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Palaeosol-based stratigraphy of late Quaternary deposits from the Po Basin, between Bologna and the Po River (Northern Italy)

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ABSTRACT

Stratigraphic studies carried out over the last decades in Italy and elsewhere testify a growing interest in Quaternary deposits and in the influence of climate change on their architecture. The availability of progressively more detailed (millennial-scale) palaeoclimatic records for the Late Pleistocene-Holocene has prompted the research on the stratigraphic response of depositional systems to high-frequency climate variations. The subsurface of the Po Plain, in its topmost portion, is made up of alluvial deposits organized in depositional cycles at different scales. Cyclic changes in stratigraphic architecture at the Milankovitch (eccentricity cycles) scale (about 100 ky) have been detected in the subsfurface of the coastal plain, beneath the Po channel belt, and at the Apenninic margin. Only in areas characterized by peculiar concentration of stratigraphic information, millennial temporal resolution has been achieved.

This PhD thesis provides millennial-scale stratigraphic reconstruction of the Late Pleistocene-Holocene deposits beneath the southern Po Plain, based on basin-scale correlation of laterally-extensive buried soil horizons. Far from the aim of characterizing palaeosols from a mineralogical and geochemical point of view, we focused on the physical and stratigraphic significance of these horizons.

In the Bologna urban area, which hosts an abundance of stratigraphic data, the correlation between seventeen continuously-cored boreholes led to the identification of five vertically-stacked palaeosol-bounded sequences within the ^{14}C time window. In a wide portion of the alluvial plain north of Bologna, far away from the Apenninic margin and from the Po River, where subsurface stratigraphic architecture is dominated by markedly lenticular sediment bodies, palaeosols revealed to be the only stratigraphic marker of remarkable lateral continuity. These horizons are traceable over distances of 50 km and are characterized by peculiar resistance values, which make them easily identifiable via pocket penetration tests. Palaeosols reveal specific geometric relationships with the associated alluvial facies associations, allowing reliable estimates of soil development as a function of alluvial dynamics. The whole study area records transition from weakly developed Late Pleistocene palaeosols, characterized by peculiar resistance signature, to poorly developed Holocene palaeosols. This trend of decreasing paleosol maturity upsection is interpreted to reflect post-glacial increasing accommodation.

With the aid of sixty new radiocarbon dates, a reliable age attribution and likely time intervals of exposure were assigned to each palaeosol. Vertically-stacked palaeosols delimitate short-term depositional cycles, likely related to the major episodes of climatic change of the last 40 ky.

Through integration of stratigraphic data with 750 archaeological reports from the Bologna area, the impact of human settlements on depositional and pedogenic processes during the late Holocene was investigated. A prolonged phase of river stability and soil development, between 3000 and 1500 BP, coincides with maximum diffusion of human settlements in the Bologna and surrounding areas, and was likely related to the widespread control on the river network achieved by the Iron Age and Roman populations. Renewed alluvial activity was paralleled by a generalized crisis of the human society and by a new phase of climate deterioration.

RIASSUNTO

Le indagini stratigrafiche condotte in Italia e nel mondo negli ultimi decenni testimoniano un crescente interesse per i depositi quaternari e per l'influenza esercitata dalle variazioni climatiche sulla loro architettura. La disponibilità di informazioni paleoclimatiche sempre più raffinate a scala millenaria, per il periodo di transizione tra l'ultimo acme glaciale e l'attuale interglaciale e per l'Olocene, ha spinto gran parte della comunità scientifica a focalizzare la propria attenzione sulla ricerca di elementi stratigrafici che testimonino una risposta dei sistemi deposizionali a variazioni climatiche ad alta frequenza. Il sottosuolo della Pianura Padana è composto, nella sua porzione più superficiale, da sedimenti alluvionali organizzati in cicli deposizionali a diversa scala. Variazioni deposizionali a scala milankoviana (circa centomila anni) sono state riscontrate nel sottosuolo delle aree costiere, lungo la fascia di divagazione del Fiume Po e al margine appenninico. Solo in aree limitate, caratterizzate da una particolare concentrazione di informazioni stratigrafiche, è stato possibile raggiungere una risoluzione temporale dell'ordine delle migliaia di anni.

Questa tesi di dottorato si occupa della ricostruzione stratigrafica a scala millenaria dei depositi tardo-pleistocenici e olocenici del Bacino Padano, tra Bologna e il Fiume Po, basata sulla correlazione a scala regionale di orizzonti pedogenizzati lateralmente estesi e persistenti. Lungi dal voler caratterizzare i paleosuoli da un punto di vista mineralogico e geochimico, questo lavoro si focalizza sul significato di questi orizzonti in termini di stratigrafia fisica.

In una prima fase, la ricerca si è concentrata sul sottosuolo della città di Bologna, per il quale è disponibile un'eccezionale densità di dati stratigrafici. La correlazione di diciassette sondaggi a carotaggio continuo ha portato alla definizione di un quadro stratigrafico dettagliato basato sull'individuazione di cinque paleosuoli all'interno della finestra del carbonio 14. Successivamente l'area di indagine è stata estesa all'area di pianura a nord di Bologna, lontana dal margine

appenninico e dal Fiume Po, caratterizzata nel sottosuolo principalmente da corpi sedimentari a geometria lenticolare. In questo contesto i paleosuoli si sono rivelati gli unici orizzonti guida tracciabili per decine di chilometri all'interno della successione tardo-quaternaria. Questi orizzonti sono caratterizzati da valori elevati di resistenza alla compressione, come dimostra la loro caratterizzazione geotecnica mediante misure eseguite con penetrometro tascabile, e sono legati alle facies deposizionali di ambiente alluvionale da particolari rapporti geometrici, riflesso di precise relazioni intercorrenti tra pedogenesi e dinamiche alluvionali. In tutta l'area di studio si registra il passaggio graduale da paleosuoli pleistocenici poco evoluti (Inceptisuoli), caratterizzati da elevati valori di resistenza, a paleosuoli olocenici fortemente immaturi (Entisuoli). Questa diminuzione del grado evolutivo verso l'alto è interpretata come il risultato di un incremento dello spazio di accomodamento durante la fase post-glaciale.

Tramite la realizzazione di sessanta datazioni, associate a numerosi dati di letteratura, a ciascun paleosuolo è stata assegnata un'età e un tempo medio di esposizione. Il quadro stratigrafico e cronologico che ne deriva ha permesso l'individuazione di cicli deposizionali a scala sub-milankoviana e la loro correlazione con le variazioni climatiche degli ultimi quarantamila anni. Tramite l'integrazione dei dati stratigrafici con un *dataset* di 750 relazioni di scavi archeologici, infine, è stato possibile valutare quanto sia stato determinante l'impatto della sempre più diffusa presenza dell'uomo sul territorio bolognese, sulle dinamiche fluviali, e quindi sulla formazione e sul seppellimento dei suoli in età tardo-olocenica. Stabilità dei corsi d'acqua e pedogenesi caratterizzano il periodo tra 3000 e 1500 anni fa. Questa fase corrisponde alla massima diffusione degli insediamenti antropici sul territorio bolognese ed è probabilmente da ricondursi al controllo sulla rete idrografica esercitato dalle popolazioni dell'Età del Ferro e di Età Romana. La ripresa dell'attività alluvionale è concomitante ad una crisi generalizzata delle società umana e ad una fase di deterioramento climatico.

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1. INTRODUCTION

Geological disciplines have historically developed in mountainous areas, where rocks and sediments are often exposed in spectacular outcrops. For this reason, up until the half of the last century, the flat and monotonous landscape of the alluvial plains, lacking exposures and evidences of tectonic activity, was considered an unattractive site to be investigated from geologists. The recent development of new methods of subsurface investigation, coupled with the increasing demand of water and fossil combustible, led to a growing interest for the alluvial plains. These areas have hosted the development of human societies, probably owing to the large availability of water supply. Starting from the settlement of the first stable communities, a strong interaction between humans and water sources was installed and perpetuated to present day. Repeated and devastating flooding events through time led to the advancement of hydraulic techniques and to the achievement of a strict control of the alluvial plains drainage network. Recently, a new perception of the long-term consequences of human intervention on fluvial systems is spreading over the scientific community, outlining the importance of high-resolution stratigraphic reconstructions as a useful tool to depict human-landscape interactions on a millennial-centennial temporal scale. The long-term evolution of the fluvial systems and the surrounding environments, and their response to rapid climate change and human disturbance should be taken into account in an area affected by flood risk, such as the Po Plain. Landscape management based upon short-term historical information only lacks predictive capability in case of significant environmental changes.

The Po Plain is one of the most densely populated areas of the Italian peninsula. One third of the population and most of the industrial activities are concentrated here. The Po Basin represents an appealing target for water and hydrocarbon research, and for this reason in the last forty years it has been object of several subsurface investigations. These studies led to the reconstruction of the large-scale architecture of the Po Basin fill (Pieri and Groppi, 1981; Dondi et al., 1982; Ricci Lucchi et al., 1982; Castellarin et al., 1985; Ori, 1993; Regione Emilia-Romagna and ENI-AGIP, 1998). In the last decades, in line with the increasing interest on late Quaternary deposits, several investigations of the topmost portion of the Po Basin fill were carried out, as a part of the geological mapping of Italy project (CARG) to scale 1:50,000. Contrary to the large-scale investigations carried out between 1970 and 2000, relying upon seismic profiles and well log interpretations, these studies were based on sedimentological, palaeontological, petrographic, mineralogical, and geochemical analyses of continuously-cored boreholes.

The first CARG maps in Emilia-Romagna were constructed in the coastal areas and led to the definition of a stratigraphic framework mainly controlled by glacio-eustatic fluctuations (Amorosi et al., 1999, 2003). The identification of cyclic changes in fluvial-channel stacking patterns, in areas close to the basin margin prompted the debate about the driving factors of non-marine stratigraphic architecture and raised the issue on how and how far from the coast the influence of eustatic fluctuations can propagate. The superposition of factors other than eustasy, such as tectonics and climate, close to the mountain front, imposed to adopt a careful approach in determining the influence of base-level fluctuations on the architecture of alluvial sediments (Amorosi et al., 1996). The interpretation of selected pollen profiles carried out during the CARG mapping project enabled the basin-scale correlation of the depositional cycles, from beneath the coastal plain to the basin margin (Amorosi and Colalongo, 2005). Facies changes are characterized by the alternation of glacial and interglacial pollen associations, falling in the Milankovitch band (about 100 ky).

Although the astronomically-driven fluctuations represent a well-established motif in the Quaternary palaeoclimatic record, increasing attention has been given in the last twenty years to climate changes at the sub-Milankovitch scale, especially at the transition between the Last Glacial Maximum (LGM) and the present interglacial (Bond at al., 1997; Thompson et al., 2002; Rasmussen et al., 2007), and during the Holocene (Davis et al., 2003; Mayewsky et al., 2004, Wanner et al., 2008). A complex response of the alluvial systems to high-frequency climate fluctuations has been detected in many areas (Hsieh and Knuepfer 2001; Saijo and Tanaka, 2002; Boyer et al., 2005; Huang et al., 2009; Persico and Meyer, 2009; Dutta et al., 2011; Pierce et al., 2011). Millennial-scale variations of the depositional architecture are well documented for the coastal areas of the Po Plain (Amorosi et al., 2005) and for the intramontane Apenninic valleys (Eppes et al., 2008; Picotti and Pazzaglia, 2008; Wegman and Pazzaglia, 2009), whereas only rare and local studies have addressed the response of fluvial systems to the Late-Pleistocene/Holocene climate changes in the most internal portions of the southern Po Plain. The Bologna urban area, close to the Apenninic foothills, has been described as a mud-dominated interfluve between two main fluvial-channel complexes, supplied by the Reno River to the west and the Savena River to the east (Amorosi and Farina, 1995). Weakly developed palaeosol were detected at various stratigraphic levels in the mud-prone succession (Amorosi et al., 2001). These palaeosols formed during periods of reduced or no sediment supply, during which the land surface was exposed to chemical and physical weathering processes, and biological activity. Due to their lateral extension and continuity, these palaeosols represent powerful stratigraphic markers across alluvial plain sedimentary successions (Bown and Kraus, 1987; Platt and Keller, 1992; Wright and Marriott, 1993; Kraus, 1999; McCarthy et al., 1999; Trendell et al., 2012). Particularly, palaeosol stratigraphy has become one of the most applied techniques in basin-margin settings to depict cyclic alluvial architecture on time scales of 1-100 ky (Aslan and Autin, 1998; Autin and Aslan, 2001; Gouw and Erkens, 2007; Autin, 2008).

The aim of this work is to evaluate the correlation potential, physical properties and stratigraphic significance of weakly developed palaeosols formed at the southern margin of the Po Basin, on the Bologna interfluve and in the adjacent alluvial plain. Through lateral tracking and dating of buried soils, we point to unravel the relationships between (i) river incision and pedogenesis in the interfluves; (ii) climate change, base-level fluctuations and soil development (allogenic versus autogenic forcing). This study does not focus on the mineralogical and geochemical properties of soil profiles, but palaeosols are examined from a stratigraphic and physical point of view. Specific objective of this research is to address the role of anthropogenic forcing on landscape evolution, and more specifically on fluvial sedimentation and soil development, during the mid-late Holocene.

As almost everywhere in the Mediterrean, the subsurface of urban areas bears evidence of repeated phases of human occupation, which outline the evolution of human societies in a framework of changing palaeoenvironments. This is the case of the town of Bologna, where a vast array of archaeological surveys documents human presence since already the Palaeolithic. Humans occupied this area during the Neolithic and Eneolithic, but the first occurrence of permanent urban settlements belongs to the Iron Age: Bologna became an Etruscan centre in 534 BC, and then a Roman colony, in 187 BC. The continuously increasing archaeological documentation on the Bologna area, coupled with conspicuous geological background knowledge and large availability of stratigraphic information, makes this town an excellent test site to perform high-resolution investigations.

This study is a collaboration of the University of Bologna (Department of Biology, Earth and Environmental Sciences) with the Geological, Seismic and Soil Survey of Regione Emilia-Romagna. This latter made available more than 4000 stratigraphic descriptions, including core and drilling logs, radiocarbon dates and pollen profiles. The geological dataset was implemented by about

1000 data from stratigraphic investigations carried out in the Bologna area for engineering and water research purposes. About 70 new cores and outcrops were analyzed and 60 radiocarbon dates were produced. A collaboration with the Superintendence to Archaeological properties (SAER) and *Istituto per i beni artistici, culturali e naturali* (IBC) of Regione Emilia-Romagna was started to create a geo-archaeological dataset, resulting in the realization of the Geo-Archeological Map of Bologna.

2. GEOLOGICAL SETTING

2.1. Structural setting

The Po Plain is the superficial expression of a foreland basin bounded by two main mountain belts (the Apennines to the south and the Alps to the north), showing opposite polarity of tectonic transport.

The formation of the Apenninic chain, related to the subduction of Adria under the European crust, started in the Oligocene during the post-collisional phases of the Alpine orogenesis (Vai and Martini, 2001). Crustal shortening and compressional focal mechanisms close to the mountain front (Frepoli and Amato, 1997; Boncio and Bracone, 2009), associated to an internal extensional earthquake belt (Pondrelli et al., 2002), led to the definition of a slab rollback and upper plate retreat model for the Northern Apennines (Malinverno and Ryan, 1986; Royden, 1988), confirmed by deep tomographic profiles into which the Adria slab is observable (Castellarin et al., 1994; Piromallo and Morelli, 2003).

Up until the Seventies, the Apenninic mountain front was assumed to be a system of reverse faults (Pedeappenninc Lineament of Castellarin et al., 1985 or Pedeappenninic Thrust Front - PTF of Boccaletti et al., 1985), bordering the Apennine foothills. Here, geological and geomorphological evidence of active tectonics, including growing folds and both compressional and extensional faults, has been documented (Ghisetti and Vezzani, 2002; Benedetti et al., 2003; Boccaletti et al., 2004; Picotti et al., 2009). A series of deep seismic profiles and wells carried out by Agip led to the identification of north-verging blind thrusts and folds beneath the southern Po Plain, as the buried prosecution of the Apenninic chain (Pieri and Groppi, 1981). Blind thrusts are organized in four main folded arcs, namely from west to east: Monferrato Arc, Emilia Arc, Ferrara Arc and Romagna Arc (Fig 2.1). The Ferrara Arc represents the most external structural element of the Northern Apennines, through which the Mesozoic units ramp on the Cenozoic undeformed Pedealpine-Adriatic monocline. Along the outer thrust of the Ferrara arc, borehole breakout analysis shows the presence of a predominant compressional area characterized by approximately N-S maximum horizontal stress (Montone and Mariucci, 1999). In more internal position, the thrusts of the Romagna arc ramp on the Ferrara Folds (Fig 2.1). Folds and thrusts in the southern Po Basin are covered by a Pliocene-Quaternary sedimentary wedge, up to 8000 m thick (Pieri and Groppi, 1981). Up until the last decade, these structures were assumed to be inactive, because of the considerable thickness of the apparently undeformed overlying sedimentary units. Recently, on the basis of geomorphological geological and geophysical evidence (Burrato et al., 2003; Scrocca et al., 2007; Carminati and Vadacca, 2010) a recent activation of several thrusts (Mirandola Anticline, Ferrara Arc) has been invoked. The M 6.0 2012 earthquake (Caputo et al., 2012) confirmed that the southern Po Plain is tectonically active.

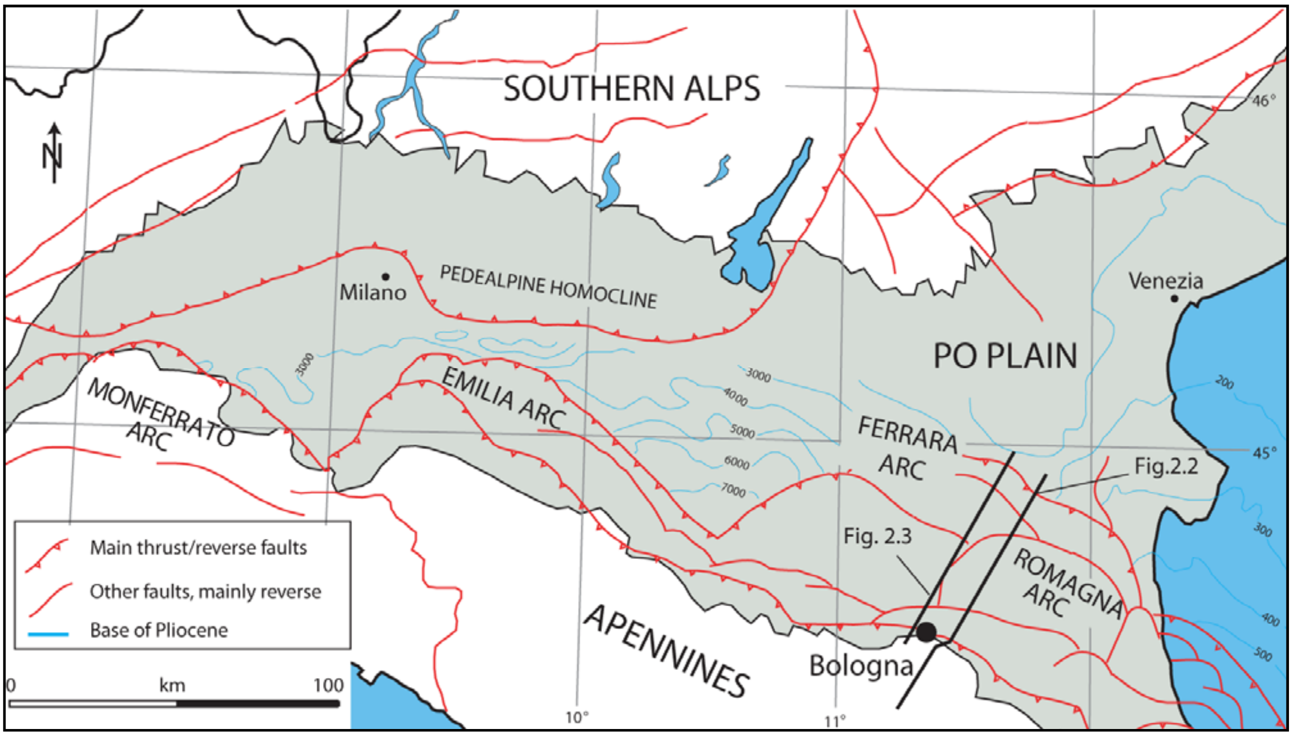

Fig. 2.1 Simplified structural map of Northern Italy (modified from Burrato et al., 2003)

The orographic relief of the Northern Apenninic margin has been described as either the result of the activity of the PTF thrust system (Boccaletti et al., 2004) or the topographic expression of a mid-crustal blind ramp, with associated high-angle normal faults in the upper crust (Picotti and Pazzaglia, 2008, Fig. 2.2). The uplifting of the Apenninic front started during the Early Pleistocene (Bartolini et al., 1982; 2003), with uplift rates of about 0.7-2.0 mm/y (Zattin et al., 2002; Argnani et al., 2003; D'anastasio et al., 2006), in agreement with short-term GPS measurements (Baldi et al., 2009; Cenni et al., 2013). The generalized uplift of the Northern Apennines caused the progressive incision of the drainage network, with the formation of steeply cut valleys perpendicular to the mountain margin. In the Middle Pleistocene extensional faults were activated in the Apennine foothills, with the consequent tilting of the footwall beds towards the Po Plain (Bertotti et al., 1997).

Long-term natural subsidence of about 2.5 mm/y has been estimated for the Po Plain (Carminati and Di Donato, 1999). Maximum values of 70 mm/y were measured in areas affected by intense water pumping and/or hydrocabon extraction (Carminati and Martinelli, 2002; Baldi et al., 2009).

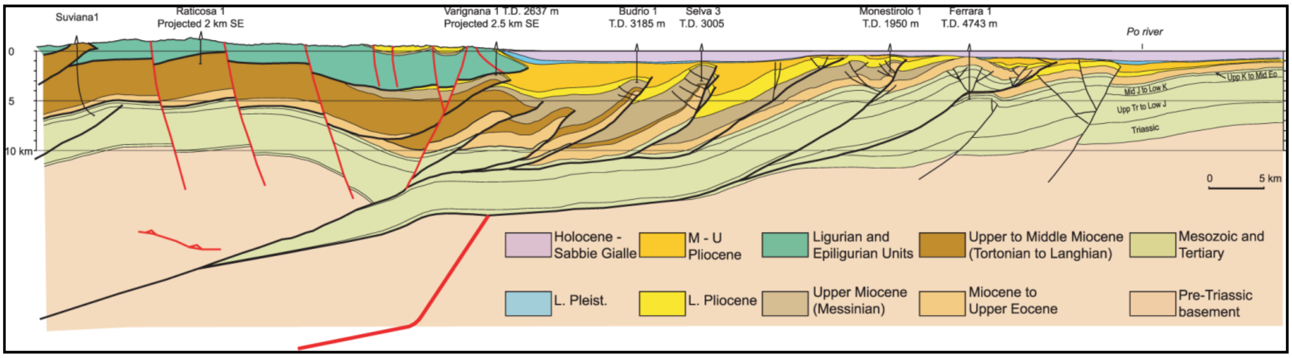

Fig. 2.2. Interpretation of a seismic profile between Bologna and Ferrara (from Picotti and Pazzaglia, 2008). Location on Fig. 2.1

2.2. Depositional architecture of the Po Plain

Seismic mapping and well-log interpretation led to the internal subdivision of the Pliocene-Quaternary basin fill, south of Po River, into six third-order depositional sequences (*sensu* Mitchum et al., 1977), showing typical geometries of syntectonic units (Regione Emilia-Romagna and ENI-AGIP, 1998 - Fig 2.3): minimum thickness (less than 100 metres) in ramp anticline zones and maximum (several hundred of metres) in the depocentral areas. Tectonic deformation typically decreases upsection. In the Geological Map of Italy (1:50,000 scale), the two topmost units are reported as unconformity-bounded stratigraphic units (UBSU) and termed the *Lower Emilia-Romagna Synthem* (AEI) and the *Upper Emilia-Romagna Synthem* (AES). Syntems AEI and AES are grouped into the higher-rank *Emilia-Romagna Supersynthem*.

