal bedding are commonly observed. Silt and clay intercalations are largely subordinate. Wood fragments represent common accessory material, while fossils are virtually absent. Organic-rich layers locally capping the FU successions are interpreted to have formed following channel abandonment.

The overbank facies association consists of a monotonous succession of massive, locally pedogenized, floodplain silts and clays, with subordinate sand intercalations and faint horizontal lamination. Clays with fine disseminated plant debris, freshwater gastropods, and peat horizons are present at distinct stratigraphic levels, and interpreted to have formed in freshwater swamps. Sand-silt alternations, showing either sharp or gradational transitions, are inferred to represent natural levee deposits. Major sedimentary structures include horizontal lamination and subordinate, small-scale cross lamination. Sediment bodies with sharp lower boundary and internal fining-upward trends, but lesser thickness and grain size than their fluvial counterparts, are interpreted to represent crevasse-channel deposits, while coarsening-upward successions with transition to underlying mud are argued to represent crevasse splays. Laterally extensive organic-rich clays, interpreted as paludal deposits, are locally abundant.

4. – AQUIFER STRATIGRAPHY OF THE UPPER PO SYNTHEM

The following section explores the stratigraphic zonation of the Upper Po Synthem based on mappable aquifer systems and clay-dominated permeability barriers, with the aid of six geological cross-sections (figs. 4 to 9). For each section, the

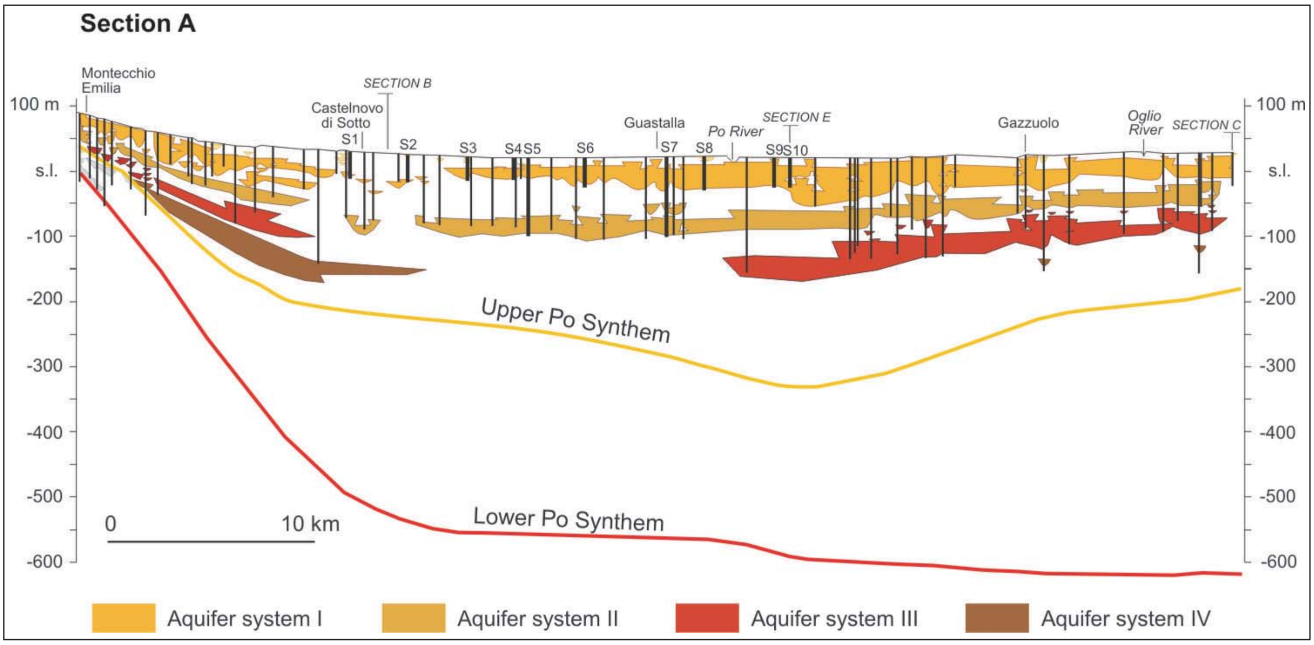

Fig. 4 - Stratigraphy of Po Supersynthem, transversal to the Apenninic chain, across alluvial fan and alluvial plain deposits (see fig. 1, for location). Selected stratigraphic data only are shown. Fluvial-channel gravel and sand deposits (aquifer systems) are highlighted with colours. The grey color indicates indifferentiated coarse-grained bodies of the Lower Po Synthem. Small light yellow bodies below ground surface are Holocene coarse-grained deposits. The two major unconformities (red and yellow lines) are drawn based upon seismic and well-log data from REGIONE EMILIA-ROMAGNA & ENI-AGIP (1998) and REGIONE LOMBARDIA & ENI-DIVISIONE AGIP (2002).

- *Stratigrafia del Supersintema Padano attraverso depositi di conoide e pianura alluvionale (v. ubicazione in fig. 1). In sezione sono riportati i dati stratigrafici maggiormente attendibili. In colore sono indicati unicamente corpi sedimentari sabbioso-ghiaiosi (sistemi acquiferi). In grigio sono indicati corpi sedimentari grossolani indifferenziati appartenenti al Sintema Padano Inferiore. I corpi lenticolari di limitata estensione al di sotto del piano campagna corrispondono a corpi sedimentari grossolani di età olocenica. Le due superfici di discontinuità principali sono ricostruite sulla base della calibrazione con dati di sismica e di pozzo operata da REGIONE EMILIA-ROMAGNA & ENI-AGIP (1998) e da REGIONE LOMBARDIA & ENI-DIVISIONE AGIP (2002).*

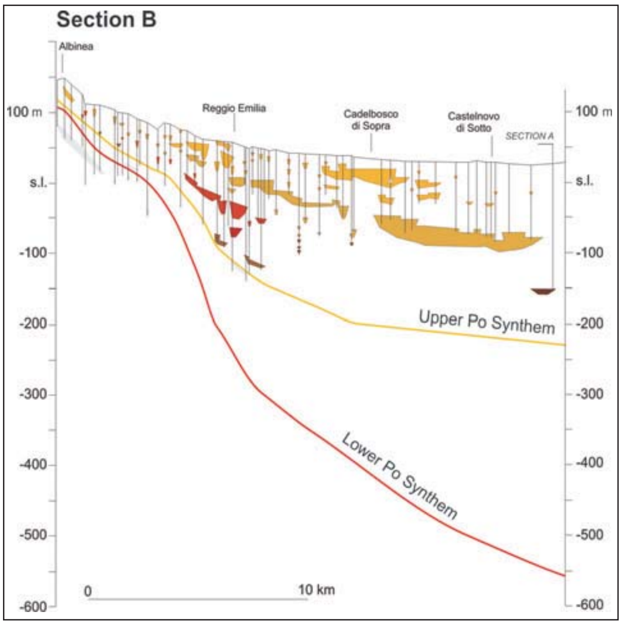

Fig. 5 - Stratigraphy of Po Supersynthem, transversal to the Apenninic chain, between alluvial fan depositional systems (see figure 1, for location).
- *Stratigrafia del Supersintema Padano in area di interconoide (v. ubicazione in figura 1).*

lower boundaries of Po Supersynthem (red line) and Upper Po Synthem (yellow line) were derived from Regione Emilia-Romagna & ENI-AGIP (1998) and Regione Lombardia & ENI-Divisione AGIP (2002). These two major unconformities represent important stratigraphic markers that help significantly in internal correlations, especially were data are scarce or insufficient.