The Po Basin fill displays an overall shallowing-up tendency, from Pliocene open-marine to Quaternary marginal-marine and then alluvial deposits. The Quaternary deposits are about 1000-1500 m thick (Pieri and Groppi, 1981). The boundary between marine and alluvial Quaternary units, traditionally referred to as cycles Qm and Qc, respectively (Ricci Lucchi et al., 1982), is clearly exposed at the Apenninic foothills, where it is represented by a stratigraphic unconformity through which alluvial (cycle Qc) deposits overlie the littoral *Imola Sands* (IMO) and the open-marine *Argille Azzurre* formation (FAA). This unconformity has been correlated in the subsurface with the boundary between IMO and the overlying *Emilia-Romagna Supersynthem* (Regione Emilia-Romagna and ENI-AGIP, 1998)

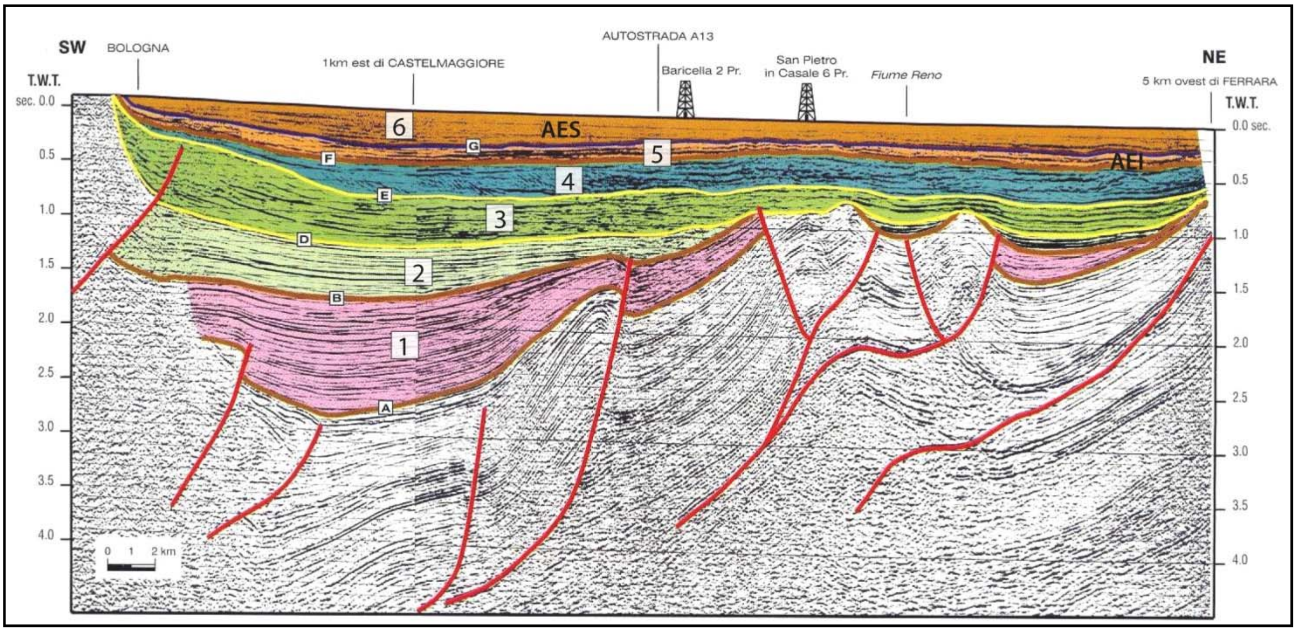

Fig. 2.3. Third order depositional sequences identified in the Pliocene-Quaternary basin fill south of Po River (from Emilia-Romagna & ENI-AGIP, 1998). Location on Fig. 2.1

The stratigraphic architecture of the *Upper Emilia-Romagna Synthem* reveals distinctive cyclic changes in lithofacies and channel stacking patterns of fluvial deposits, which allow its subdivision into 4th-order depositional cycles, covering a time span of about 100 ky (Amorosi, 2008). Each cycle is characterized by peculiar downstream facies changes and has distinctive pollen signature throughout the basin. Beneath the modern coastal plain, sedimentary wedges of nearshore and shallow-marine units occur in regular alternation with alluvial plain deposits. These wedges record the landward migration of beach-barrier-lagoonal systems, followed by delta and strandplain progradation, with return to alluvial sedimentation. Radiocarbon dates, pollen profiles and Electron Spin Resonance (ESR) dating allowed the correlation of this cyclic pattern with the oxygen isotope curve and sea-level curve (Amorosi et al., 1999; Antonioli et al., 2009).

Each cycle, interpreted as a trangressive-regressive (T-R) sequence, is the result of a 100 ky glacio-eustatic fluctuation, and consists of four systems tracts: above the transgressive surface (TS), which represents the cycle boundary, the transgressive systems tract (TST) is characterized by a well-developed retrogradational stacking pattern of coastal plain and estuarine facies, while the overlying highstand systems tract (HST) includes progradational, deltaic and coastal facies (Amorosi at al., 1999; 2003). The maximum flooding surface (MFS) is placed at the transition between offshore and prodelta facies associations. The upper part of the T-R cycle marks the boundary between interglacial and glacial deposits, and includes the falling-stage and lowstand systems tracts (FST and LST). These systems tracts record channel incision, palaeosol development on the interfluves and deposition of thin fluvial sediments in the lower part of the valley bodies.

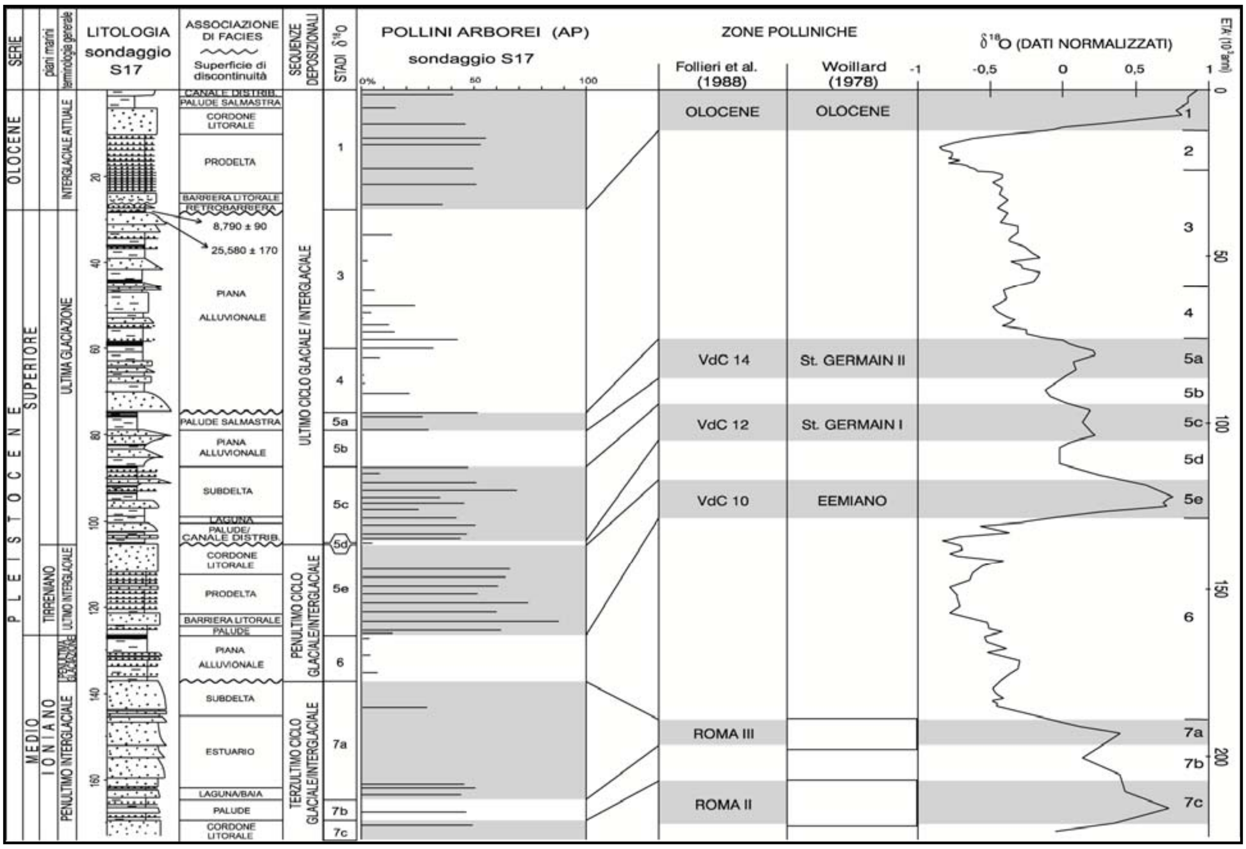

Fig 2.4. Correlation scheme between the pattern of facies evolution and the curve of arboreal pollens (AP) recorded from a 137 m deep core, pollen zones from two selected European series, and the oxygen-isotope record of Martinson *et al.* (1987). From Amorosi et al. (1999).

Ultra-high resolution palaeontological analysis of the Holocene succession, through the identification of twelve microfossil associations, has shown that TST and HST consist of a series of millennial-scale depositional cycles (parasequences) (Fig 2.5), which testify a step-wise sea-level rise followed by discontinuous delta progradation (Amorosi et al., 2005).

The landward equivalents of the T-R sequences detected in the subsurface of the Adriatic coastal plain are depositional cycles made up of mud-dominated interglacial deposits, with thin and lenticular fluvial-channel sands, showing upward transition to increasingly amalgamated and more laterally extensive fluvial-channel bodies, characterized instead by glacial pollen signature. This stacking pattern characterizes the central Po Plain, beneath the modern Po River (Amorosi et al., 2008), and the southern Po Plain, close to the Apennine margin (Amorosi et al., 1997; 2001). Based on the pollen signature of these deposits, the transgressive surfaces (TSs) have been traced throughout the basin from the base of nearshore deposits beneath the coastal plain, to the top of laterally extensive fluvial-channel complexes (Amorosi and Colalongo, 2005). Five T-R sequences are identified within the *Upper Emilia-Romagna Synthem*, each corresponding to a subsynthem in the CARG maps (AEI 4-8). The uppermost T-R sequence (AES8), of post-LGM age, is incomplete, and lacks almost entirely its upper, regressive portion. The T-R sequences have been correlated to the Marine Isotopic Stages (Fig 2.6).

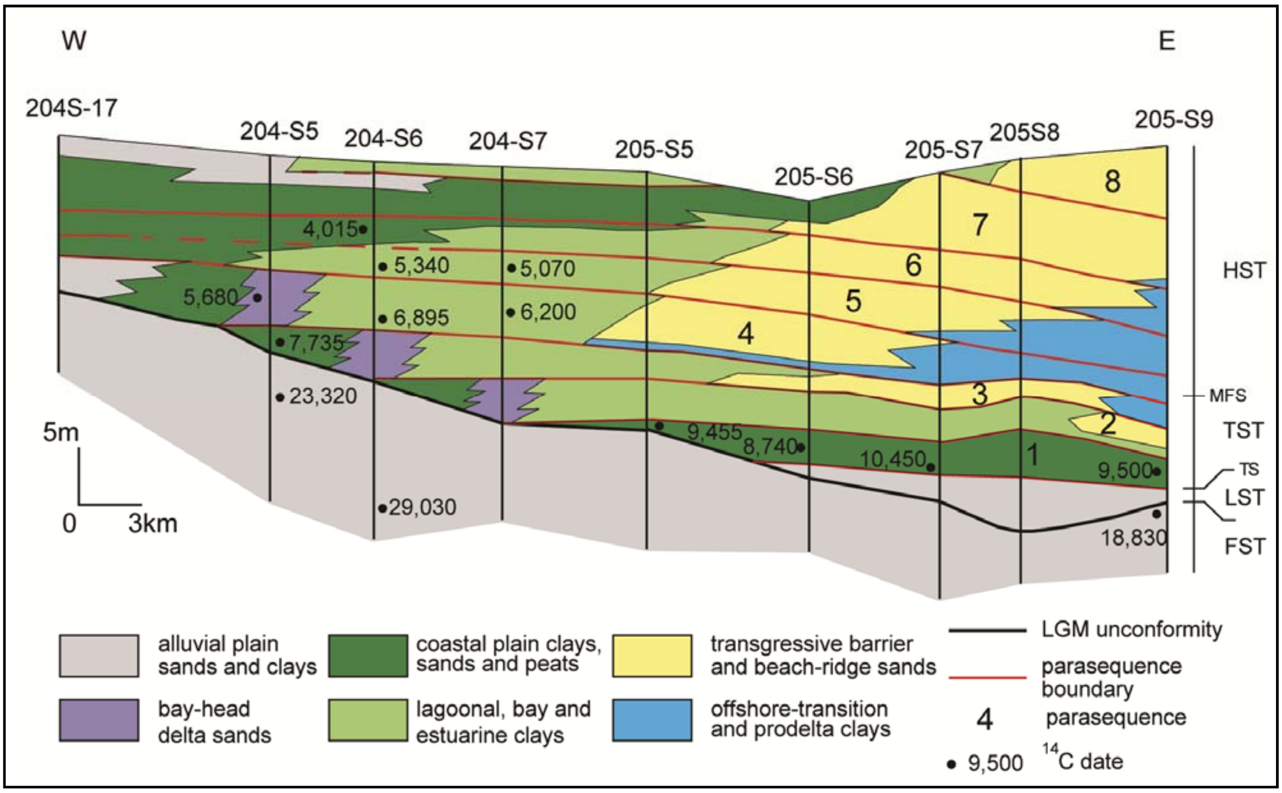

Fig. 2.5. stratigraphic cross-section showing parasequence architecture beneath the modern Po coastal plain. FST: falling stage systems tract, LST: lowstand systems tract, TST transgressive systems tract, HST: highstand systems tract; MFS maximum flooding surface.

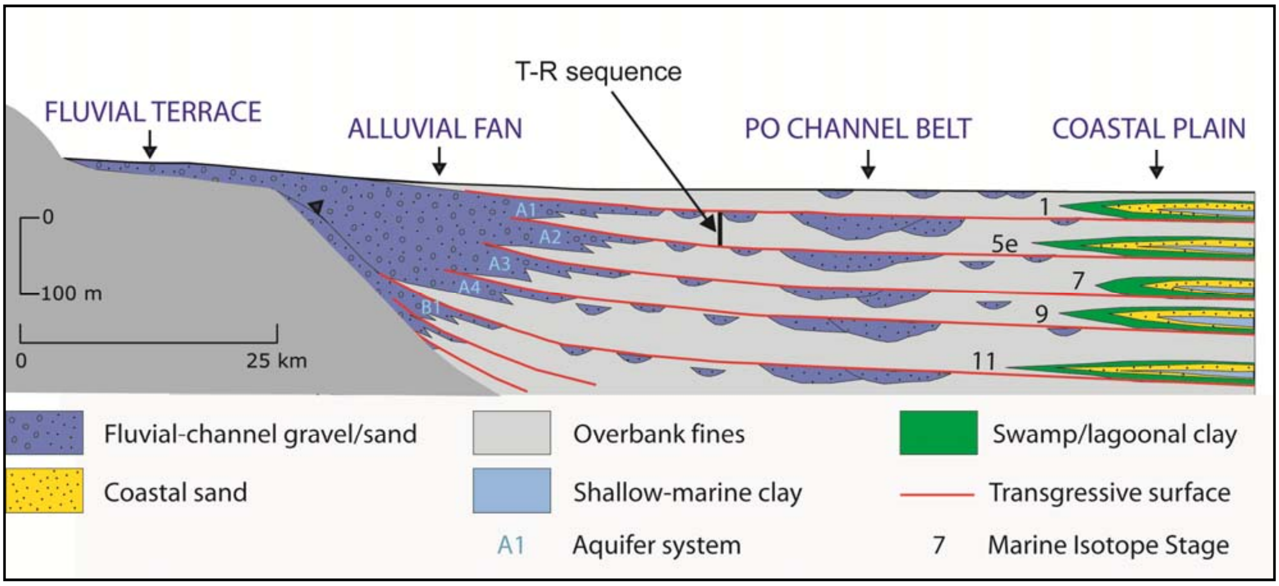

Fig. 2.6. Schematic geological cross-section across the Po Basin, showing the linkage between alluvial and coastal systems (from Amorosi, 2008)

The stratigraphic architecture of the Quaternary units of the Po Basin fill has important hydrostratigraphic implications: an aquifer system is associated to each T-R cycle (Fig. 2.7; Table 2.1); beneath the coastal plain aquifers made up of coastal deposits overlie the TSs, while beneath the modern Po River and at the basin margin aquifers of fluvial origin underlie the TSs (Fig 2.6). The aquifer systems have been grouped in three higher-rank hydrostratigraphic units (aquifer groups A, B, C) each corresponding to a 3rd-order depositional sequence (AES, AEI, IMO) (Regione Emilia-Romagna and Eni-Agip, 1998).

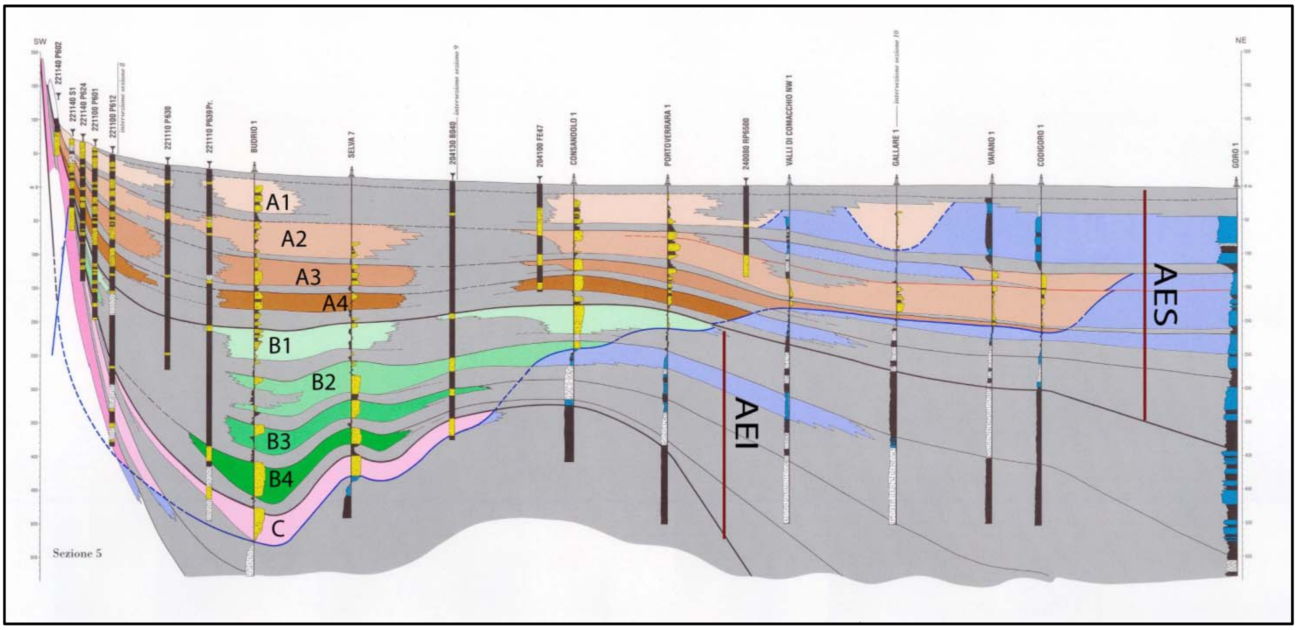

Fig. 2.7. Hydrostratigraphic cross-section across the Po Plain, from the basin margin to the coastal areas (from Emilia-Romagna and Eni-Agip, 1998). Grey deposits are aquitards. Blue line represents the limit of saline water intrusion. For labels A1-A4, AES, AEI see following the table

STRATIGRAPHIC UNITS (Geological Map of Italy to scale 1:50,000)			**HYDROSTRATIGRAPHIC UNITS (Regione Emilia-Romagna and Eni-Agip, 1998)**	
Supersynthem	**Synthem**	**Sub-synthem**	**Aquifer group**	**Aquifer systems**
Emilia-Romagna Supersynthem	Upper Emilia-Romagna Synthem (AES)	AES8	A	A0
		AES7		A1
		AES6		A2
		AES5		A3
		AES4		A4
	Lower Emilia-Romagna Synthem (AEI)		B	B1
				B2
				B3
				B4
Imola Sands (IMO)			C	

Table 2.1. Correlation between stratigraphic and hydrostratigraphic nomenclature of the southern Po Basins depositional units.

2.3. Late-Quaternary alluvial stratigraphy at the Apenninic margin

The subsurface of the Po Plain at its southern margin is composed, for several hundred metres, of fluvial-channel gravels, mostly abundant close to the Apenninic valley outlets, and by predominant overbank fines between two successive valley outlets (i.e., in interfluve position). Due to the point-sourced feeding systems and the short distance between successive valleys, a few km downstream of the basin margin the fluvial channel complexes tend to coalesce in a unique coarse-grained sedimentary body elongate parallel to the Apennine foothills. In more distal position fine-grained intercalations, up to 40 m thick can form between gravel strata. Mean grain-size and gravel/mud ratio decrease downstream. Sheet-like gravel bodies occur at preferential alignments and their top can be correlated to the top of intensely pedogenized gravels cropping out at the Apennine foothills (Amorosi et al., 1997).