Following the hydrostratigraphic sections by Regione Emilia-Romagna & ENI-AGIP (1998) and the conceptual model of Amorosi & Colalongo (2005) and Amorosi *et alii* (2008), the surfaces chosen for stratigraphic subdivisions are placed at the generally abrupt facies shift from laterally extensive, amalgamated fluvial-channel bodies (aquifer systems I to IV) to overlying, organic-rich muddy units (figs. 4 to 9). This subdivision, which leads to identification of stratigraphic units with a lower, mudstone-dominated portion, and an upper interval characterized by increasing clustering of sand bodies, is here preferred from an operational point of view to depositional cycles bounded by channel-fill sand facies. Specifically, the tops of the aquifer systems can be physically traced throughout the basin and represent comparably smoother (and more easily mappable) surfaces than lower bounding surfaces. The latter show evidence of incision of up to several metres into the underlying substrate, and thus appear considerably more irregular.

Six sections (A to F in figs. 4 to 9) are shown. Sections A (58 km) and B (25 km), transversal to the Apenninic chain, depict subsurface stratigraphy of the southern Po Plain, from proximal (alluvial fan) to distal (alluvial plain) depositional systems. Section C (28 km) shows stratigraphic architecture North of Po River. Section D (77 km) crosses the northern Po Plain, from the Alpine glacial deposits to the Po River, showing detailed stratigraphy of the Po channel belt. Section E (77 km) crosses the central Po Plain, parallel to Po River. Finally, Section F (56 km) represents the SE prolongation of Section E toward the Adriatic Sea.

Section A (fig. 4) crosses the Reggio Emilia and Mantua alluvial plain and is based upon 140 borehole data, including 10 continuously-cored boreholes performed by the Regione Emilia-Romagna Geological Survey. Between Montecchio Emilia and Guastalla, Section A has SW-NE direction, transversal to the Apenninic chain, while North of Po River it follows a SE-NW direction (fig. 1). The two major unconformities (yellow and red lines in fig. 4) diverge from the basin margin toward the depocentre. The lower boundary of Po Supersynthem (red line) displays a relatively flat geometry North of Castelnovo di Sotto, and is recorded around 500-600 m depth across 40 km. In contrast, the base of Upper Po Synthem (yellow line) has a concave-up geometry, with maximum depth of -330 m a.s.l. close to the intersection with Section E, and a depth of -180 m a.s.l. North of Po River, close to the intersection with Section C. Aquifer I and Aquifer II can be easily identified and tracked across most of the study area. Aquifer III and Aquifer IV can be identified uniquely at the section margins, while they are too deep in the depocentre to be reached by borehole data. In general, aquifers are very closely spaced in the Montecchio Emilia area (Enza alluvial fan) and beneath Oglio River, while they are separated by thicker muddy units in the depocentre (Po channel belt). In the Castelnovo di Sotto area, a 5 km wide succession of mud-prone alluvial plain deposits constitutes the physical separation between the Apenninic alluvial fan aquifers (to the South) and the Po channel belts (to the North).

Despite very close position to Section A (fig. 5), Section B shows striking differences in terms of lithology and facies architecture, being characterized by a remarkably low sand-to-mud ratio with a predominance of lens-shaped bodies. Scarcity of gravel and sand bodies along this section is due to the fact that Section B runs in an intermediate position between Enza and Secchia rivers (fig. 1). Coarse-grained bodies have poor lateral continuity, with a very low degree of interconnectedness. The section is based upon 80 borehole data. Relatively continuous sand bodies,

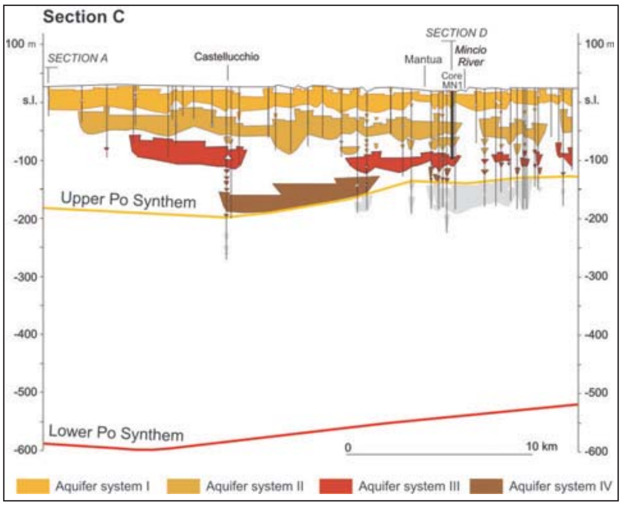

Fig. 6 - Stratigraphy of Po Supersynthem North of Po river (see figure 1, for location).
- *Stratigrafia del Supersintema Padano a Nord del Fiume Po (v. ubicazione in figura 1).*