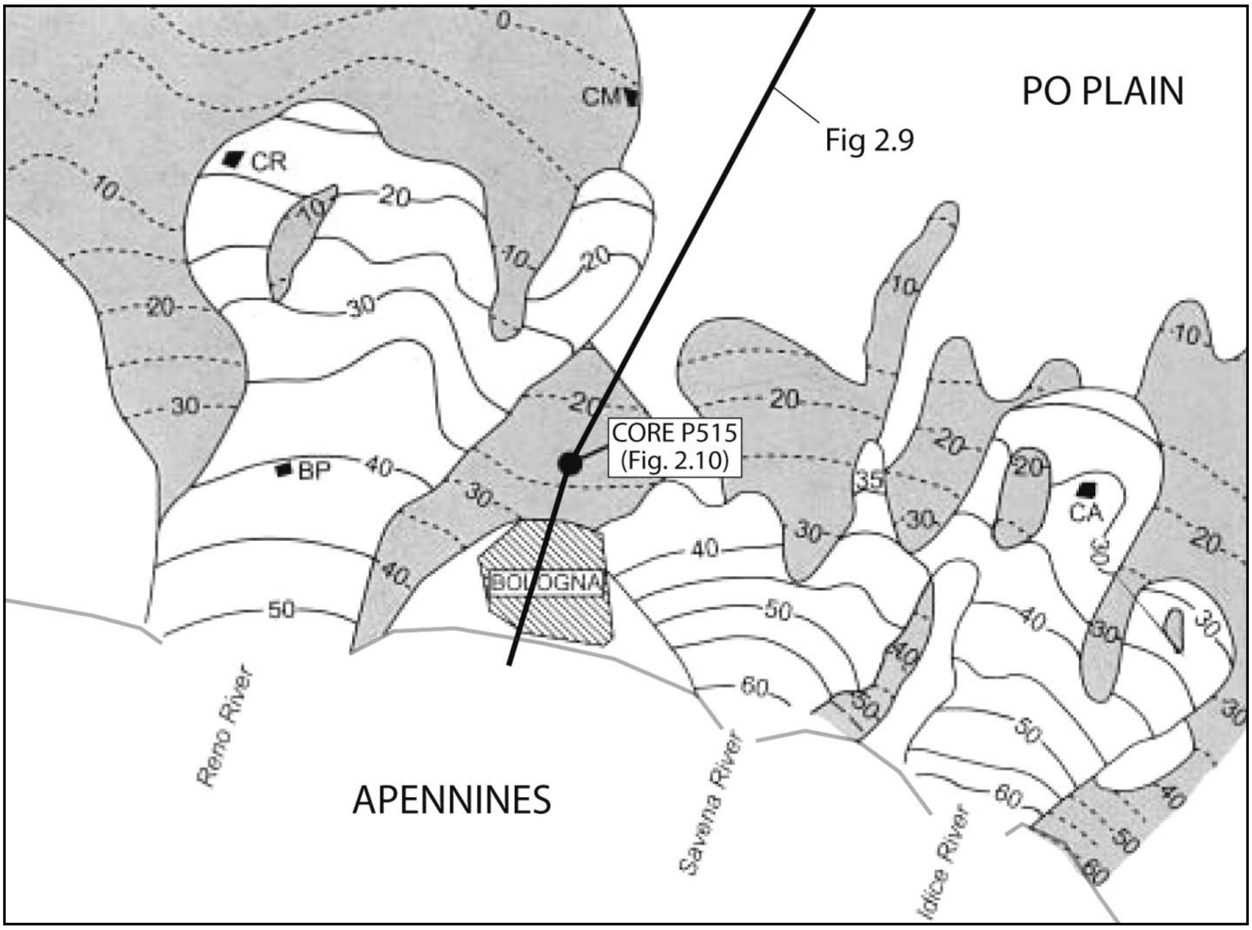

Fig. 2.8. Top of the gravel fluvial-channel complexes (m asl) at the southern margin of the Po Basin close to Bologna (from Amorosi et al., 2001). Gravels in white belongs to aquifer system A0, whereas gravels in grey belongs to the underlying aquifer system A1. Notice the position of Bologna between the Reno and Savena channel complexes (interfluve)

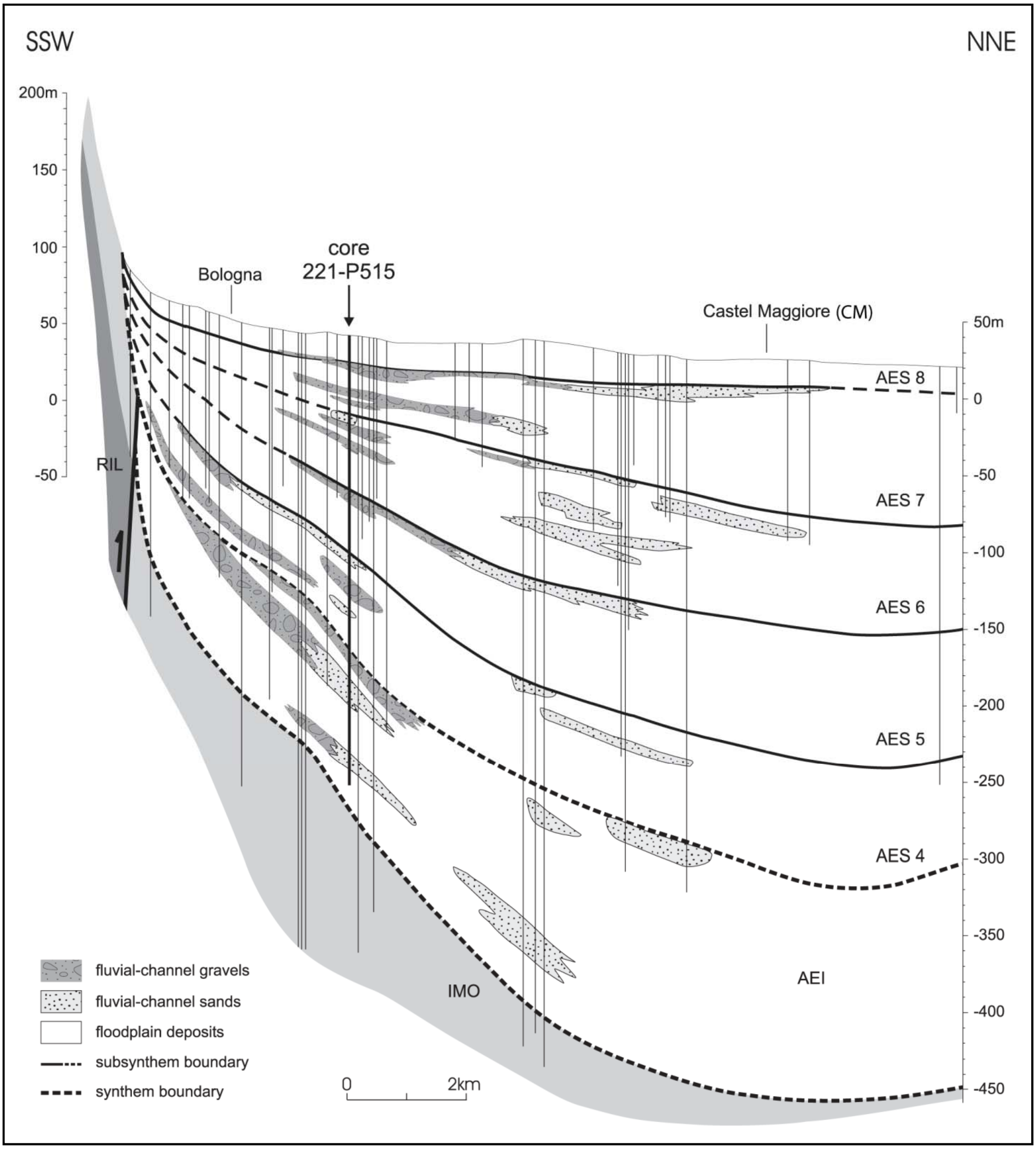

Fig. 2.9. Depositional architecture of the Late Quaternary alluvial deposits in the Bologna area. For labels AES 4-8, AEI and IMO see Tab 2.1. Location on Fig 2.8.

The town of Bologna is located between Reno and Savena Rivers, which border the city to the west and to the east, respectively. The subsurface depositional architecture of the Bologna urban area is strongly influenced by its geographic position, close to the Apennine foothills and between two rivers: well-log correlations indicate contrasting facies patterns between the periurban areas, dominated by fluvial-channel gravels, and the historical town centre, corresponding to the interfluve, consisting of a monotonous succession of fine-grained sediments (Elmi et al., 1984; Amorosi and Farina, 1995). The 300 m-deep core 221-P515 (Amorosi et al., 2001 - Fig 2.10) crossed the alluvial Quaternary succession without encountering its base, which is attested about 400 m below the ground surface (Francavilla et al., 1980; Di Dio and Caporale, 1988).

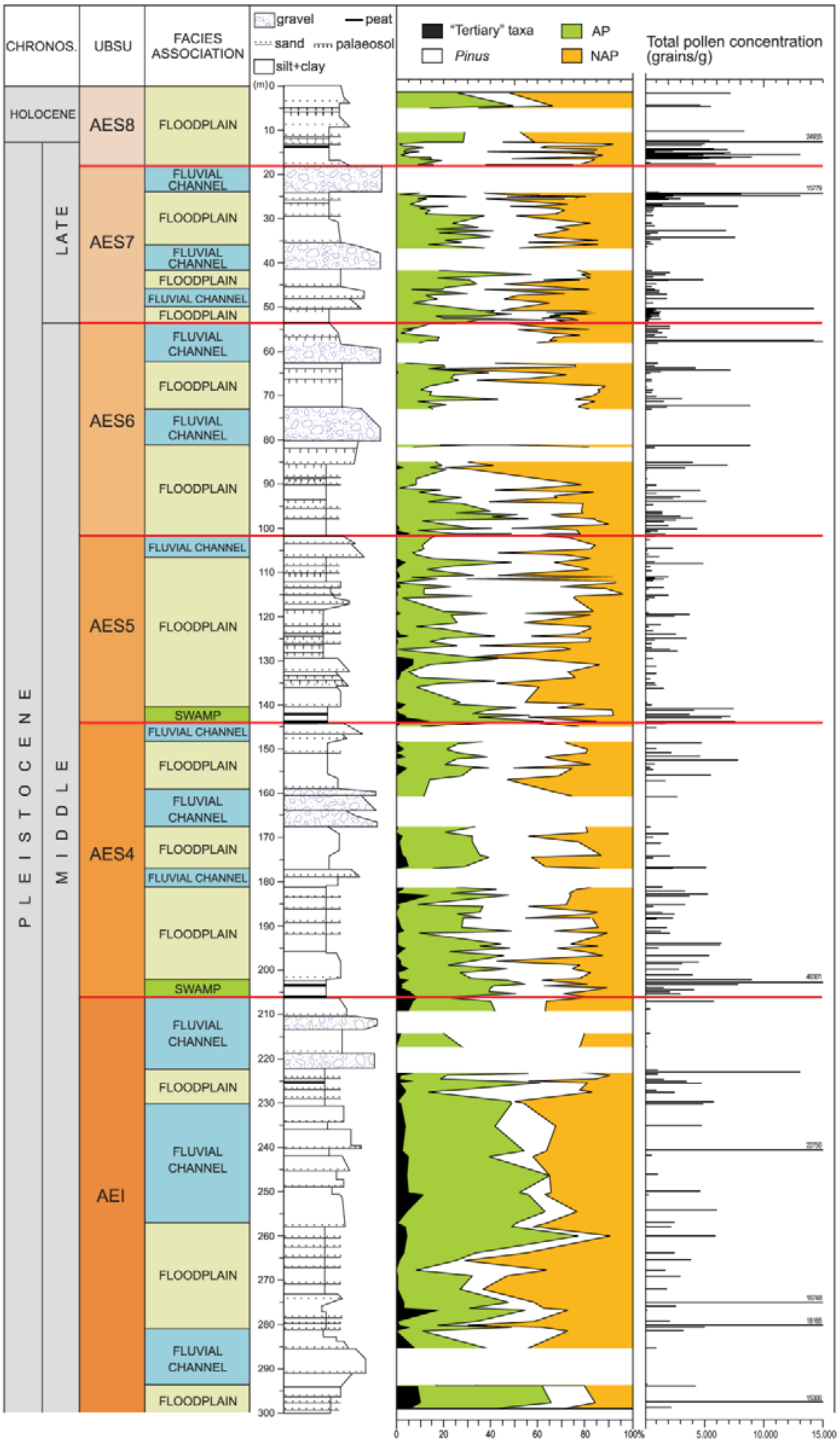

Fig. 2.10. Depositional architecture of the late Quaternary alluvial deposits in the Bologna area. For labels AES 4-8, AEI and IMO see Table 2.1. Location on Fig 2.8

Pollen profiles from the uppermost 200 m of the core record alternating phases of thermophilous forest development (high arboreal pollen of temperate climate associations – AP) and retreat (high *Pinus* and non-arboreal pollen associations – NAP). Thermophilous forest development (AP) is related to warm (interglacial) periods, while *Pinus* forests and herbaceous vegetation cover are associated with cold (glacial) periods. The characteristic cyclic pattern of pollen distribution shows a striking coincidence with depositional facies alternations. Particularly, an increase in NAP is detected close to fluvial channel gravels, while AP are predominant in floodplain deposits, suggesting a decisive climate control on fluvial sedimentation.

Poorly mature palaeosols occur at various stratigraphic levels within floodplain deposits in the uppermost 150 m of the core. Despite large availability of scientific literature on buried soils (Watanabe et al., 1996; Bronger et al., 1998; Dramis et al., 2003; Golyeva et al., 2003; Sedov et al., 2003; Balco et al., 2005; Alekseeva et al., 2007; Presley et al., 2010), previous studies at the Apenninic margin have been limited to soils developed on exposed terrace surfaces (Cremaschi, 1979; Amorosi et al., 1996; Eppes et al., 2008, Wegmann and Pazzaglia, 2009).

Close to Bologna, along the lower reaches of the Reno valley, a staircase of ten orders of alluvial terraces (Qt0-Qt9) borders the valley flanks (Picotti and Pazzaglia, 2008, Fig. 2.10). At the mountain front, these terraces dip toward the Po Plain, where they correlate in subsurface to fluvial-channel gravels belonging to AEI and AES and to nearshore sands (IMO). Reno terraces are described as strath terraces with thin alluvial fills, made up of well sorted and stratified axial stream gravel showing upward transition to overbank sands and silts (Picotti and Pazzaglia, 2008). Terrace fills exhibit in their upper parts evidence of pedogenesis, with increasing degree of soil development from the younger to the older terraces (Eppes et al., 2008). The terrace treads can partially be covered by colluvial, alluvial fan or aeolian deposits. Qt0, Qt1 and Qt2 are scattered remnants of terraces of inferred Middle Pleistocene age. Qt3 has been correlated to subsurface fluvial-channel deposits assigned to the Oxygen Isotyope Stages (OIS) 8 and 6. Terraces Qt4-Qt9 have Late Pleistocene-Holocene age and are laterally continuous and well exposed, with the exception of terrace Qt7, which is only locally preserved. Qt4 and Qt7, for which numerical ages are not available, have been correlated based on their degree of soil development, to equivalent terraces in the adjacent valleys, dated to 30±5 and 9±1 ky, respectively (Table 2.2). In the lowermost 7 km of the Reno valley, fluvial terraces are well preserved mostly on its western side, due to the activity of the Reno fault, a normal fault bordering the eastern flank of the valley (Picotti et al., 2009) that induced preferential fluvial erosion in this sector.

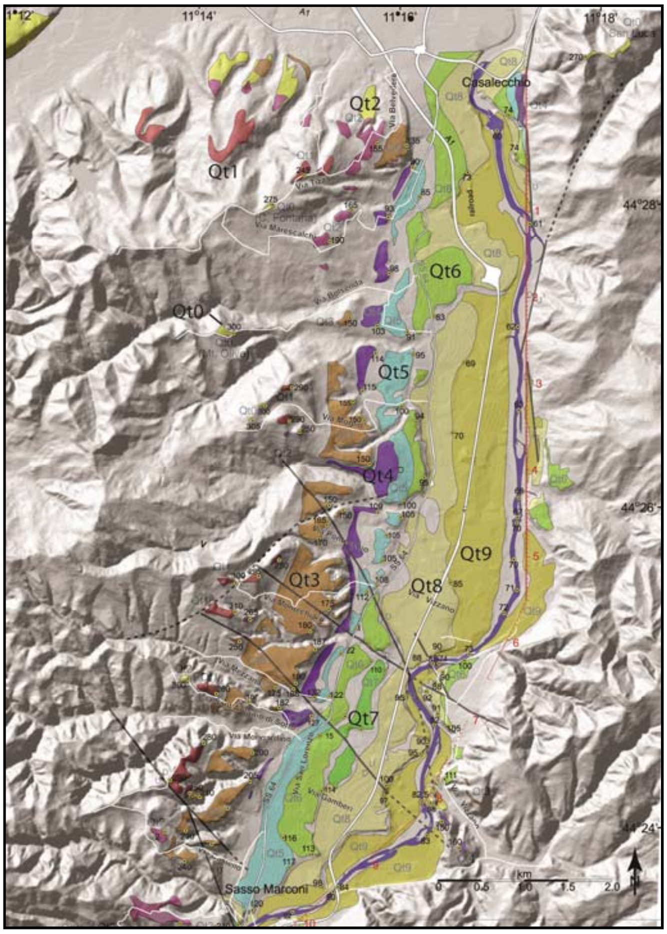

Fig. 2.11. Fluvial terraces (Qt0-Qt9) in the Reno Valley close to Bologna (modified after Picotti and Pazzaglia, 2008).

2.4. Archeological setting of the Bologna Area

The southern margin of the Po Plain has long represented an attractive site to be settled by prehistoric populations because of its topographic position slightly elevated on the surrounding plains. A position protected by floods, but at the same time far enough from steep unstable slopes. Water supply in these areas was likely provided by numerous springs bordering the Apennine foothills. The Bologna area provides many evidences of human presence in prehistoric times (Scarani, 1957), and Neolithic or Early Eneolithic settlements are frequently encountered (Ferrari and Steffè 2006; Ferrari et al., 2006). With the diffusion in the last decades of underground parking areas and train stations, the documentation of prehistoric settlements has received a rapid increase. This is due to the fact that both Neolithic and Eneolithic rests generally lie more than five metres below the ground surface, a depth that has not frequently been reached by older excavations. Indeed, archaeological investigations in the Bologna area are generally emergency surveys following casual findings during engineering excavations. The recent development of stratigraphic techniques and protocols (Harris, 1979), which allow vertical digging only in a few test trenches and impose the progressive removal of the sub-horizontal stratigraphic units, likely favoured the documentation of prehistoric evidences, difficult to detect in cross section, but clearly observable in plan view (Fig. 2.12).

Fig. 2.12. Map view of the traces of a Late Eneolithic hut (from Cadeddu et al., 2011)

Contrary to the increasing documentation on the Neolithic and Early Eneolithic settlements in the Bologna area, rare notes only are available for the period between the Late Eneolithic and the Early-Middle Bronze Age. Late Eneolithic settlements are found 10 km NE of Bologna, around the town of Castenaso (Cadeddu et al., 2011), while the Bronze Age population of the *Terramare* preferentially settled the lower Po Plain, from about 20 km downstream of Bologna (Cattani et al., 2010; Vinci, 2012) to the Po River (Bernabò Brea and Cardarelli, 1997; Cremaschi et al., 2006; Nicosia et al., 2010).

On the other hand, an extremely vast and detailed documentation exists on the Iron Age and Roman settlements (Bergonzoni, 1965; Scagliarini, 1970; Gualandi, 1973; Gelichi and Ortalli, 1987; Ortalli, 1986; 1989; 1993; 1999; Curina, 1990; 2010; Rigdway, 1994; De Angelis and Rezza, 2000), the first reports belonging to the end of 19th and the beginning of the 20th century (Gozzadini, 1870; Zannoni, 1907). From these studies, we know that the Bologna area was inhabited from four different cultures from the Early Iron Age to the Late Roman Age: the Villanovans (9th– 8th century BC), the Etruscans (7th – 6th century BC), the Boii (6th – 5th century BC) and the Romans (5th century

BC – 4th century AD). Particularly, the Etruscan founded the city of Felsina in 534 BC, and the Romans the colony of Bononia in 187 BC. The realization of the *Via Aemilia*, a road running along the Apennine foothills from the Adriatic coast to the Po River, is dated back to 185 BC (Livy, *Ab Urbe Condita,* XXXIX 1). Subsequently, wide areas of the southern Po Plain were reclaimed and divided into a regular grid of squared agricultural plots, assigned to the veteran of the Roman Army (centuriation). Each plot was about 50 hectares wide and delimitated by roads and ditches parallel and perpendicular to the *Via Aemilia*.

The archaeological documents on the Bologna area are generally focused on a single archaeological site, excluding rare reconstructions of the Etruscan (Taglioni, 1999) and Roman urban areas (Bergonzoni and Bonora, 1976). According to these studies, the Bononia urban area was about 1/70 of the modern city delimitated by the 1970 motorway (Fig 2.13). Investigations on a larger scale are related to the modern rural areas, where the Roman centuriation is well preserved (Casini, 1907; Ortalli, 1994; 1995).

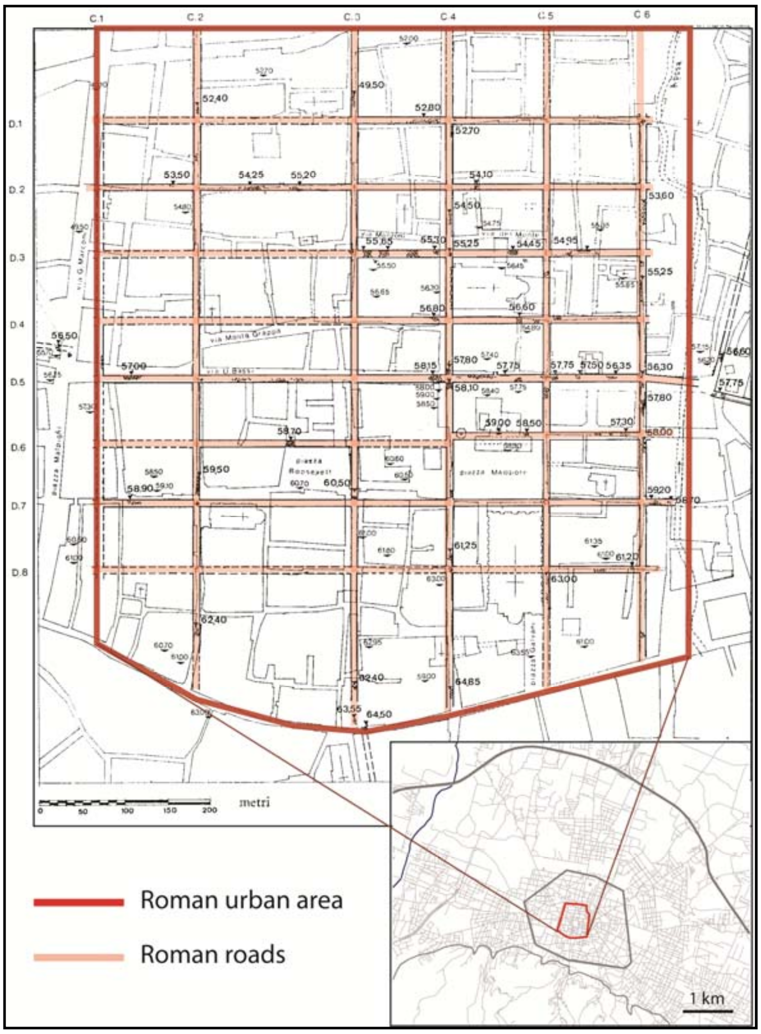

Fig 2.13. Reconstruction of the Roman urban area with its road layout (modified after Begonzoni and Bonora, 1976)

3. METHODS

Subsurface investigation in this work was carried out through the construction and interpretation of vertical stratigraphic profiles at different scales (from 0.5 to 56 km long) and with different mean data spacing (from 0.35 to 23 data/km). The depth of investigation spans between 10 and 80 m. Stratigraphic correlations were based on geometric criteria, locally supported by radiocarbon dates and archaeological data. Two-dimensional profiles were not analyzed separately, but compared with the horizontal distribution of facies associations. To this purpose, map reconstructions were carried out. Stratigraphic boundaries were also contoured, in order to obtain palaeo-topographic maps: automatic contouring (using ArcGis spatial analyst) was refined by hand in order to outline geometries of sedimentary bodies consistent with the natural depositional systems.

Various type of stratigraphic information were correlated into the cross sections and the maps. These are described in the following section.

3.1. The geological-archaeological dataset

This study relies upon a huge geological and archaeological dataset composed of more than 5000 stratigraphic logs (Fig 3.1), stored at the Geological, Seismic and Soil Survey of Regione Emilia-Romagna, plus about 750 archaeological reports archived at the SAER and at the IBC of Regione Emilia-Romagna.

For the Bologna area, the geological dataset, originally composed of 1550 stratigraphic descriptions, was implemented through 945 new data (730 boreholes and 215 penetration tests), collected from various public agencies (Bologna Municipality, *Provincia di Bologna*, *Rete Ferroviaria Italiana*). Additional 59 cores and 12 outcrops were analyzed. The result is a geo-database characterized by a mean density of stratigraphic information of 0.5 data/km^2, with maximum values in the Bologna urban area (20 data/km^2).

The archaeological dataset was created entirely during this research project and consists of 450 published studies and 300 unpublished archeological reports. All these data were archived in a geographic information system (GIS).

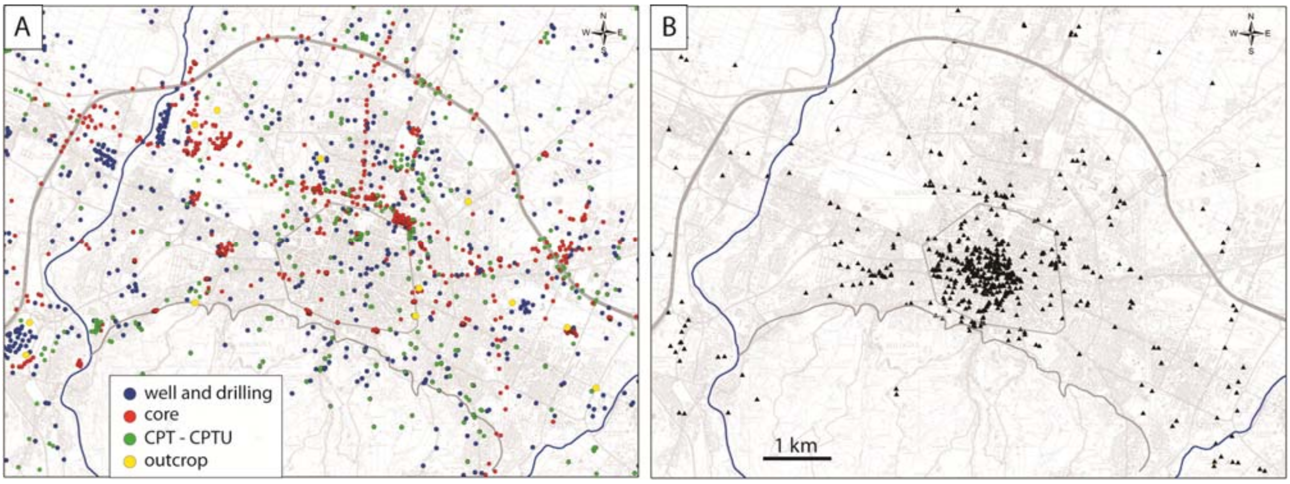

Fig. 3.1. The geological (A) and archaeological (B) dataset of the Bologna area.

The geological-archaeological dataset is composed of different types of stratigraphic information, related to different methods of investigations, with peculiar vertical resolution, mean and maximum depth, quality of the descriptions. The major sources of data are as follows:

- *Drillings for water wells*. The aim of these drilling is to encounter aquifers; for this reason the stratigraphic descriptions associated, characterized by scarce vertical resolution, is restricted to the identification of three lithofacies: gravel, sand (aquifers) and clay (aquitard). Rare annotations on color or consistency are reported. Despite the poor level of detail, these logs are the deepest stratigraphic information available, with mean depth of about 150 m and maximum of 450 m. These descriptions were used uniquely to identify fluvial-channel bodies, especially the oldest (and deepest) ones, lying more than 40 m below the ground surface, and for this reason generally beyond the depth of common geotechnical investigations.
- *Continuously cored boreholes*. This is one of the most efficient tools for stratigraphic reconstructions. Facies analysis on cores allows to obtain detailed sedimentological information, associated to high stratigraphic resolution: grain-size tendencies, colour, consistency, contacts, and accessory material. Additional information can be supplied by *in situ* instrumental analyses on core (pocket penetrometer test - PPT, vane test - VT). Samples can be collected for laboratory analyses (radiocarbon dating, palaeontological, palaeobotanical, geochemical and petrographic characterization). Excluding the cores directly observed during this research (Fig 3.2), the geological dataset is composed of core descriptions carried out by the Regione Emillia-Romagna geologists during the CARG mapping project (Fig 3.3), and those realized for non-stratigraphic purposes (Fig 3.4). CARG stratigraphic logs have high-resolution and may include stratigraphic, pedological, geothecnical (PPT-VT), palaeoclimatic,

palaeobotanic (pollen profiles), palaeontologic and chronological (^{14}C dates) information. On the other hand, the quality of the descriptions realized for non-stratigraphic purposes largely depends on the type of investigation: core descriptions for hydrogeological surveys, for instance, generally lack information about consistency, PPT and VT values. The mean depth of these drilling is around 40 m.

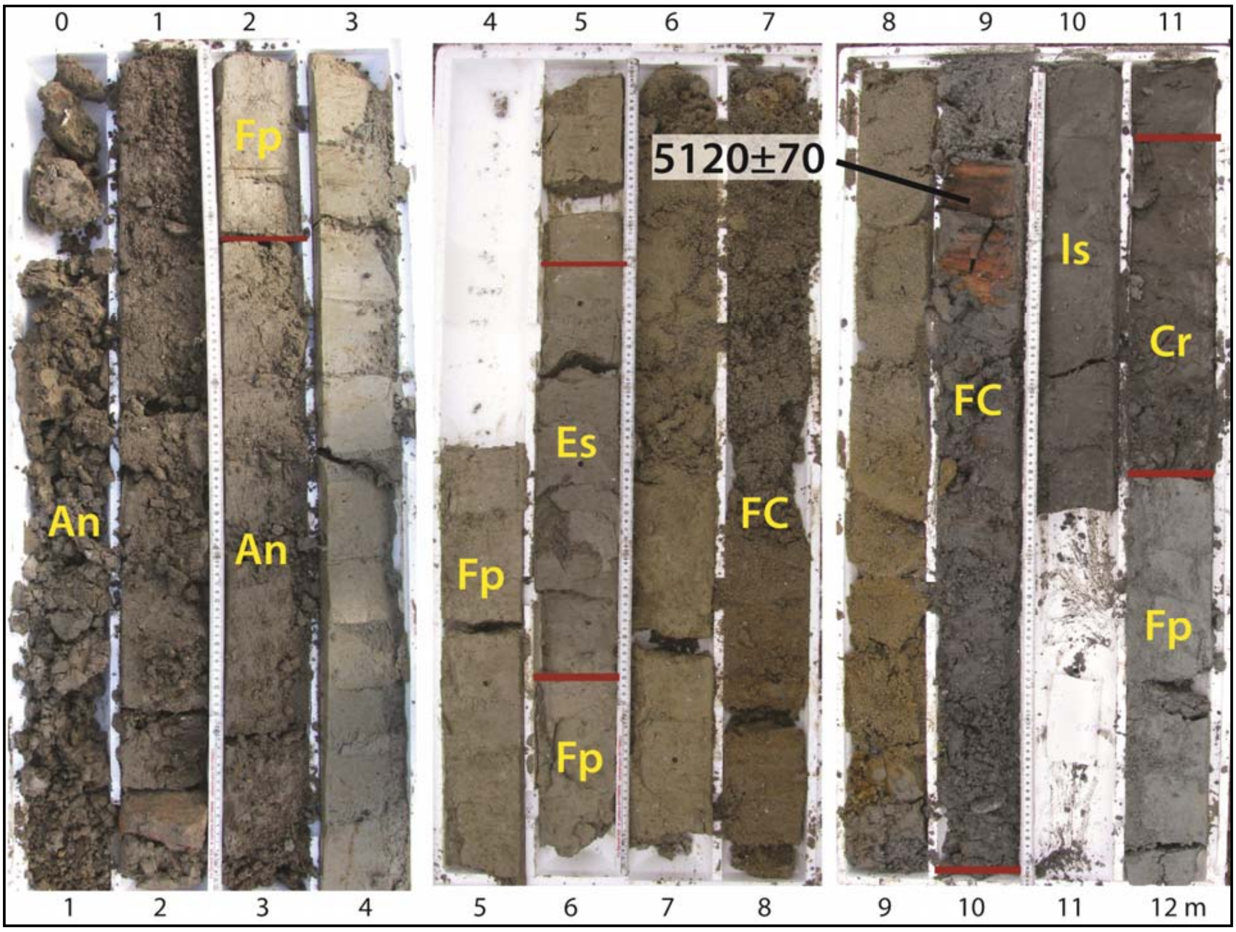

Fig 3.2. Facies analysis and radiocarbon dates on core carried out during this research project. Depositional facies association: An Anthropogenic, Cr crevasse, FC fluvial channel, Fp floodplain. Palaeosols: Es Entisol, Is inceptisol

- *Excavations.* Rare, temporary outcrops can be produced in quarries or excavations for building foundations (Fig 3.5). These sites offer the same possibilities of stratigraphic investigation as core analysis, with the additional chance to observe lateral extension, sedimentary structures and the two-dimensional geometry of sedimentary bodies. The major disadvantages of this stratigraphic tool are relatively low depth of excavation (5-20 m) and poor spatial density.
- *Cone penetration tests (CPT) and piezocone tests (CPTU).* Peculiar cone resistance, sleeve friction and pore pressure values can be associated to distinct facies associations; we refer the reader to Amorosi and Marchi (1999) for detailed description. This type of indirect investigation

is characterized by high vertical resolution (Fig 3.4) and relatively low costs. Local execution of CPT close to drilling sites is requested to calibrate borehole data with cone resistance profiles.

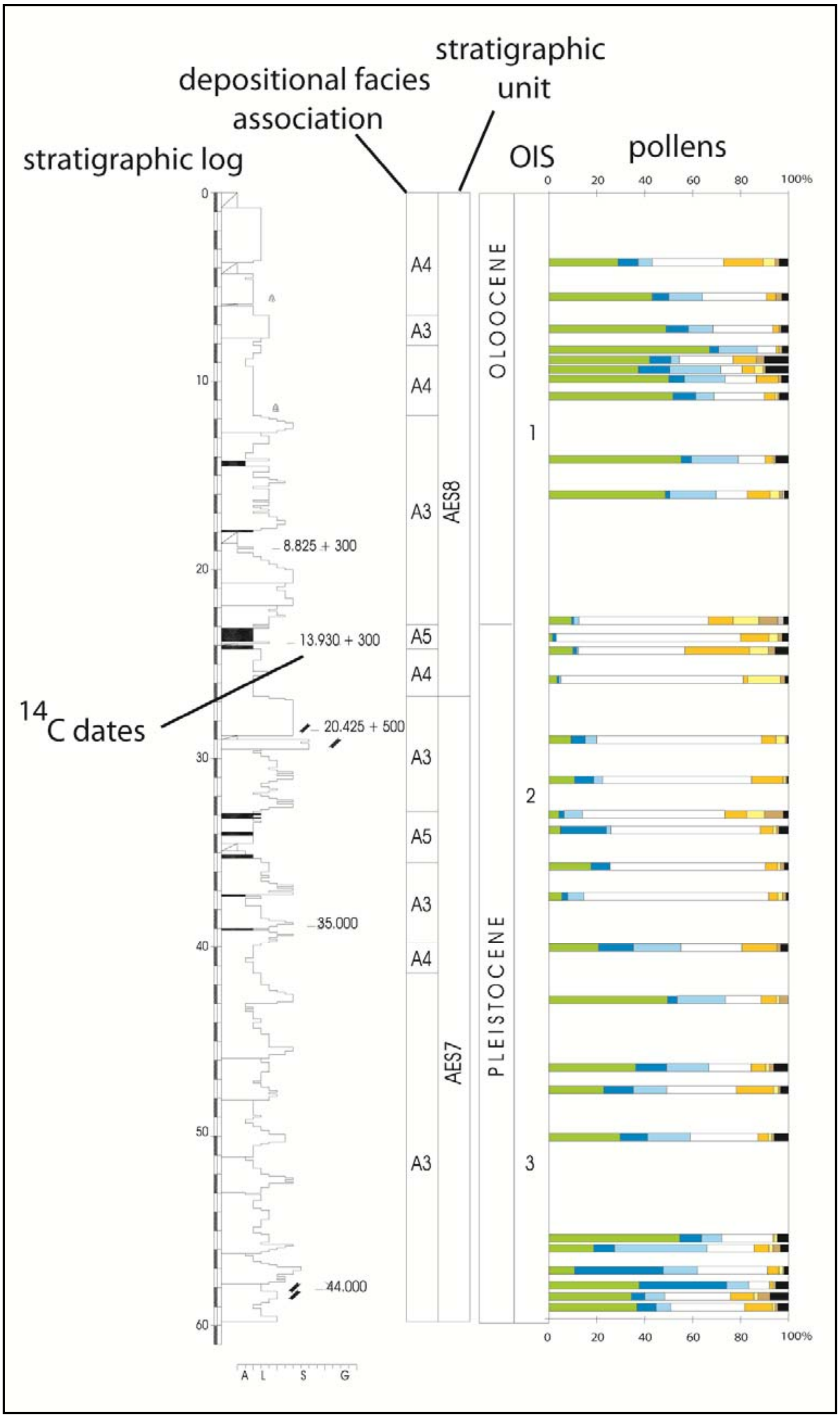

Fig 3.3. Core description from Sheet 220 of the Geological Map of Italy to scale 1:50,000 (Martelli et al., 2008)

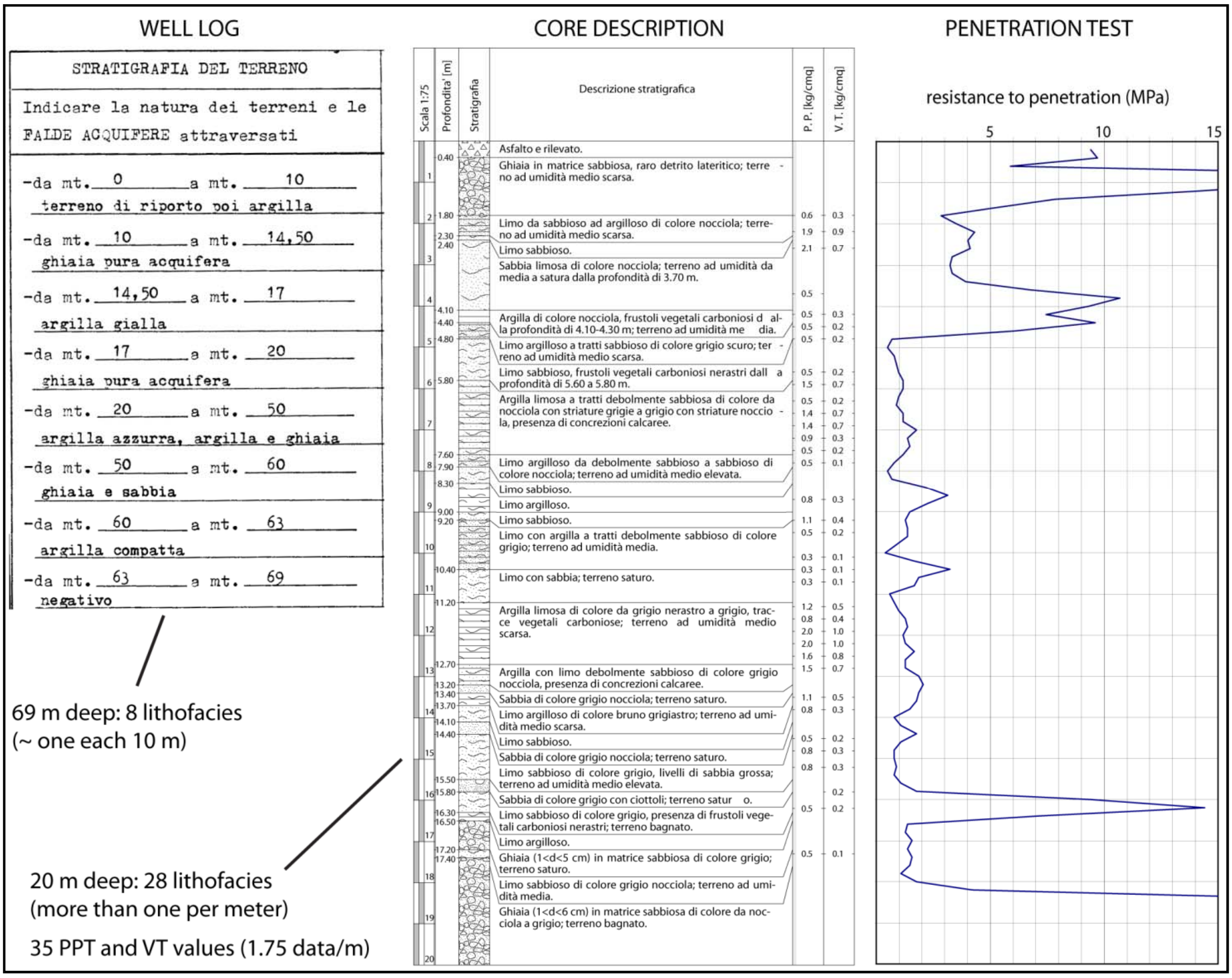

Fig. 3.4. Types of stratigraphic information with different vertical resolution: comparison between low-resolution well log and high-resolution core description and penetration resistance profile

Fig 3.5. Two different types of outcrop in the Bologna area. Left: urban excavation for engineering purposes. Right: quarry in the periurban area.

- *Archaeological reports*. Descriptions of archaeological sites may include stratigraphic, sedimentological, palaeoenvironmental and chronological information about mid-late Holocene deposits. The spatial and temporal resolution of these descriptions varied considerably through time. Particularly, post-1980 reports, in line with the development of the Harris matrix (Harris, 1979), contain a subdivision of the archaeological successions into stratigraphic units, with ultra-high spatial (cm) and temporal (100 y) resolution (Fig 3.6). The information extrapolated from the archaeological reports are: mean elevation above sea-level and depth below ground surface of the settlement, type of settlement, engineering and agricultural techniques, stratigraphic and palaeoenviromental information. Extremely useful for our purposes is the occurrence of dating material, such as coins or particular kinds of ceramics (see chapter 8 for details). Depths of investigation is less than 10 m.

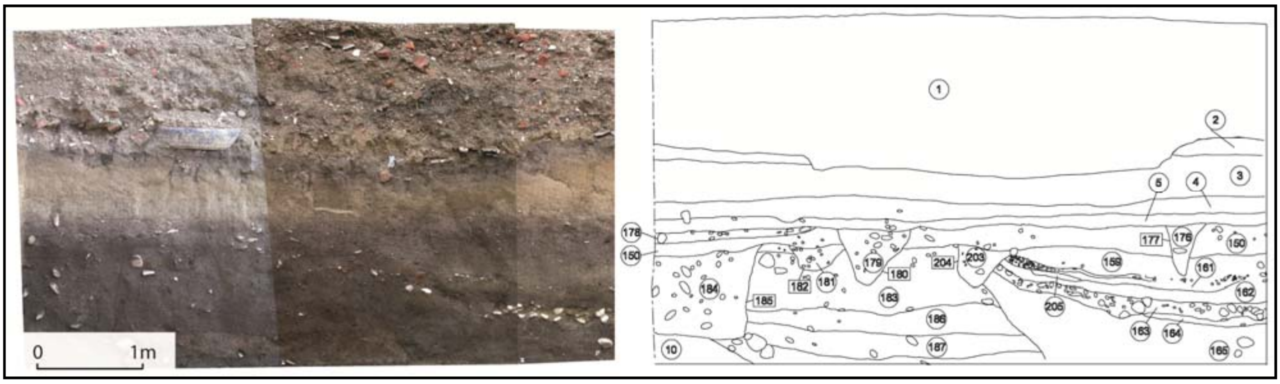

Fig. 3.6. Example of ultra high-resolution archaeo-stratigraphic cross section (from SAER archive)

All stratigraphic information described in this section were re-interpreted under a stratigraphic and sedimentological perspective. The vertical succession of the depositional facies associations, directly observed in cores and outcrops, was reconstructed for the archive material, based on the information available (lithology, grain-size tendencies, stratigraphic contacts, resistance, accessory material). Particularly, we focused on those indications that might enable the identification of a palaeosol: colour and consistency of the fine-grained sediments, occurrence of organic material, carbonate concretions, Fe and Mn oxides, increase in consistency. For each element of the dataset, the stratigraphic log was associated to depositional facies interpretation (Fig 3.7). The resulting stratigraphic logs were plotted in cross sections and maps.