corresponding to aquifer systems I and II, are identified in the Cadelbosco-Castelnovo area, close to the intersection with Section A. These aquifers are interpreted to represent the eastern termination of the Enza alluvial fan depositional system observed in Section A.

Section C (fig. 6) represents the prosecution of Section A in W-E direction (Mantua alluvial plain - fig. 1), and is based upon about 60 borehole data, including continuous core MN1. This core, 117 m long, has been recently characterized by a detailed, multi-proxy (sedimentological, gamma ray and pollen) investigation (AMOROSI *et alii*, 2008), and represents a fundamental tie point in the central Po Plain for the geometric characterization of aquifer systems I to III. Stratigraphic architecture is quite regular, as it can be observed by the geometry of the two major unconformities, which are gentle dipping to the West from -200 to -120 m a.s.l. (yellow line) and from -600 to -500 m a.s.l. (red line), respectively. Aquifer systems I and II display impressive lateral continuity and homogeneous thickness. The deepest stratigraphic data enable identification and correlation of the older aquifer systems (III and IV). Based upon seismic data interpretation (REGIONE LOMBARDIA & ENI DIVISIONE AGIP, 2002), Aquifer IV is interpreted to exhibit an onlapping contact onto the basal Upper Po Synthem unconformity (yellow line in fig. 6) and should not be in lateral continuity with coarse-grained bodies observed at the same depth, but is interpreted instead to represent the upper part of Lower Po Synthem. Tectonic deformation decreases from base to top, as documented by sub-horizontal geometry of Aquifers I to III.

Section D (fig. 7) was constructed on the basis of 100 borehole data crossing the Mantua plain. Between Pozzolo and San Benedetto Po it has NW-SE direction, transversal to the Alpine chain, whereas East of S. Benedetto Po the section follows a WNW-ESE direction, roughly coincident with Po River. According to the overall basin geometry, which shows an increasing thickness of the Quaternary deposits from the basin margin to the central Po Plain (ORI, 1993), the two major unconformities (yellow and red lines) are progressively deeper moving from Garda Lake to the depocentre, and shallower when approaching the Ferrara folds, at the ESE termination of the section. It is remarkable that here the base of Po Supersynthem (red line) was identified at just -110 a.s.l., while the same surface is deeper than 500 m a.s.l. close to Mantua (fig. 7). With the exception of the Pozzolo-Marmirolo area, where only Aquifers I and II were identified, stratigraphic architecture along Po River, East of San Benedetto Po, is similar to that depicted by Section C, with a striking lateral continuity and sub-horizontal geometry of Aquifers I to III. The local presence of a fifth sedimentary bodies, of uncertain age attribution and provisionally attributed to Aquifer system IV, is suggested in the depocentre by correlation of two deep boreholes, among which ENEL Core SLS1.

Section E (fig. 8), based upon 75 borehole data, cuts the Mantua alluvial plain roughly parallel to Po River, following a W-E direction and providing a physical link between Section A (Core S10 at Villastrada – see fig. 1) and Section D (almost intersected in Poggio Rusco). East of Poggio Rusco, this section moves toward Ferrara, with NW-SE direction. Data density is relatively low, although several high-quality data are available for the uppermost 40 m. For the construction of this section, additional data derive from unpublished passive seismic interpretation (PIERI, 2008; PAVESI, 2009). Similarly to what observed in sections C and D, aquifer systems I, II and III display an impressive lateral continuity West of Poggio Rusco. Tectonic deformation, however, affects significantly aquifer architecture at the SE termination of the section, due to the presence of the Ferrara folds (fig. 8). Specifically, close to Casaglia, *i.e.* in coincidence of the Ferrara structural high, the lower boundary of Upper Po Synthem climbs up from -320 m to -50 m a.s.l. A very similar geometry is shown by the base of Po Supersynthem, which moves from -580 m a.s.l. to -170 m in the Ferrara area. Similarly to what observed in previous sections, aquifer systems II, III and IV display a likely onlapping geometry onto the lower bounding unconformity.

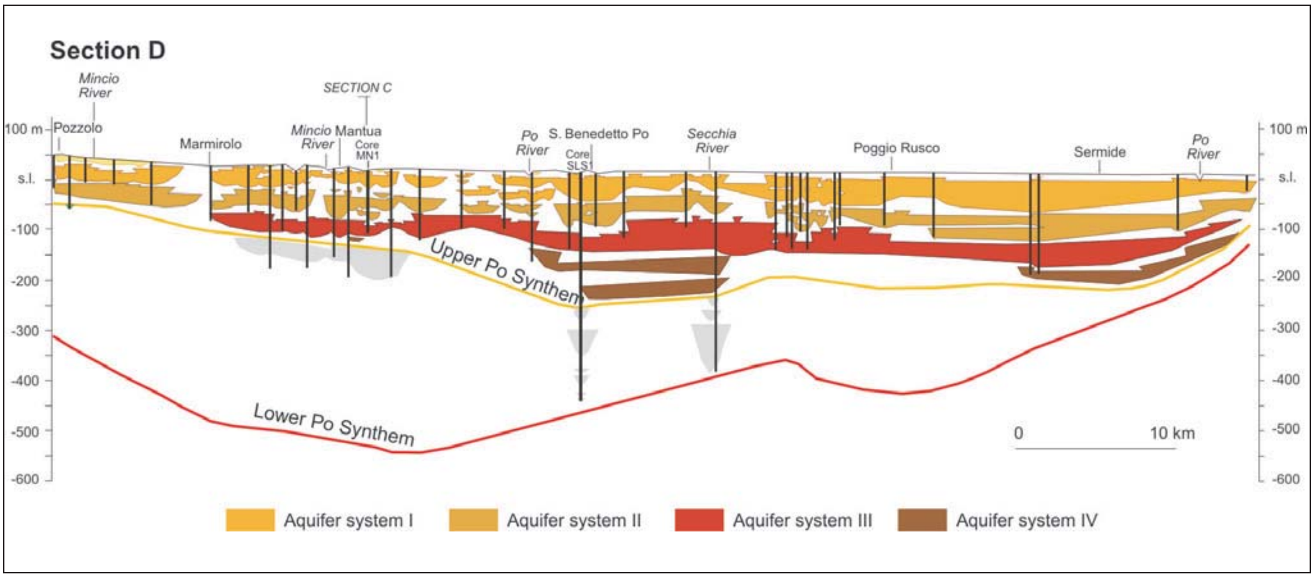

Fig. 7 - Stratigraphy of Po Supersynthem transversal from the Alpine glacial deposits to Po River (see figure 1, for location).
- *Stratigrafia del Supersintema Padano dalla cerchia morenica alpina al Fiume Po (v. ubicazione in figura 1).*

Section F (fig. 9), representing the prolongation of Section E across the Ferrara coastal plain toward the Adriatic Sea, documents the stratigraphic relationships between the Quaternary fluvial deposits of the Po Basin and their distal (nearshore) counterparts. The subsurface of the Ferrara coastal plain has been depicted in detail by MOLINARI *et alii* (2007) through a number of geological cross sections, and for this reason will not be described here. The reader is referred to that paper for accurate reconstruction of stratigraphic architecture. Selected core data from MOLINARI *et alii* (2007), however, were incorporated in this section in order to enable correlation with their work. Subsurface stratigraphy beyond the Ferrara folds mirrors the one depicted by Section E, with the lower boundary of Upper Po Synthem dipping toward SE, from -50 m to -350 m a.s.l. Alluvial sedimentation, however, displays remarkably different characteristics. In particular, the thick aquifer systems observed in Section E are replaced between Ferrara and Comacchio by a succession of distinct, relatively thinner and finer-grained sand bodies separated by thicker mud-dominated units. According to the sequence-stratigraphic model proposed by AMOROSI (2008) for the Po Basin, these sedimentary bodies are interpreted to represent two different facies associations (fig. 9): i) thinner and less extensive flu-