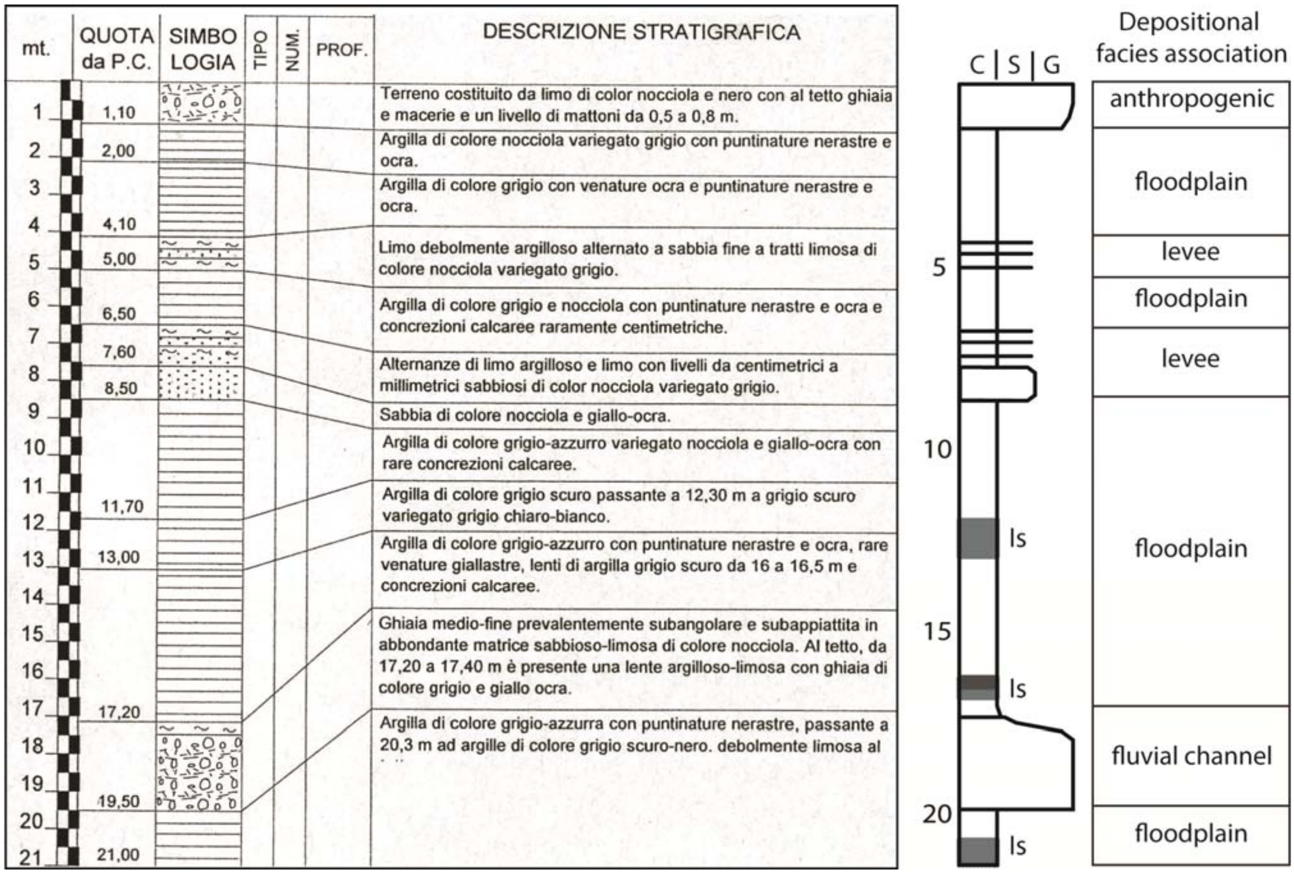

Fig. 3.7. Example of stratigraphic log obtained from the interpretation of a core description stored in the geological-archaeological dataset. Is: inceptisol

3.3 Radiocarbon dating

Different types of samples were collected following facies analysis on cores and outcrops, including bulk sediment, peat, plant macrofossils, wood, charcoal fragments (Fig 3.8). All samples were prepared for radiocarbon analyses, which were carried out using two methods: (i) accelerator mass spectrometry (AMS) at Ion Beam Laboratory, ETH (Zurich-Switzerland) and at Poznan Radiocarbon Laboratory (Poland); (ii) benzene-LSC (liquid scintillation counting) at ENEA Laboratory, Bologna (Italy). I personally worked on samples at Ion Beam and ENEA laboratories.

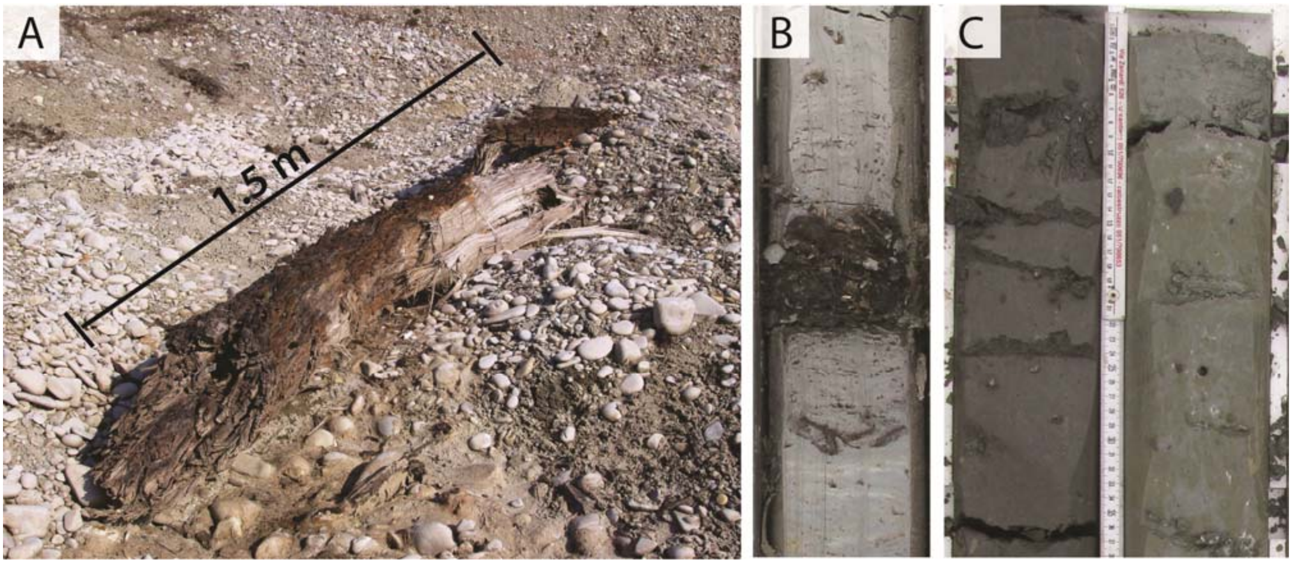

Fig. 3.8. Type of samples collected for radiocarbon dating. A: wood, B: peat, C: organic clays

The first step in sample preparation is mechanical cleaning, to separate different fractions of the sample (sediment, macrofossil, contaminants), and chemical pretreatment by standard acid–base–acid (ABA) method, which should remove all possible contaminants containing either modern or fossil carbon. The ABA method is composed of three steps: in the first step, HCl is added to the sample in order to remove secondary calcite concretions; then, the sample is washed with distillated water and brought back to neutral pH values. In the base step KOH is added to the sample to induce precipitation of humic acids; these are then removed from the sample; in four cases at Ion Beam Laboratory humic acids were dated separately, and the results compared with the standard cleaned samples: in three cases the humic acids gave an age older than the cleaned samples, and in one case we obtained the opposite result (Table 3.1). Since no trend was found and four examples do not represent a suitable number for statistical analysis, this part of laboratory activity was not incorporated in the research results. During the base step, the alkali solution into which the sample is immersed can favour the solution of external CO_2, which can rejuvenate the sample; for this reason, a new acid step is needed. At the end of the chemical pretreatment the sample is washed with distillated water and dried.

Cleaned samples are then combusted in a stream of pure oxygen and CO_2 is obtained. CO_2 can be converted to graphite and analyzed via AMS or to benzene and analyzed with LSC method. The first technique is very accurate, but highly expensive, while the second is very demanding, though rather popular. To obtain benzene, indeed, lithium carbide is produced from the reaction between CO_2 with lithium at 700–900°C, and subsequently hydrolyzed to acetylene by adding distilled water. Acetylene is ultimately trimerised to benzene (Fig 3.9). For counting, 15 mg of butyl-PBD scintillator is added per 1 g of benzene (Bronić et al., 2009). To obtain 1 g of benzene (minimum weight needed to determine ^{14}C activity) about 500 g of bulk sediment, 200 g of peat, 20 g of wood or charcoal is requested. This is clearly the most evident limit of this technique, compared to AMS, for which 5 g of bulk sediment or 0.1 g of peat, wood or charcoal is needed. Liquid scintillator counters (Quantulus™ 1220 at the ENEA Laboratory) detect, in a given time period, flashes of light caused by the beta particles emitted by ^{14}C as they interact with the fluorescing agent added to the benzene. Since the mass of the sample is known, this can be converted to a standard measure of activity. AMS counts the atoms of ^{14}C and ^{12}C atoms in a given sample, determining the $^{14}C/^{12}C$ ratio directly.

Lab Nr.	Sample Code	Material	Depth (m)	C14 age BP	DeltaC13 (%o)
ETH-45294.1	SD1_1	humic acid	16.15	29565 ± 115	-30,7 ± 1,1
ETH-45294.2	SD1_1	TOC	16.15	28550 ± 110	-26,5 ± 1,1
ETH-45307.1	SD7_2	humic acid	9,60	22790 ± 70	-31,0 ± 1,1
ETH-45307.2	SD7_2	TOC	9,60	21830 ± 100	-37,9 ± 1,1
ETH-45318.1	SD9_1	humic acid	9.55	24530 ± 80	-26,2 ± 1,1
ETH-45318.2	SD9_1	TOC	9.55	21980 ± 95	-35,1 ± 1,1
ETH-45321.1	SD10_2	humic acid	8,35	22955 ± 70	-26,2 ± 1,1
ETH-45321.2	SD10_2	TOC	8,35	23930 ± 95	-30,7 ± 1,1

Table 3.1. Comparison between ^{14}C ages obtained from humic acid and standard cleaned samples

At ENEA laboratory, a new system for CO_2 absorption and liquid scintillation counting (LSC) was designed and developed (Canducci et al., 2013). This method is based on the same basic principle as the benzene-LSC method, but the CO_2 produced from the sample combustion is directly absorbed into a suitable cocktail with high CO_2 affinity and immediately counted by LSC. This method results in significantly reduced analysis time and cost compared to the traditional method, and allows to analyze lighter samples (1/4 in weight). Unfortunately, the standard deviation of the ^{14}C Age obtained is still too much high to be used for chronostratigraphic purposes, and for this reason this method was not used in this work.

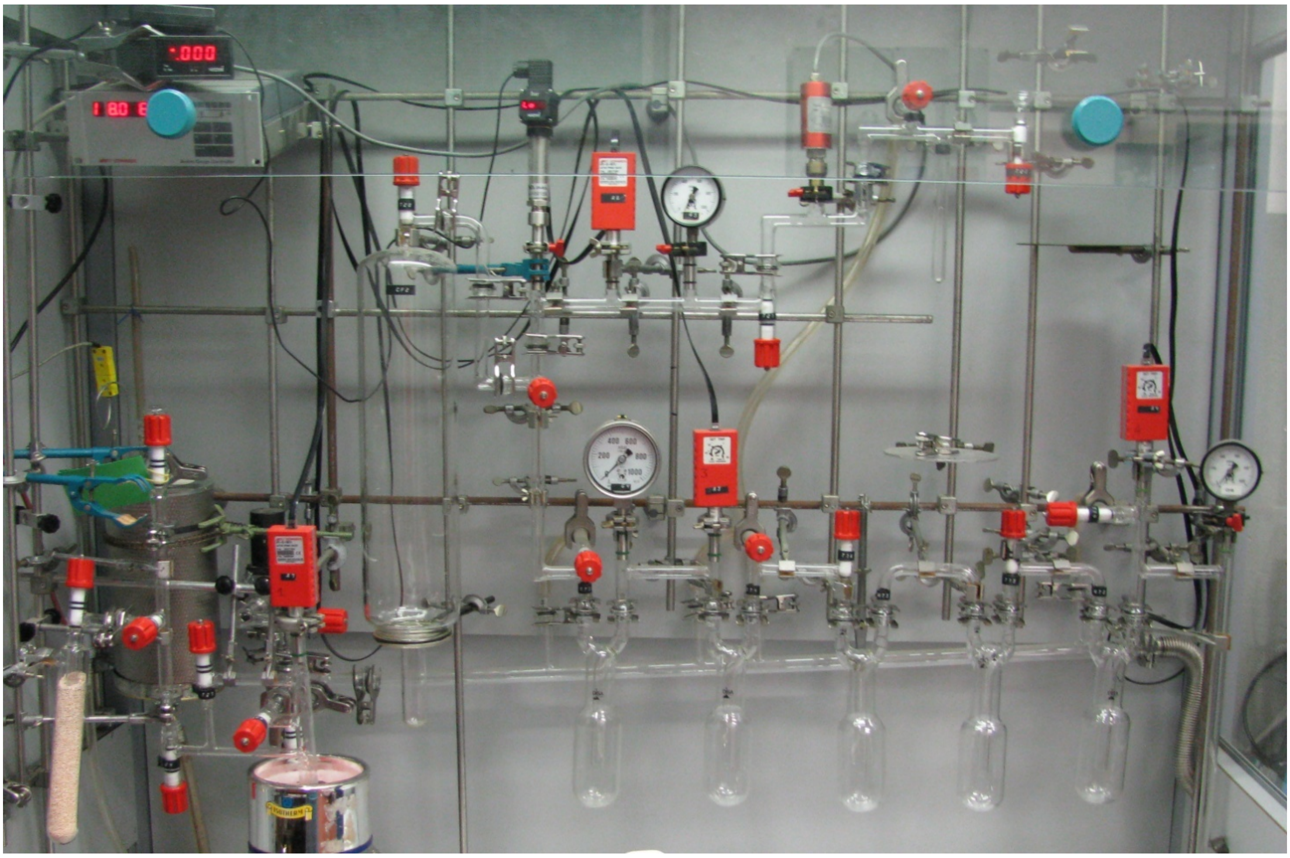

Fig 3.9. Vacuum line for the absorption of acetylene and synthesis of benzene, ENEA Laboratory, Bologna

Sixty samples were dated during this research project (Table 3.2), the majority of which (37 samples) at Ion Beam Laboratory. A total amount of 40 bulk sediment samples were dated; these were analyzed preferentially at ETH, due to the possibility of dating sediments even with low organic carbon content. Wood and peat samples were preferentially analyzed at ENEA Laboratory. Conventional ^{14}C ages obtained with both methods were calibrated with OxCal 4.1 and 4.2 (Bronk Ramsey 2009), using the Intcal-09 and Intcal-13 calibration curves (Reimer et al., 2009; 2013).

Laboratory	sediment	humic acids	wood	peat	charcoal	plant rests	total
ETH	27	4	1	0	2	4	37
ENEA	10	0	5	2	2	0	19
POZNAN	3	0	1	0	0	0	4
Total	40	4	7	2	4	4	60

Table 3.2. List of radiocarbon analyses executed during this research project.

4. PAPER SUMMARY

This study was carried out at various spatial scales, each characterized by specific data density. Ultra high-resolution stratigraphic reconstructions are useful to create depositional models that can be applied at larger scales. However, restricted areas of investigation may prevent the clear distinction between local and basin-scale forcing factors controlling the alluvial sedimentation. Thus, we used the extremely high concentration of data in the Bologna area to define in this region a well constrained stratigraphic (Paper 1) and geoarcheological (Paper 4) model. Subsequently, we expanded the area of investigation to verify the lateral persistency of this model (Paper 2) and place it tentatively into a source-to-sink (alluvial) context (Paper 3).

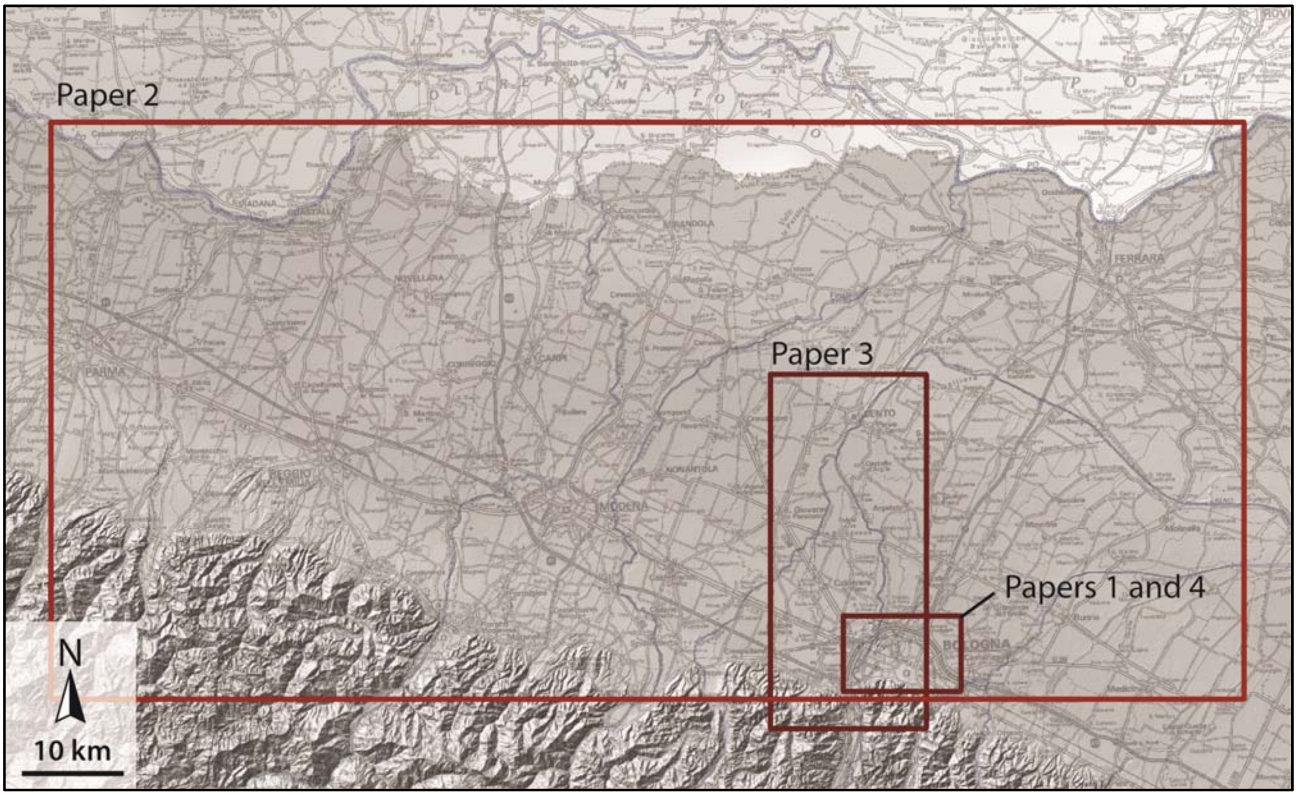

Fig 4.1. Study area of the four papers composing this thesis

Paper 1. **Paleosol architecture of a late Quaternary basin-margin sequence and its implications for high-resolution, non-marine sequence stratigraphy**

Amorosi A[1], **Bruno L[1]**, Rossi V[1] , Severi P[2] and Hajdas I[3]

Global and Planetary Change, 112 (2014) 12-25

In this paper, we provide a palaeosol-based, high-resolution stratigraphic reconstruction, on a millennial scale, of the Late Pleistocene-Holocene succession of the Bologna interfluve. The study has been prompted by the drilling of 12 continuous cores, advanced at depths of about 30 m, as part of the 6 km-long tunnel project for the Line 1 of Bologna Underground. Additional cores were acquired from a recently renovated area that hosts the new Bologna Municipality buildings. Accurate facies analysis on cores revealed the presence of repeated paleosol sequences. Detailed stratigraphic correlations between cores, ensured by 29 radiometric dates, testify that paleosols have great lateral extent and correlation potential and that can be used as stratigraphic markers within apparently homogeneous, mud-prone deposits. Radiocarbon dates enabled to assign an age and a time of exposure for each palaeosol. The chronological framework achieved suggests that vertical variations in palaeosol maturity can be consistent with short-term accommodation trends.

I performed facies analysis on three cores and participated in the construction and interpretation of the stratigraphic cross-sections and in drafting the manuscript. With the exception of four samples that were sent to the Poznan Radiocarbon Laboratory, I personally prepared and analyzed all samples for radiocarbon dating at Ion Beam (Zurich) and ENEA (Bologna) Laboratories.

Paper 2. **The value of pocket penetration tests for the high-resolution stratigraphy of late Quaternary non-marine deposits**

Amorosi A [1], **Bruno L** [1], Campo B [1] and Morelli A [1]

Submitted to *Sedimentary Geology*

In this part of the research we expanded the study area from 75 to 6750 km^2, to evaluate the lateral persistency, in a more distal position, of the palaeosol-stratigraphy depicted at the basin margin. To improve the data coverage of the study area (markedly lower than the one of the Bologna urban area) we tested a method to identify palaeosols even from poor lithologic core descriptions, based on the detailed analysis of pocket penetration profiles. We used three new cores as reference for facies analysis and 40 stratigraphic logs, bearing PPT values, provided by the Geological Survey of Regione Emilia-Romagna. Weakly developed palaeosols, with typical A-Bk-C profile, revealed to be overconsolidated horizons traceable over distances of 30 km, due to their peculiar penetration resistance signature. We verified that only a small proportion of palaeosol recognizable through pocket penetration analysis is generally identified in core by geologists with no specific sedimentological training. This study demonstrates that, through calibration with a limited number of core data, vertical profiles of pocket penetration values can be used as an inexpensive tool to significantly expand the coverage of well-described core data.

I participated in facies analysis of cores, in the reconstruction of the stratigraphic architecture and in drafting the manuscript. I prepared and analyzed the samples for radiocarbon dating.

Paper 3. **High-frequency depositional cycles within the late Quaternary alluvial succession of Reno River (Northern Italy)**

Bruno L [1], Amorosi A [1], Severi P [2] and Bartolomei P [4]

Submitted to the *Italian Journal of Geosciences*

We present in this work the Late Pleistocene-Holocene depositional architecture along the Reno River axis, from the intramontane valley to the lower alluvial plain (up to 30 km downstream of the valley outlet). We integrated background information on the Apenninic valley (river terraces) with new data on alluvial plain buried deposits. More than 60 stratigraphic logs and 70 radiocarbon dates compose the geological and chronological dataset. Palaeosol-based correlations enabled the identification of depositional sequences at the millennial time-scale within the post-Last Glacial Maximum alluvial succession. Each cycle, composed by overbank and fluvial facies sealed by a palaeosol, was correlated across the Apenninic margin to a specific single terrace of the Reno valley, and tentatively linked to the late Pleistocene-Holocene climate variations.

I performed facies analysis on cores and outcrops, along with radiocarbon dating. I constructed and interpreted the stratigraphic profiles and wrote the manuscript.

Paper 4. **Human-landscape interactions in the Bologna area (Northern Italy) during the mid-late Holocene, with focus on Roman period**

Bruno L [1], Amorosi A [1], Curina R[5], Severi P [2] and Bitelli R[6]

The Holocene, 23/11 (2013) 1560 - 1571

This paper is a geo-archaeological investigation of the mid-late Holocene deposits from the subsurface of Bologna. The aim of this paper is to unravel the complex relationship between the diffusion of human settlements, soil development/burial, and climate change. We integrated the previously tested methods of subsurface investigation, based on the lateral tracking of buried soil, with detailed archaeological information. Special emphasis was given to the period between the Iron Age and the Late Roman Period, for which a vast array of archaeological artifacts is reported. Archaeological data, historical documentation, and palaeosol-based stratigraphic correlations enabled the accurate reconstruction of the Roman topography, including natural (river network) and anthropogenic (road layout) elements. This paper documents the increasing impact of human activities on the environment, and in particular on fluvial systems during the Late Holocene, in a context of changing palaeoclimate.

I analyzed more than 700 archaeological reports and about 3000 stratigraphic log to reconstruct the Roman palaeo-topography. I performed facies analysis on cores and outcrops and radiocarbon dating. I constructed and interpreted the stratigraphic profiles and developed a first draft of the manuscript, with continuous confrontation with the co-authors.