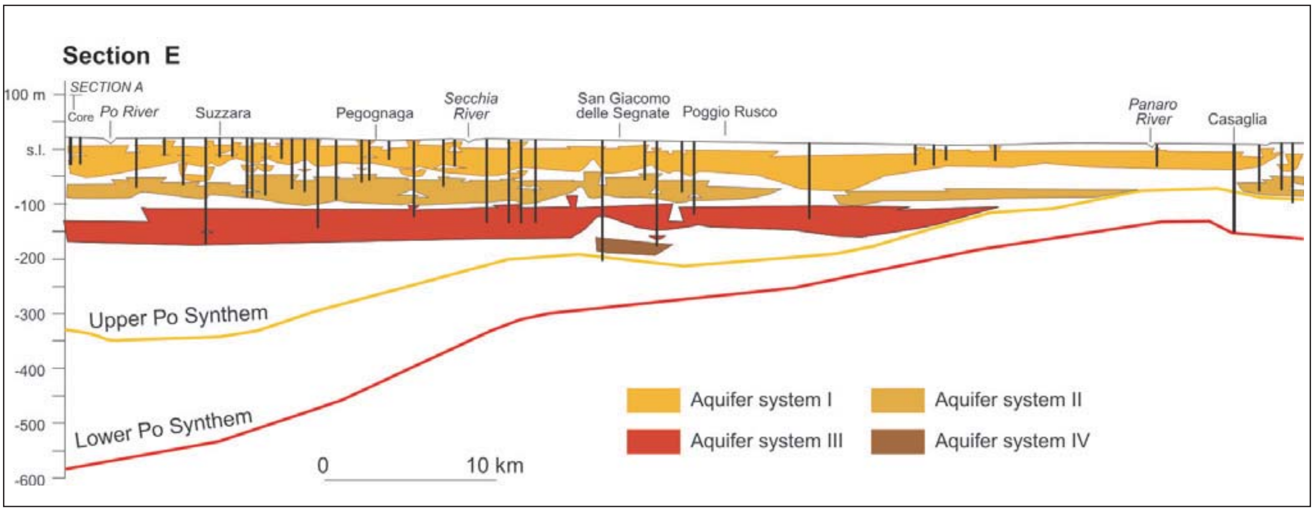

Fig. 8 - Stratigraphy of Po Supersynthem across the central Po Plain (see figure 1, for location).
- *Stratigrafia del Supersintema Padano nella Pianura Padana centrale (v. ubicazione in figura 1).*

vial units than the aquifers of the Po channel belt, ii) prograding deltaic and coastal sand bodies, formed during phases of sea-level highstand. The characteristic wedge-shaped sand bodies identified from core correlations beneath the coastal plain (AMOROSI *et alii*, 1999b; 2004) are not apparent here, due to the fact that the transgressive shoreface sands are too thin and fine-grained to be detected by poor-quality borehole data.

5. – CONTROL OF CYCLIC FLUVIAL ARCHITECTURE

The cross sections of figures 4 to 9 allow to summarize the general features of Quaternary alluvial architecture across a significant portion of the Po Basin. The Po Supersynthem displays a maximum thickness of about 650 m in the depocentre, and typically wedges out either toward the basin margins, *i.e.* the Apenninic and Alpine foothills, or in coincidence of structural highs (e.g., Ferrara folds). The post-450 kyr unit (Upper Po Synthem) exhibits a maximum thickness of about 400 m (Sections E and F), although over wide areas (Sections C and D) is less than 250 m thick. Four major aquifer systems (I to IV), corresponding to units A1-A4 of REGIONE EMILIA-ROMAGNA & ENI-AGIP (1998), can be recognized and tracked in the Upper Po Synthem across the entire study area. In the central Po Plain, beneath the present Po River course, these comprise laterally extensive, high net-to-gross stacked channel belts, with excellent continuity, separated by laterally continuous mud-dominated permeability barriers. In contrast, the aquifer systems tend to be amalgamated close to the basin margins, where fluvial sands are replaced by gravels formed in proximal alluvial-fan systems. Despite correlation and delineation of zones of generally high permeability may be relatively simple within the aquifer systems, internal correlation is difficult due to the lenticular shape of individual channel bodies, and sediment bodies are very likely to display a typical "jigsaw puzzle" pattern (WEBER & VAN GEUNS, 1990; GALLOWAY & SHARP, 1998).

The striking regularity shown by the middle-late Pleistocene record across a significant portion of the Po Plain indicates an allocyclic control as the driving mechanism for the observed cyclic facies architecture. Syn-depositional tectonics exerted a marked influence on facies and aquifer distribution over the last million years, through the continuous creation of accommodation, tectonic uplift, changes in sediment transport pathways, localisation of depocentres, and restriction of older aquifer systems to the resulting topographic lows.

Pronounced climatic fluctuations and, to a certain extent, sea-level oscillations, however, played a fundamental role in shaping stratigraphic architecture, leading to remarkable changes in sediment supply and in the type of sediment delivered to the basin. Although the influence of climate on fluvial succession is a still largely neglected issue, previous work on long-cored pollen successions of the Po Basin has shown that the distinctive cyclic facies architecture documented in this paper was paralleled by cyclic changes in vegetation patterns during the last hundred thousands of years (AMOROSI

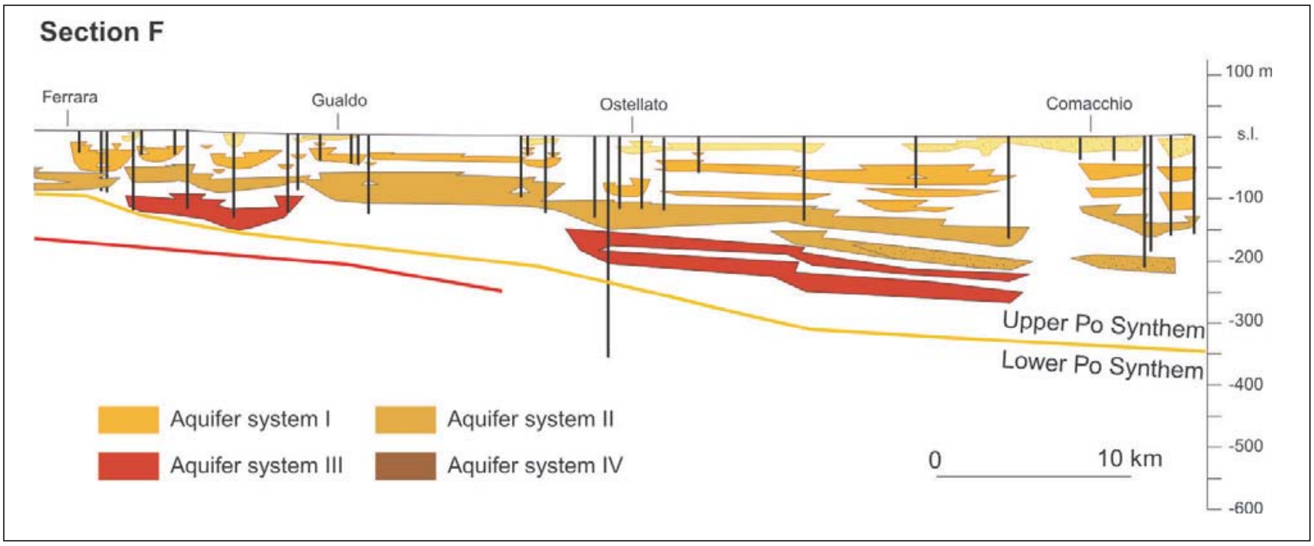

Fig. 8 - Stratigraphy of Po Supersynthem across the central Po Plain (see figure 1, for location).
- *Stratigrafia del Supersintema Padano nella Pianura Padana centrale (v. ubicazione in figura 1).*

et alii, 2001, 2008). In particular, the laterally continuous muddy units that overlie the aquifer systems appear to be invariably associated with forest expansions. This indicates that major phases of channel abandonment, with generalized development of paludal areas and widespread floodplain aggradation, took place at the onset of warm-temperate (interglacial) climatic conditions, during phases of rapid sea-level rise.