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5. MANUSCRIPTS

Paper 1. **Paleosol architecture of a late Quaternary basin-margin sequence and its implications for high-resolution, non-marine sequence stratigraphy**

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Global and Planetary Change, 112 (2014) 12 - 25

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Highlights

- Paleosol stratigraphy is used to reconstruct alluvial architecture of a basin-margin sequence
- We document an example of high-resolution interfluve versus fluvial stratigraphy
- Immature paleosols are sequence stratigraphic markers on time scales of few thousand years
- Vertical changes in paleosol maturity are consistent with short-term accommodation trends
- Models of paleosol distribution from ancient rocks are extended to Quaternary counterparts

Abstract

Paleosol stratigraphy, a technique commonly applied in basin-margin settings to depict cyclic alluvial architecture on time scales of 10-100 ky, can be consistent with regional accommodation trends at even higher temporal resolution (1-10 ky), having strong implications for the sequence stratigraphy of late Quaternary, non-marine deposits. Three closely-spaced late Pleistocene paleosols (P1-P3), dating back approximately to 42-39, 35-31, and 29-26 cal kyr BP, respectively, form prominent stratigraphic markers across a lithologically homogeneous interfluve succession in the subsurface of Bologna, close to the Apenninic foothills. These paleosols are weakly developed (Inceptisols) and can be tracked continuously for 6 km across the triangle-shaped interchannel zone between two gravel/sand-filled channel systems (Reno and Savena rivers). In particular, the thickest paleosol (P3) is a distinctive stiff horizon that can be traced into laterally extensive, erosional-based fluvial bodies. We infer the correlation between (P3) soil development (and channel downcutting) and the final stage of the stepwise Late Pleistocene sea-level fall that culminated at the marine isotope stage 3/2 transition around 29 cal kyr BP (low accommodation systems tract). A fourth laterally extensive Inceptisol, encompassing the Pleistocene-Holocene boundary (PH), represents the major phase of soil development since the Last Glacial Maximum and is inferred to be related to channel entrenchment at the onset of the Younger Dryas. With the exception of the Iron Age-Roman paleosol, which reflects a predominantly anthropogenic control, the Holocene paleosols are laterally discontinuous and invariably more immature (Entisols) than their Pleistocene counterparts. This trend of decreasing paleosol development (and correlatability) upsection is interpreted to reflect increasing (transgressive-equivalent) accommodation during sea-level rise, thus confirming the possible extension of models used to interpret the ancient rock record to short-term depositional cycles.

Keywords: Paleosol, Sequence stratigraphy, Alluvial architecture, Interfluve, Late Pleistocene; Holocene

1. Introduction

Paleosols represent a powerful tool for stratigraphic correlations in alluvial plain deposits (Bown and Kraus, 1987; Platt and Keller, 1992; Wright and Marriott, 1993; Kraus, 1999; McCarthy et al., 1999; Trendell et al., 2012). With the advent of sequence stratigraphy, an increasing role has been given to paleosols as regional stratigraphic markers to trace genetic packages across sequence-bounding unconformities, on a variety of scales (Demko et al., 2004; Hanneman and Wideman, 2006; Ruskin and Jordan, 2007). In particular, paleosols that formed at interfluve sequence boundaries, adjacent to incised-valley systems (Van Wagoner et al., 1990; Aitken and Flint, 1996; McCarthy and Plint, 1998; Plint et al., 2001), are commonly regarded as one of the most prominent key components of non-marine sequence-stratigraphy.

Studies on pre-Quaternary paleosols have focused on soils that typically developed at the 3^{rd}-order (Wright and Marriott, 1993) or 4^{th}-order (McCarthy and Plint, 2003) scale, i.e. on temporal scales of tens of thousands of years (Plint et al., 2001) to hundreds of thousands of years. Within the Quaternary record, climatic and environmental evolution related to the astronomical timescale has been documented from continuous loess-paleosol sequences in several parts of the world, including central China (Kemp et al., 1995; Zhisheng and Porter, 1997), New Zealand (Berger et al., 2002) and Serbia (Marković et al., 2012). At these locations, loess-paleosol sequences have been observed to preserve an important terrestrial record of paleoclimate changes (Kemp et al., 2001; Tang et al., 2003).

Although the literature on paleosols formed during the last glacial-interglacial cycle (100 ka) is fairly robust, paleosol stratigraphy from the post-Last Glacial Maximum (LGM) deposits buried beneath the modern alluvial and coastal plains has received comparatively little attention. Cyclic paleosol-bearing successions falling in the sub-milankovitch band have been probably overlooked by both soil specialists and sedimentologists for a number of reasons: (i) owing to comparatively short time available for soil development, post-LGM buried soils generally fall within a single category (Protosols of Mack et al., 1993; Slightly developed soils of Duchaufour, 1982) or two (Entisols and Inceptisols of Soil Survey Staff, 1999) of soil evolution; (ii) stratigraphic reconstructions of post-LGM deposits and related soil characterization are mostly restricted to core analysis (Srivastava et al., 2010; Feng et al., 2011); (iii) autogenic and allogenic factors, which might potentially control alluvial architecture, show complex superposition on millennial time scales. With the exception of local studies carried out on the Rhine-Meuse system (Gouw and Erkens, 2007; Autin, 2008) and the Mississippi delta (Aslan and Autin, 1998; Autin and Aslan, 2001), the relationships between paleosol development and short-term sea-level and climate change during the last 30 kyr are still a poorly explored field.

The subsurface of Bologna (Fig. 1), at the northern margin of the Apenninic chain, represents an excellent site to help fill this gap. This area, for which conspicuous background stratigraphic information is available from river terraces (Picotti and Pazzaglia, 2008) and the adjacent alluvial plain (Amorosi et al., 1996), corresponds to a narrow, slightly elevated, triangle-shaped zone comprised between two adjacent fluvial systems (Reno River to the west and Savena River to the east) and fed by a system of small coalescing alluvial fans directly supplied from the hinterland. The area hosts an abundance of stratigraphic data (about 3,000 stratigraphic logs), stored in the Emilia-Romagna Geological Survey database, which ensures fine-scale data density and temporal resolution. The recent drilling of 12 continuous cores (1-12 in Fig. 1) as part of the 6 km-long tunnel project for the Line 1 of Bologna Underground yielded fresh, high-quality material for high-resolution stratigraphic correlations across the Bologna interfluve. Accurate core examination revealed the presence of thin, repeated paleosol sequences as the only stratigraphic marker within apparently homogeneous, mud-prone deposits. Additional cores were acquired from a recently renovated area that hosts the new Bologna Municipality buildings (cores 15-16 in Fig. 1) and from previously drilled boreholes (cores 13, 14 and 17 in Fig. 1). In this paper, we provide an example of palaesol-based, high-resolution stratigraphy on a millennial scale. Detailed stratigraphic correlations between cores were ensured by 29 radiometric dates and additionally supported by the Regione Emilia-Romagna stratigraphic database.

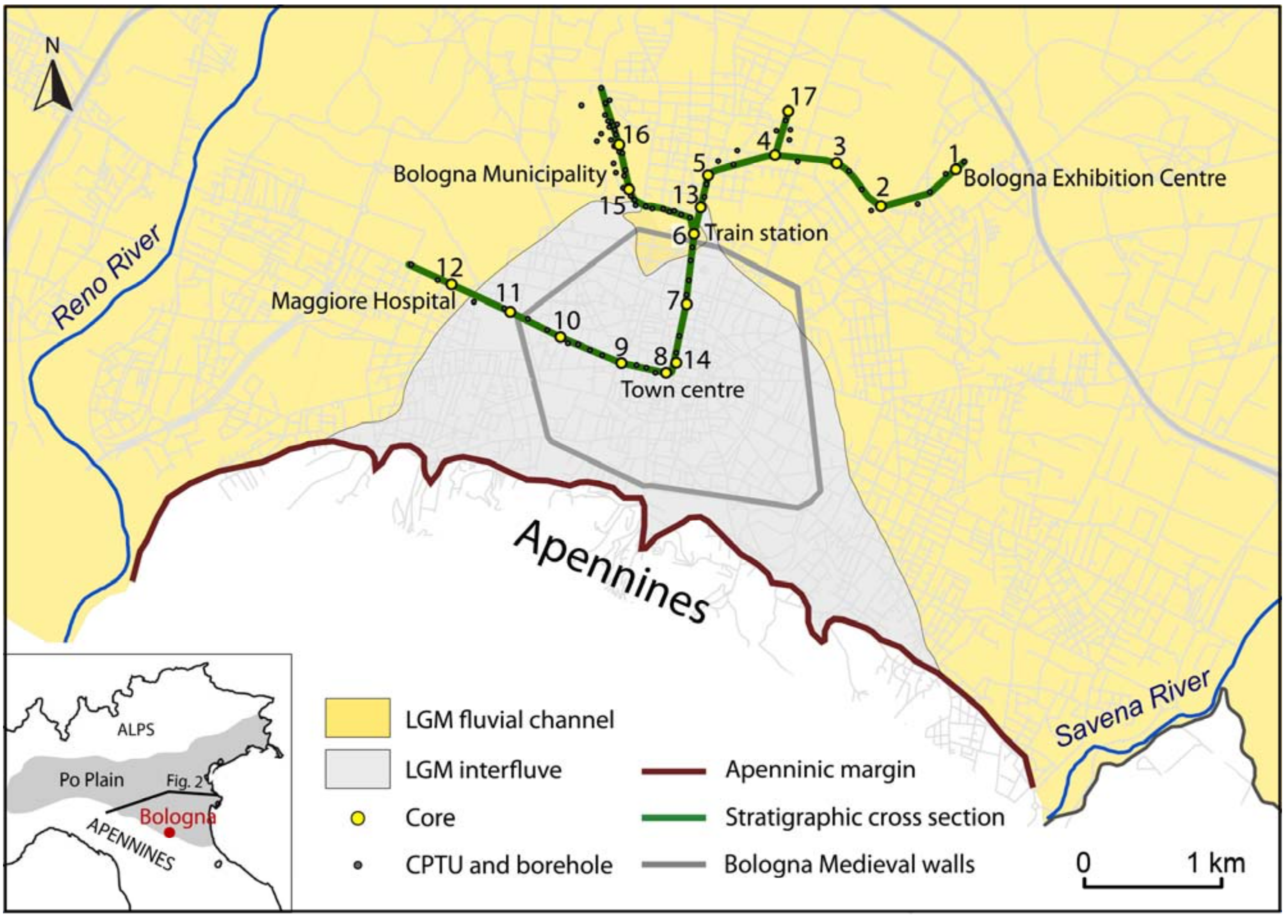

Fig. 1. Study area, with indication of the section traces of Figures 2 and 5-8. The boundaries of the Last Glacial Maximum (LGM) interfluve in the Bologna area are modified from Amorosi et al. (1997). Core 17 corresponds to Core P515 in Amorosi (2001).

2. Geological Setting

The Po Plain is the surface expression of a subsiding foreland basin, bounded by two fold-and-thrust belts, the Alps to the north and the Northern Apennines to the south. The Northern

Apenninic mountain front and its adjoining foothills are riddled with geological and geomorphological evidence of active tectonics, including growing folds and faults that collectively represent the near-surface structural response of the Adria-Europe convergence (Picotti et al., 2009). The low-relief Po sedimentary basin is intensely deformed by buried, north-verging thrusts (Pieri and Groppi, 1981; Regione Emilia-Romagna and ENI-AGIP, 1998), and the entire area is tectonically active (Carminati et al., 2003), with historical earthquakes up to magnitude 6.5 (Burrato et al., 2003). An ongoing tectonic activity characterizes the study area, as documented by the recent May 2012 (M 6.0) earthquake and its noticeable aftershock sequence, with an epicentre approximately 50 km NW of Bologna (Caputo et al., 2012).

The stratigraphy of the Pliocene-Quaternary basin fill has been depicted primarily through integration of seismic studies with well-log interpretations (Pieri and Groppi, 1981; Regione Emilia-Romagna and ENI-AGIP, 1998; Regione Lombardia and Eni Divisione Agip, 2002). These studies have led to the subdivision of the Po Basin fill into a series of unconformity-bounded stratigraphic units. Prominent cyclic facies architecture is the dominant feature of the Quaternary succession (Fig. 2), with transgressive-regressive (T-R) cycles representing the building block of subsurface stratigraphy (Amorosi and Colalongo, 2005).

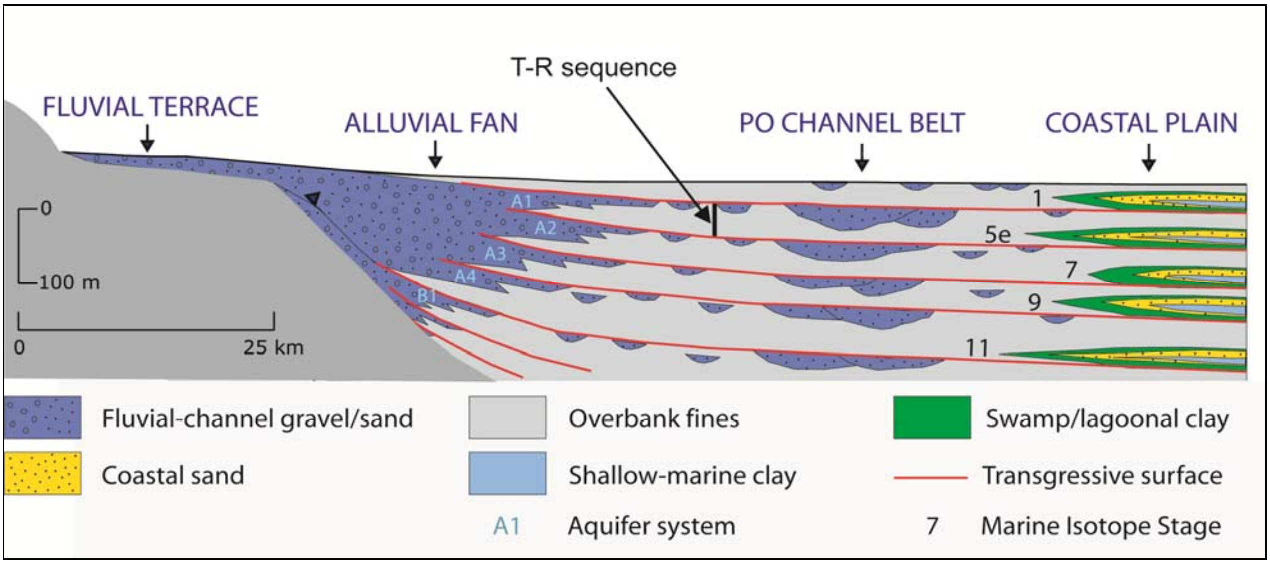

Fig. 2. The linkage between alluvial and coastal depositional systems as revealed by middle-late Quaternary deposits of the Po River basin (based on Amorosi and Colalongo, 2005). Updip tracking of the transgressive surfaces, from distal to proximal locations, allows stratigraphic subdivision into transgressive-regressive (T-R) sequences. Not to scale. For section trace, see Fig. 1.

On the basis of refined facies and pollen characterization, the T-R cycles have been observed to reflect Milankovitch-scale cycles falling in the 100 ky band (Amorosi et al., 1999; 2004; 2008). The transgressive surfaces are easily identifiable in the subsurface of the modern coastal plain, where they separate coastal to shallow-marine (interglacial) facies from underlying alluvial (glacial) deposits (Fig. 2). Close to the basin margin, where the Quaternary succession is made up almost entirely of alluvial deposits (Amorosi et al., 1996), the landward equivalents of these surfaces generally mark the abrupt boundary between laterally extensive fluvial bodies and overlying floodplain-dominated deposits (Fig. 2). Isolated gravel bodies, however, may commonly overlie the "transgressive surfaces".

Over the last decades, several studies have focused on the intricate Quaternary geology at the boundary between the northern Apenninic margin and the adjacent Po Plain (Castellarin et al., 1985; Boccaletti et al., 1985, 2004; Ghisetti and Vezzani, 2002; Benedetti et al., 2003), with a major focus on the Bologna area (Bertotti et al., 1997; Picotti and Pazzaglia, 2008). Quaternary deposits close to the Apenninic margin consist of locally coalescing fluvial gravel bodies (Figs. 1 and 2). At the outlets of the intramontane valleys, fluvial depositional systems are made up of amalgamated gravels, up to hundreds of metres thick, which grade basinward into rhythmical alternations of gravel/sand and mud alluvial bodies (Fig. 2). Overbank deposits in the lower parts of cycles include pollen diagnostic of warm-temperate climatic conditions, while the overlying fluvial bodies mark the transition to cold-climate (glacial) vegetation (Amorosi et al., 2008).

A reliable chronological framework for the middle-late Quaternary sedimentary cycles in the subsurface of Bologna is ensured by detailed pollen characterization of a 300 m-long core (Amorosi et al., 2001; see core 17 in Fig. 1), and its comparison with the coeval, well-known pollen record of changing climate from the Mediterranean area (Tzedakis et al., 1997). According to diagnostic vertical changes in pollen composition and consistent cyclic patterns of arboreal versus non-arboreal pollen, Amorosi et al. (2001) placed the MIS 6/5 transition in the Bologna area at 53 m core depth. At this stratigraphic level, a marked upward increase in pollen concentration is associated with the transition from shrubby-herbaceous communities with abundant *Pinus* to pollen indicating a major expansion of relatively thermophilous forests, with *Quercus* as the dominant tree.

The historical centre of Bologna, founded by the Romans in 189 BC, corresponds to the core of the Reno-Savena interfluve, which is today about 7 km wide (Fig. 1), with a relief of about 20 m above the adjacent fluvial systems. During the Last Glacial Maximum, the Bologna periurban area was periodically affected by laterally migrating channels, whereas no coarse-grained fluvial deposits have been reported from within the Medieval town walls, where stable interfluvial conditions persisted up to the present day (Amorosi et al., 1996; 1997).

3. Methods

Subsurface investigations were conducted through stratigraphic correlations between continuous cores borehole and piezocone penetration tests along two cross-sections (Fig. 1). The main cross-section follows the path of Line 1 of Bologna Underground, between Maggiore Hospital and the Bologna Exhibition Centre. This section is 5,500 m long and includes data from continuous cores 1-14, 25 piezocone penetration (CPTU) tests and 5 boreholes. It is made up of two W-E transects, linked by a S-N transect, which cross the historical centre. A shorter cross-section, 1,650 m long, was drawn in NW-SE direction through a recently renovated area that hosts the new Bologna Municipality (Fig. 1). This section, which intercepts the main section at the new Bologna Train Station, close to the Medieval walls (Core 6 in Fig. 1), consists of 38 stratigraphic logs including two additional continuous cores (15-16). This section has ultra-high data density, with average spacing of just 43 m.

Stratigraphic correlations were conducted on the basis of detailed facies analysis from 17 cores. A timeframe for the study succession was ensured by radiocarbon dating on a total of 29 core samples from organic matter, charcoal and woods (Table 1). In order to avoid contamination from drilling fluids, bulk samples were collected fresh from the innermost part of the core, then desiccated, grinded and passed through 0.05 mm sieves. Charcoal or macrofossils were extracted and dated separately. No optically stimulated luminescence (OSL) dating of sands was possible on the cores due to the bad preservation conditions. All samples were cleaned from contaminations through acid-alkali-acid pre-treatment. Twenty samples were AMS dated at Laboratory of Ion Beam Physics (ETH, Zurich, Switzerland), while other four were dated in Poznan Radiocarbon Laboratory. Five samples were dated at Bologna Enea Radiocarbon Laboratory using liquid scintillation counting and their ^{14}C concentration was measured with either liquid scintillation counting at Bologna ENEA Laboratory (Italy) or AMS technique at Poznan Radiocarbon Laboratory (Poland) and Laboratory of Ion Beam Physics (ETH, Zurich, Switzerland). The ^{14}C dates were calibrated with Oxcal 4.1 (Bronk Ramsey, 2009), using the Intcal-09 calibration curve (Reimer et al., 2009). Additional stratigraphic information derive from the stratigraphic database stored at the Geological, Seismic and Soil Survey of Regione Emilia-Romagna. Relative paleosol maturity was determined based on comparison with modern soils of the Po Plain (Regione Emilia-Romagna, 1999). The chronological framework benefited also from stratigraphic correlations and pollen data from Sheets 220 (“Casalecchio di Reno”) and 221 (“Bologna”) of the Geological Map of Italy (1:50,000 scale). For precise positioning of MIS 5 deposits (and older interglacials) based on pollen distribution, the reader is referred to Amorosi et al. (2001).

Core - location	sample	lab code	depth(m)	C14 age	cal years BP 2σ	dated material	depositional environment
4 - Bolognina	4_1	ETH-45298	4,35	2515±30	2740-2490	TOC	swamp
16 - Comparto R52	16_1	ENEA-956	7	4410±80	5145-4850	charcoal	floodplain
15 - Comparto R52	15_1	POZ-35947	9,2	4565±35	5190-5055	wood	fluvial channel
15 - Comparto R52	15_2	POZ-36012	11,3	6110±50	7160-6890	TOC	swamp
4 - Bolognina	4_2	ETH-45299	11,6	6505±35	7485-7410	charcoal	swamp
16 - Comparto R52	16_2	ETH-48056	7,6	7385±30	8325-8160	TOC	floodplain
13 - Matteotti	13_1	ETH-46107	10,5	9180±30	10420-10245	TOC	floodplain
8 - Piazza Maggiore	8_1	ETH-45313	5,4	9405±40	10735-10550	TOC	floodplain
12 - Malvasia	12_1	ENEA-931	9,4	9600±200	11410-10365	TOC	floodplain
4 - Bolognina	4_3	ENEA-948	12,5	10080±120	12060-11250	TOC	floodplain
16 - Comparto R52	16_3	ENEA-924	10,8	10170±270	12615-11145	TOC	floodplain
13 - Matteotti	13_2	ETH-45848	10,65	10210±35	12060-11770	TOC	floodplain
3 - Fiera	3_1	ENEA-947	11,65	11000±100	13110-12660	TOC	floodplain
2 - Fiera RER	2_1	ETH-45296	12,6	11110±30	13130-12810	TOC	floodplain
12 - Malvasia	12_2	ETH-45328	10,37	11375±45	13360-13130	TOC	floodplain
13 - Matteotti	13_3	ETH-45849	11,05	11680±35	13685-13390	TOC	floodplain
10 - Riva Reno	13_3	ETH-45320	6,8	15695±40	18985-18640	TOC	floodplain
16 - Comparto R52	16_4	ENEA-925	14	21550±180	26300-25080	TOC	floodplain
7 - Indipendenza	14_2	ETH-45307.2	9,55	21830±100	26720-25870	TOC	floodplain
9 - Ugo Bassi	9_1	ETH-45318.2	9,55	21980±95	26820-26015	TOC	floodplain
15 - Comparto R52	15_3	POZ-35948	14,4	22870±160	28100-26915	TOC	floodplain
10 - Riva Reno	10_2	ETH-45321.2	8,4	23930±95	29220-28375	TOC	floodplain
16 - Comparto R52	16_5	ETH-45650	16	26645±115	31310-30995	TOC	floodplain
11 - Saffi	11_2	ETH-45326	14,25	27035±105	31500-31140	TOC	floodplain
1 - Fiera Europa	1_1	ETH-45294.2	16,15	28550±110	33400-32385	TOC	floodplain
6 - Stazione	6_1	ETH-45303	13,45	29310±215	34590-33355	TOC	floodplain
8 - Piazza Maggiore	8_2	ETH-45315	13,9	30925±265	36300-34890	TOC	floodplain
15 - Comparto R52	15_4	POZ-36013	21,7	34200±600	40855-37580	TOC	floodplain
6 - Stazione	6_2	ETH-45305	19,4	36960±525	42655-41110	TOC	floodplain

Table 1. List of radiocarbon dated samples.

4. Sedimentary facies

Detailed core analysis enabled identification of five major facies associations on the basis of lithology, grain-size tendencies, contacts, accessory materials (organic matter, wood and macrofossils fragments) and geotechnical properties (CPTU tests).

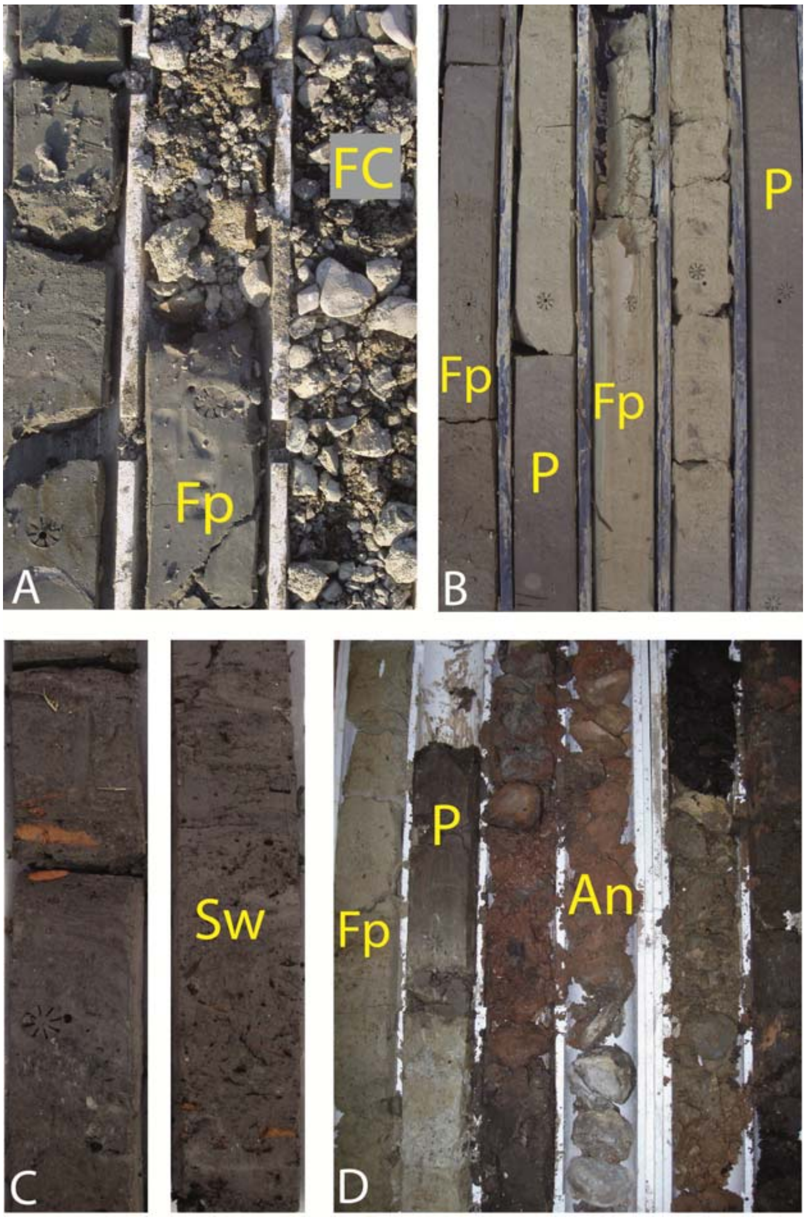

Fig. 3. Representative core photographs of Late Pleistocene-Holocene deposits in the Bologna area. A. erosional lower boundary of fluvial-channel gravels (FC) onto floodplain clays (Fp); Core 1. B. Paleosol-bounded (P) packages of overbank clays (Fp); Core 9. C. Organic-rich, swamp clay (Sw) with wood fragments; Core 2. D. Pedogenized (P) floodplain clay (Fp) overlain by a composite anthropogenic unit (An) recording distinct phases of human occupation (from the Iron Age to the Roman Period); Core 7. Core bottom is lower left corner. Core width in the photographs is 10 cm. For core location, see Fig. 1.

4.1. Fluvial-channel facies association (FC)

Description. This facies association consists of gravel and sand bodies, with erosional lower boundary (Fig. 3A) and marked fining-upward (FU) tendencies, with silty sand and silty layers at their top. The upper boundary to the overlying mud is either sharp or transitional. Clays are strongly subordinate. Gravel bodies range in thickness between 3 and 7 m, with local amalgamation up to 13 m, and consist of poorly sorted mixtures of calcareous cobbles and pebbles, with fine to coarse sand. Sand bodies are thinner (< 5 m), and may exhibit pebble layers at their base. Sedimentary structures, where preserved, include unidirectional, high-angle cross-stratification, a few dm thick, and sub-horizontal bedding. Rip-up clasts, woods and tree trunks are common accessory materials. Organic-rich layers may cap the FU succession. No fossils were observed in this facies association. Sand bodies have diagnostic piezocone test (CPTU) signature (Qc > 3 MPa), with distinctive upward decrease in tip resistance and remarkably low pore-pressure values. Cone penetration was stopped at top of gravel bodies.

Interpretation. The combination of lithology, thickness, erosional base, FU trend, sedimentary structures and accessory components enable interpretation of this facies association as fluvial-channel deposits. This interpretation is supported by the presence of unidirectional flow structures and abundance of floated wood within bar deposits. The characteristic FU tendency observed in core is confirmed throughout the study area by the upward decreasing tip-resistance values along with the low basal pore pressure values, this latter indicating higher permeability. The sharp versus transitional boundary to the overlying mud-prone deposits reflects either abrupt or gradual channel abandonment, respectively. In general, the amalgamated and poorly sorted gravel bodies with mostly unidirectional, high angle cross stratification are interpreted as the result of longitudinal/alternate? bar migration in a network of braided channels (Bridge, 1993; Miall, 1996). The thickest fluvial units are inferred to reflect superposition of individual lens-shaped bodies. Braided to meandering channel patterns have been described by Ori (1982) from (now buried) quarries 3 km west of the study area, where he observed gravel bodies with crude horizontal stratification, medium- to large-scale cross-stratification and laterally inclined (epsilon) bedding. The thinner and finer (sand) sediment bodies are interpreted to represent narrow, ribbon-shaped bodies formed in an aggrading alluvial plain.

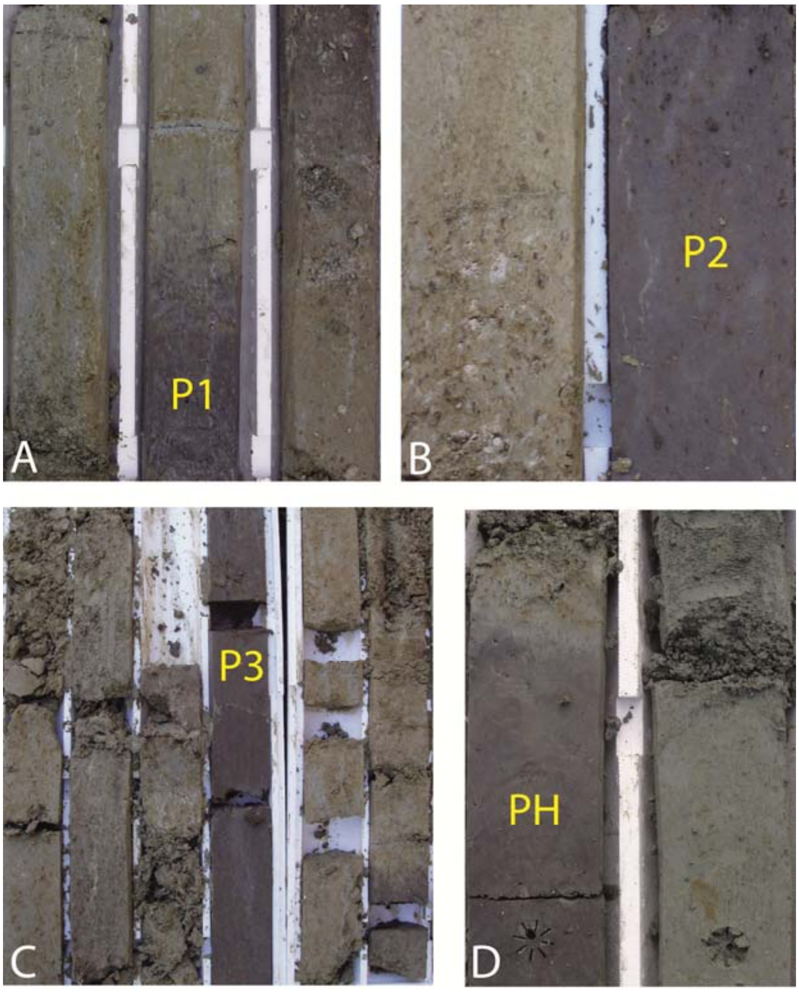

Fig. 4. Representative core photographs of Late Pleistocene Inceptisols (see Figs. 5-7 for stratigraphic overview). P1 is from Core 7, P2 and P3 from Core 10, PH from Core 3. Core bottom is lower left corner. Core width in the photographs is 10 cm. For core location, see Fig. 1.

4.2. Crevasse and levee facies association (CL)

Description. This facies association, 0.5 to 2 m thick, consists primarily of medium to coarse sand, with fine to very fine sand-silt intercalations. Sand bodies exhibit either FU trends, with erosional lower boundaries, or subordinate coarsening-upward (CU) tendencies, with gradual transition to underlying mud deposits. Rhythmical alternation of very fine sand and silt on a few cm to 20 cm scale is another common feature of this facies association. Sand-silt contacts are either sharp or gradational, and locally wavy. Horizontal lamination and small-scale cross-lamination are the most abundant sedimentary structures.

Interpretation. This facies association is interpreted to reflect a wide variety of depositional sub-environments formed as channel-related facies. Particularly, sand bodies with sharp lower boundaries and internal FU trends are interpreted as short-lived splay channels. These crevasse channels clearly differ from their fluvial counterpart by the significantly lesser thickness and grain size. On the other hand, CU silty sand to sand successions with gradational lower boundary are argued to represent crevasse splay deposits. Sand-silt couplets reflect traction plus fallout deposition in proximal overbank (natural levee) deposits. Where the sand-silt ratio is very low, these alternation are interpreted as distal levee deposits, reflecting decreasing flow strength with increasing distance from the channel axes.

4.3. Floodplain facies association with paleosols (Fp)

Description. This facies association, up to 10 m thick, is made up of a monotonous succession of thoroughly bioturbated, rooted and pedogenized silts and clays (Fig. 3B), with very subordinate sand intercalations, a few mm to cm thick. Mud is predominantly structureless, with faint horizontal lamination. A vertical sequence of weakly developed paleosols (Fig. 4), with Munsell colours falling in the 10yr, 2.5y and 5y range, is the typical feature of this facies association. Specifically, paleosols with A-Bw-Bk-C profiles can be identified and correlated between cores across wide distances, of several km (Fig. 5). Laterally extensive organic-rich layers (‘A’ horizons), 50-120 cm thick, are readily identified in core by their distinctive dark grey to black colours. ‘Bw’ horizons generally range from greyish brown to yellowish brown, while the ‘Bk’ horizons are typified by an enrichment in calcium carbonate nodules and display pale brown to yellowish brown colours (Fig. 4B). Paleosols with Ap-C profiles are generally less than 30 cm thick and show only incipient pedogenic modification, without well-developed horizonation. Cone tip resistance (Qc) in CPTU tests varies between 1.5 and 3.5 MPa. Paleosols display the highest Qc values, associated with the lowest pore pressure values.

Interpretation. Massive and pedogenized silt and clay deposits indicate low-energy depositional environments dominated by fallout processes, with common episodes of subaerial exposure. These features suggest deposition of overbank fines in an interfluvial setting. By comparison with modern soils from the same area (Regione Emilia-Romagna, 1999) paleosols with A-Bw-Bk-C profiles are interpreted as Inceptisols (Soil Survey Staff, 1999), while paleosols with Ap-C profiles and no horizonation are most similar to modern Entisols. The characteristics CPTU parameters recorded at these stratigraphic levels (compare with Amorosi and Marchi, 1999) represent peculiar features of indurated paleosols. Particularly, the low pore pressure values are due to cracking of these overconsolidated deposits during penetration tests.

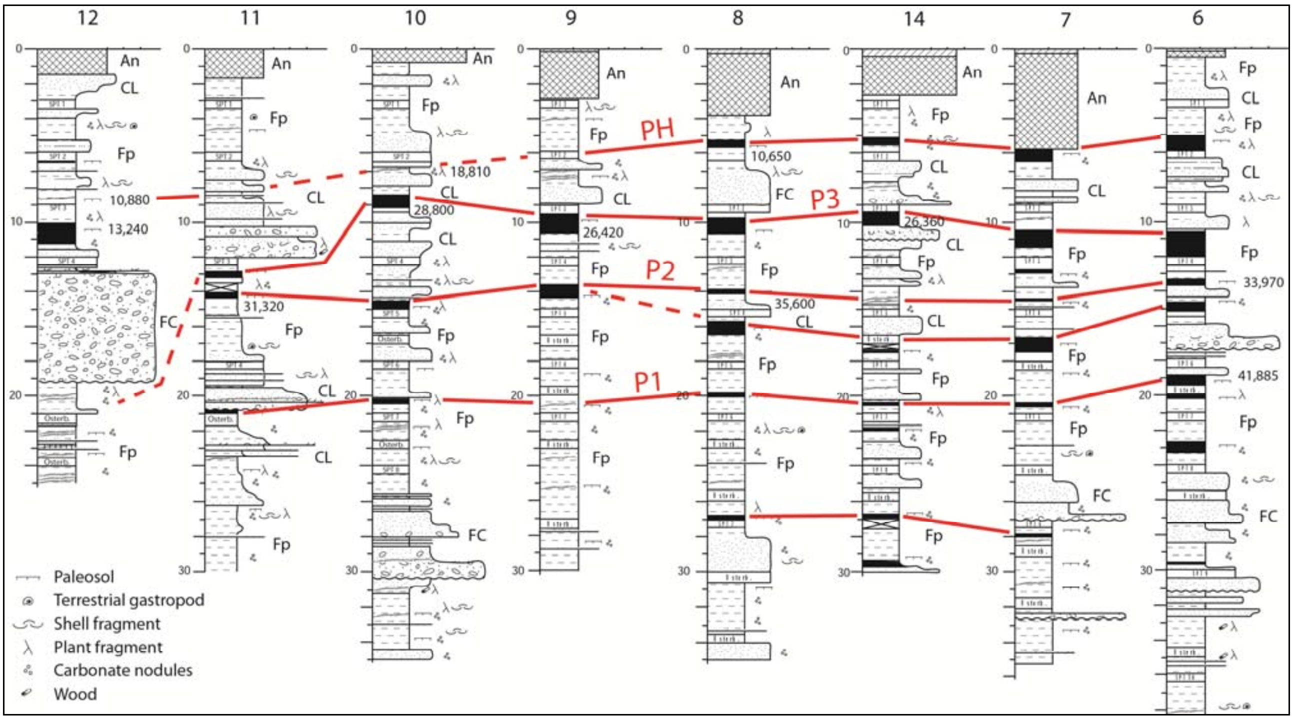

Fig. 5. Lateral tracking of three late Pleistocene paleosols (P1-P3) and the one marking the Pleistocene-Holocene boundary (PH) along a 3 km-long transect (see Fig. 1, for location). The thick 'A' horizon of paleosol P3 (in black) is the most prominent stratigraphic marker across the study area. The radiometric (2 sigma) error range associated with ^{14}C dates is given in Fig. 6. FC: Fluvial channel deposits, CL: Crevasse-levee deposits, Fp: Floodplain deposits, An: Anthropogenic deposits. SPT: Standard Penetration Test; Osterb.: undisturbed sample retrieved by means of Osterberg piston sampler. Horizontal distance between adjacent cores not to scale (for correct horizontal scale, see Fig. 6).

4.4. Freshwater swamp facies association (Sw)

Description. This facies association, less than 1 m thick, is made up of bioturbated, organic-rich soft clay with disseminated wood fragments. It can be easily identified by its dark grey to black colour. Peat layers are locally observed. These deposits are occasionally encountered atop fluvial-channel bodies or paleosols (Figs. 3C). Plant debris and terrestrial gastropods are common. Horizontal lamination is highlighted by subtle grain-size variations, from clay to silty-clay, or concentration of organic matter. Rare sand layers, a few centimetres thick, with sharp lower boundaries and fining-upward trends, are also observed. This facies association is typified by its peculiar geotechnical characteristics, showing extremely low Qc values (< 1 MPa).

Interpretation. Clay-dominated deposits associated to widespread peat development and terrestrial gastropods are interpreted to have formed in topographically depressed interfluvial areas, with high organic matter content and stagnant waters, such as ponds and swamps. The thin sand layers testify to occasional river floods.

4.5. Anthropogenic facies association (An)

This facies association, up to 6 m thick, is made up of chaotic, unconsolidated and unsorted deposits of different provenance. The coexistence of materials of both human (bricks, charcoal, plastic and iron fragments) and natural (sediment, wood) origin is the diagnostic feature of this unit. A vast array of artifacts (buildings, streets, cemetery sites, channels) testify to distinct stages of uninterrupted occupation between the Iron Age (and locally, the Late Bronze Age) and the Late Antiquity (Bruno et al., in press). These remains form a complex succession of stacked anthropogenic units that provides evidence for a sequence of settlements extending throughout the Roman Empire (Fig. 3D). These rests are commonly amalgamated with Late Medieval to modern artifacts (Bruno et al., in press).

5. Stratigraphic architecture

Detailed facies correlations between 17 continuous cores revealed the subsurface stratigraphic architecture of the Late Pleistocene to Holocene deposits of the Bologna area. The overall picture is strongly consistent with previous work (Amorosi et al., 1996; 1997), showing a clear-cut separation in terms of facies distribution between the historical centre and the adjacent areas (Fig. 6).

5.1. Stratigraphic architecture beneath the Reno and Savena rivers

The abundance of fluvial-channel bodies is the diagnostic stratigraphic feature of the Bologna periurban areas, west and east of the town centre (see Fig. 1). Outside the Medieval walls, highly contrasting net-to-gross ratios enable a two-fold stratigraphic subdivision of fluvial/overbank architecture. The Late Pleistocene portion of the study succession, about 15-40 m below the ground surface, consists of coarse-grained fluvial-channel bodies, 5-13 m thick, separated by a variable thickness (5-10 m) of overbank fines. The fluvial bodies are made up of multiple FU gravel and sand sequences, forming laterally extensive, highly interconnected tabular sheets (Figs. 6 and 7). The Holocene succession, roughly corresponding to the uppermost 15 m, records instead a significantly lower proportion of coarse-grained deposits, which are thinner (< 5 m) and appear as isolated channel bodies. At this stratigraphic level, a complex mosaic of floodplain, crevasse and levee facies associations is the dominant feature of alluvial architecture. Laterally extensive swamp deposits commonly mark the fluvial to overbank transition (Fig. 6, below).

Pollen spectra from Core 17 (Core P515 in Amorosi et al., 2001), 300 m north of core 4 (Fig. 1), provide a climate framework for this major change in stratigraphic architecture (Fig. 8). Particularly, the transition between laterally extensive fluvial bodies and the overlying floodplain succession records the dramatic climate change from glacial conditions, marked by the development of *Pinus* and shrubby-herbaceous communities (high NAP values in Fig. 8), to interglacial conditions, documented by the sudden development of warm-temperate forests (expansion of arboreal pollen, AP, in Fig. 8). It is thus apparent that laterally amalgamated fluvial-channel bodies, which suggest conditions of relatively low accommodation and high sediment supply (low accommodation systems tract), developed mostly during a period of generalized forest retreat, corresponding to the Last Glacial Maximum and the subsequent Late Glacial. The sharp upward transition from sheet-like fluvial-channel bodies to predominant swamp/overbank facies and its diagnostic pollen signature suggest that poorly drained floodplains developed in the study area at the onset of the Holocene, in response to rapid sea-level rise under warm-temperate climate conditions. During this phase, river channels were essentially non-migrating.

5.2. Interfluve stratigraphic architecture

A remarkably different facies architecture is reconstructed from beneath the Bologna town centre (Fig. 6). At this location, lack of thick fluvial-channel bodies clearly indicates that Reno and Savena rivers never reached this area during the late Quaternary. The Late Pleistocene deposits include a package of six paleosols that can be traced laterally for 5-6 km (Fig. 6). These paleosols occur in alternation with non-pedogenized silt and clay deposits, resulting in paleosol-bounded overbank cycles, 4-6 m thick (Fig. 5). The vertical stacking of dark-coloured paleosols and the tabular shape of the paleosol-bearing succession impart a distinctive colour banding to the Late

Pleistocene deposits (Figs. 4B and 5). Individual paleosols can be correlated over remarkable distances on the basis of core data, using a combination of stratigraphic position, radiometric dating, core observations (thickness, structure, colour) and physical properties (pocket penetrometer values, CPTU tests). Interfluve paleosols disappear when traced laterally over gravel to sandy channel bodies (Fig. 6).

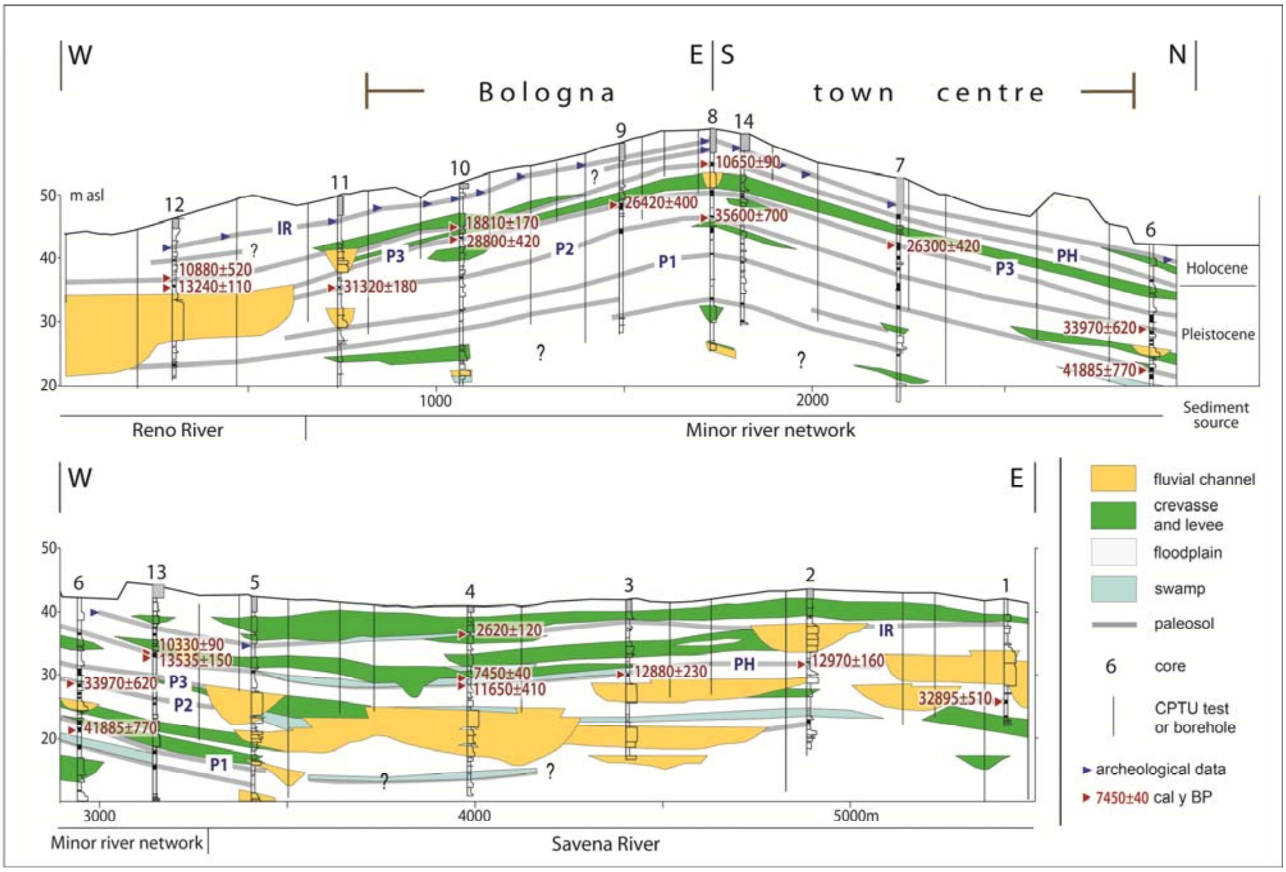

Fig. 6. Stratigraphic correlation panel across the Bologna interfluve along the tunnel project for the Line 1 of Bologna Underground (see Fig. 1, for location). For paleosol codes (P1, P2, P3 and PH) see text. IR: Iron Age-Roman paleosol.