Increased accommodation due to the combined effect of subsidence and sea-level rise allowed accumulation of conspicuous amount of fine-grained material, with preservation of small lenticular, poorly interconnected fluvial bodies on top of the aquifer systems. In terms of sequence stratigraphy, the laterally continuous permeability barriers can be interpreted as the transgressive systems tracts (TST) of 4th-order T-R sequences. The progressive decrease up-section in the relative proportion of overbank fines, which is accompanied by an increase in the thickness of fluvial-channel units, suggests decreasing accommodation during highstand conditions (HST). During very low-accommodation conditions, such as those related to forced regression (FST) and lowstand deposition (LST), overbank muds would rarely have survived fluvial erosion, favouring preservation of amalgamated sand sheets (SHANLEY & MCCABE, 1993; OLSEN *et alii*, 1995; PLINT *et alii*, 2001). The channel belts (e.g., aquifer systems) are likely to have formed as incised-valley fills, following phases of channel incision and subsequent valley widening during prolonged lowstand phases (STRONG & PAOLA, 2006). It is still a debated problem whether fluvial sedimentation took place during lowstand phases, early transgressive conditions, or both.

6. – CONCLUSIONS

Detailed stratigraphic correlations based upon a large borehole dataset enable an improved understanding of stratigraphic architecture and aquifer distribution of the middle-late Pleistocene record of the Po Basin. Five vertically stacked, 4th-order, transgressive-regressive (T-R) sequences can be identified within the uppermost (post-450 kyr BP) 3rd-order depositional sequence, here referred to as Upper Po Synthem. The T-R sequences, recognized across alluvial fan, alluvial plain and coastal plain successions, define four geologically distinct aquifer systems (I to IV), few tens of metres thick, separated by laterally extensive permeability barriers. Aquifer systems consist of thick, amalgamated alluvial-fan gravel bodies close to the basin margins. In the depocentres, aquifer systems are represented by sandy channel belts, showing considerably high continuity and overall sheet-like geometry. Channel belts are separated by laterally continuous overbank deposits, acting as permeability barriers for each aquifer group. Despite this relatively simple picture of facies architecture, several heterogeneities are identified at both the lithofacies and facies association scale, with crevasse channels and splays, unconfined and non-channelized sandy units, and laterally continuous organic-rich horizons that may locally complicate the picture.

The vertically amalgamated multi-storey bodies that form the aquifer systems of the Po Basin have highly diachronous base. In contrast, the abrupt facies shifts from these laterally extensive sedimentary bodies to the overlying, organic-rich muds represent almost isochronous, easily mappable surfaces, and for this reason are taken as major bounding surfaces in building the hydrostratigraphic model. A multi-proxy data set enables recognition of a striking cyclicity with 100 kyr recurrence time within the middle-late Quaternary succession. Permeability barriers correlate with warm episodes and mark the onset of transgressive phases. On the other hand, the four major aquifer systems appear to have formed during phases of relatively low accommodation (lowstand periods and possibly early phases of transgression).

In summary, this study shows that accurate reconstruction of stratigraphic architecture and channel/overbank proportion in the Po Basin can help significantly in developing conceptual models that can be used to delineate aquifer connectivity and predict seal lithofacies distribution. In addition, availability of a common hierarchy of architectural units based on the physical characteristics of the depositional elements and their stratal bounding surfaces (MIALL, 1991) may facilitate correlation of events on a regional scale. Examining stratigraphic architecture of fluvial deposits through a sound sedimentological model and the use of sequence-stratigraphic concepts provide a very good basis for aquifer prediction and can be of interest for water-use planners.

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