The chronological framework in the study area is narrowly constrained by 29 radiocarbon dates, which strongly support the stratigraphic correlations based upon facies and geometric criteria (Figs. 5-7). Two out of six Late Pleistocene paleosols are beyond the chronologic resolution of radiocarbon dating (> 40 kyr in Fig. 6), and for this reason are not discussed in detail. In contrast, we focus here on the relatively younger four paleosols, for which a conspicuous number of radiocarbon analyses is available (Figs. 5-7). Based on radiocarbon dates, three paleosols are of late Pleistocene age (P1-P3), while the youngest paleosol (PH) encompasses the Pleistocene-Holocene boundary.

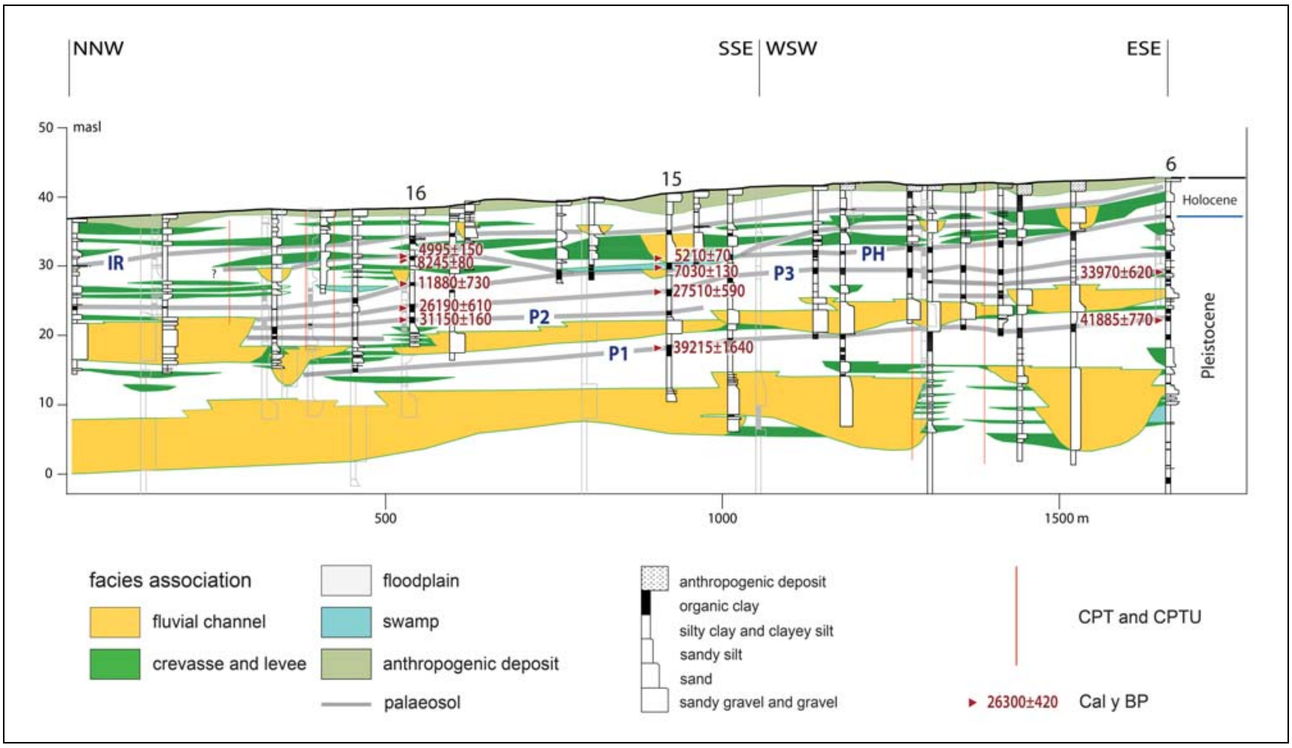

Fig. 7. Stratigraphic correlation panel beneath the new Bologna Municipality buildings. Codes as in Fig. 6. Projected data are shown as faint core logs.

Paleosols P1, P2, P3 and PH share many features in terms of maturity, colour, thickness and horizons (Fig. 4). In general, they exhibit fully developed Ap-Bw-Bk-C profiles, and for this reason classify as Inceptisols (Soil Survey Staff, 1999). Paleosols P1 and P2, dating back approximately to 42-39 and 35-31 cal kyr BP, respectively (Figs. 5-7), have similar characteristics, with 'A' horizons about 50 cm thick, and appear to bracket comparable intervals of time, on the order of 3,000-4,000 thousands of years. These paleosols are well developed in the Bologna area, whereas they are laterally truncated by fluvial-channel bodies beneath the modern Reno and Savena river systems (Figs. 5 and 6). Paleosol P3, dated to about 29-26 cal kyr BP (Figs. 5-7), is relatively more evolved, with significantly thicker (about 1 m – Fig. 4C) 'A' horizon. Finally, paleosol PH displays similar features as paleosols P1 and P2. Three samples from the 70 cm-thick 'A' horizon of paleosol PH from Core 13 in the Bologna train station area (Fig. 6) yielded radiocarbon ages between 13.5 and 10.3 cal ky BP (Fig. 9).

The Holocene paleosols differ significantly from their relatively more mature Pleistocene counterparts. They are discontinuous, calcic Entisols, with poor or no correlation potential (Fig. 5). The only exception is the Iron Age-Roman paleosol (Bruno et al., in press), which can be easily tracked throughout the study area on the basis of abundant archaeological remains (Fig. 6). This cultural horizon locally exhibits the characteristics of an Inceptisol. In this instance, however, soil maturity is not due to natural soil development, but reflects human interventions on the river network aimed at reducing flood damage.

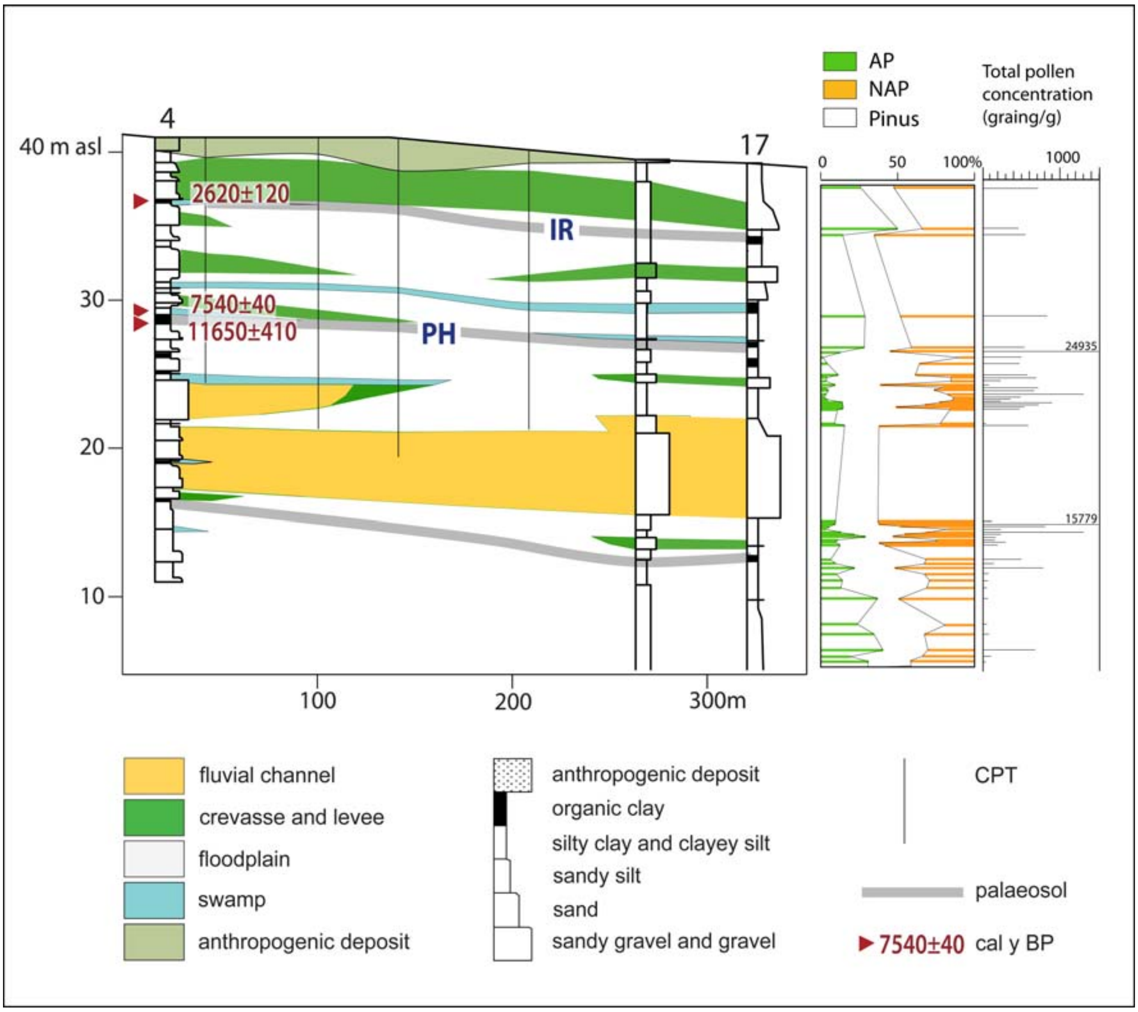

Fig. 8. Characteristic pollen profile of Core 17 (= Core P515 in Amorosi, 2001) and its correlation with late Quaternary stratigraphic architecture.

We are not able to reconstruct in detail the sediment dispersal pattern of the complex Reno-Savena interfluve, nor its evolution through time. Given the geographic position of the Bologna town centre, just in front of the mouth of five small creeks (Fig. 1), it is obvious that such small rivers acted as the only source of sediment for the entire interfluve. In this regard, the deposits related to the minor fluvial network are likely to represent the distal portion of small, coalescing alluvial fans.

	^{14}C Age	Cal y BP 2σ
13_3	9180±30	10330±90
13_2	10210±35	11910±150
13_1	11680±35	13535±150

Fig. 9. Radiometric dates across a single paleosol profile (PH in Core 13), bracketing about 3000 years. For sample codes, see Table 1. Core width in the photographs is 10 cm.

6. Paleosol development, sea-level history and accommodation trends

In this paper we presented a package of laterally continuous paleosols within an otherwise lithologically undifferentiated interfluve succession in the subsurface of Bologna. Most of these paleosols can be tracked physically for kilometers, and for this reason they represent powerful stratigraphic markers within the study succession. Two distinct packages of paleosols can be differentiated in the study area based largely on their degree of maturity and lateral extent. The three Pleistocene paleosols (P1-P3) and the paleosol marking the Pleistocene-Holocene boundary (PH) correspond to laterally continuous Inceptisols, whereas the Holocene paleosols are represented by highly discontinuous Entisols and Inceptisols.

As shown in the previous section, P3 represents the most developed paleosol in the study area, as also suggested by its thickest profile. We stress here the particular geotechnical features of this paleosol, which is a characteristic stiff, indurated horizon that separates relatively soft sediments from underlying, generally overconsolidated deposits (see also paleosols P1 and P2). Piezocone penetration test yielded a unique geotechnical signature for paleosol P3, being fingerprinted by remarkably higher sleeve friction values than the overlying deposits, concurrently with anomalously low pore pressure values (see Amorosi and Marchi, 1999).

Lack of OSL dates from the fluvial-channel bodies prevents from reconstructing in detail the complex relationships between paleosol development and the likely coeval phases of fluvial incision/aggradation of the Reno and Savena rivers. Given the cross-cutting relations between paleosols P1-P3 and the fluvial bodies (Figs. 6 and 7), it is reasonable to infer that multiple episodes of incision and lateral migration by the Reno and Savena rivers took place during successive phases of relative sea-level fall and lowstand, i.e., between > 40 and 26 cal kyr BP. During this period, erosion and deposition continuously redefined the shape of the Reno and Savena valleys (see the “valleys-that-never-were” model of Strong and Paola, 2008), west and east of the Bologna interfluve, respectively. As a consequence, the erosional surfaces at the base of the most laterally extensive fluvial bodies in both river systems are likely to represent highly diachronous features (Blum et al., 2013).

If plotted against the late Quaternary sea-level curve (Fig. 10), the development of P3 appears to be synchronous with the abrupt phase of sea-level fall (from -74 m to -107 m) that took place at the MIS 3/2 transition (Cutler et al., 2003). A primary influence of relative sea-level fall between the end of marine isotope stage 3 and the maximum period of valley incision (during isotope stage 2) has been invoked by Autin and Aslan (2001) to account for the higher maturity of terraced Pleistocene paleosols relative to their Holocene counterparts within the Mississippi meander-belt deposits of Louisiana. Fluvial valley incision probably culminating in the Late Pleniglacial has also been documented from several coeval coastal plain successions (Dabrio et al., 2000; Wellner and Bartek, 2003; Busschers et al., 2007; Blum et al., 2008; Kasse et al., 2010). We infer fluctuating water table dynamics as the possible mechanism for paleosol formation in the Reno-Savena interfluve (Bown and Kraus, 1981). Particularly, the lowering of the ground water table induced by river incision during phases of sea-level fall would have enhanced the flow of meteoric waters and subsequent leaching processes. Pedogenesis would have then stopped after few thousand years, probably in response to renewed sediment supply from the hinterland.

In a sequence-stratigraphic perspective, P3 represents an interfluve sequence boundary (Fig. 10). The sedimentary package of Pleistocene age that underlies P3, having formed during the final part of the generalized phase of sea-level fall that followed the last interglacial, constitutes the forced regressive systems tract (FST in Fig. 10) or the falling-stage equivalent of Atchley et al. (2004) and Cleveland et al. (2007).

A remarkable lack of pedogenesis typifies the Last Glacial Maximum and large portions of the subsequent Lateglacial period (Fig. 10). It is apparent that during this interval of time, which is materialized by lowstand fluvial-channel bodies (LST in Fig. 10), river incision was stopped and the Bologna periurban areas saw valley widening, lateral channel migration and channel-belt deposition. Tectonic subsidence during this period created new accommodation, which enhanced deposition of thick packages (> 15 m in Fig. 6) of amalgamated fluvial-channel deposits in valley position. At the same time, the Bologna interfluve experienced coalescence of small alluvial fan systems fed by the minor fluvial network (see the thin sand body sandwiched between paleosols P3 and PH in Fig. 5). Renewed pedogenesis took place between about 13.5 and 10.3 cal kyr BP, leading to the development of paleosol PH (Fig. 10). Similar to coeval alluvial systems, such as the Rhine-Meuse (van Balen et al., 2010; Janssens et al., 2012), this phase of channel downcutting, though not necessarily associated with soil formation, was possibly triggered by climate change at the Allerød-Younger Dryas transition.

The widespread development of paludal environments above PH during the early Holocene is interpreted to reflect the sedimentary response of the alluvial environment produced under the influence of the Holocene base-level rise (transgressive systems tract). This facies change reflects the evolution of subaerially exposed areas into topographically lower areas of active sedimentation, with development of freshwater swamps and ponds at the margins of the former interfluve (Fig. 6).

During the Holocene, sedimentation in the Reno-Savena interfluve was still decoupled from the fluvial activity of the adjacent two major rivers, being controlled instead by the activity of the minor river network in front of the modern Bologna town centre. Paleosol formation during this period was likely influenced by climatically driven changes in sediment supply from the hinterland. The thin immature paleosols with no well-developed horizonation (Entisols) reflect significantly lower time intervals (a few centuries?) over which soils developed during the Holocene. An exception are cultural horizons, such as the Iron Age-Roman paleosol (Figs. 6 and 7), the development of which was strongly controlled by human activities between the 9th century BC and 3rd century AD (Bruno et al., 2013).

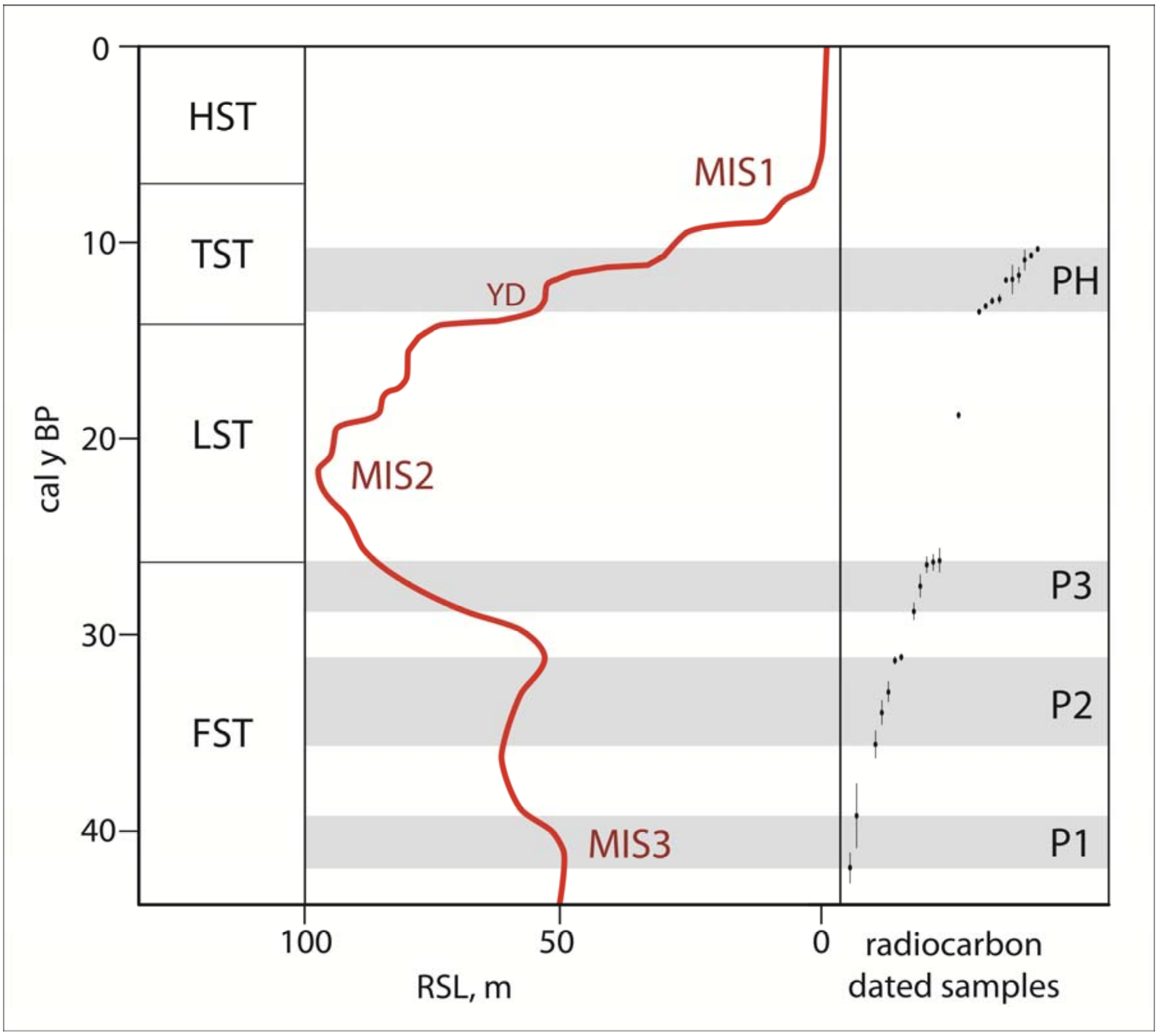

Fig. 10. Relationship between paleosol formation in the Bologna area and sea-level variations during the last 40 cal kyr BP. Reference sea-level curve is from Waelbroeck et al. (2002) and Liu et al. (2004). The stratigraphic position of radiocarbon dated samples is shown in Figs. 6 and 7.

The vertical changes in paleosol maturity observed within the late Quaternary deposits of the Bologna area are consistent with the regional accommodation trends. Pedogenesis mostly occurred during Late Pleistocene periods of base-level fall and valley incision (low-accommodation systems tract). Lower maturity of the overlying Holocene paleosols is inferred to reflect increasing (transgressive-equivalent) accommodation during rapid sea-level rise (Cleveland et al., 2007), with short-lived episodes of pedogenesis taking place in rapidly aggrading alluvial sub-environments. Under such conditions, paleosol maturity was likely governed by the complex interplay between autogenic depositional mechanisms, including channel avulsion (Bridge, 1984; Kraus and Aslan, 1999; Atchley et al., 2004; Stouthamer et al., 2010), and high-frequency climate variability, acting approximately on a similar (millennial) time scale.

As a whole, the relatively immature paleosols organized in paleosol-bounded packages described in this paper suggest that soil forming processes in the Reno-Savena interfluve took place over intervals of time of just few thousand years between successive flood stages. There is no indication throughout the interfluve of the highly weathered, reddish soil (Alfisol) related to the Last Glacial Maximum that crops out at the Po Basin margin and that has been related to a sedimentation break on the order of at least 10,000 years (*Suolo bruno fersiallitico* of Cremaschi, 1979 or Vignola Unit of Gasperi et al., 1987). This lack of a mature paleosol in the Bologna interfluve and the presence of paleosol-bounded packages suggests intermittently exposed soil horizons in response to discontinuous sediment supply from the hinterland.

This paper illustrates uniquely the stratigraphic aspects of the Bologna paleosols and does not expand upon their micromorphological features. Differences in organic preservation observed in paleosol 'A' horizons have been interpreted to be due to climatic control on rainfall, temperature, water table fluctuations and soil biota (Behrensmeyer, 1995). Given the cyclic pattern of paleosol/alluvial deposits and the age of pedogenesis, largely coeval with stadial 3 (Fig. 10), it is possible that the development of paleosols P1-P2 was induced, at least in part, by abrupt Late Pleistocene climate oscillations, such as the D-O cycles (Dansgaard, 1984; Bond et al., 1997; 1999; Schmidt and Hertzberg, 2011). However, owing to objective difficulties in correlation of morphological features in the fluvial record with specific short-term climatic events (see van Balen et al., 2010, for the larger Rhine-Meuse river system), this hypothesis cannot adequately be addressed, given the state of our observations and data.

In order to add substantially to our understanding of the Bologna paleosols, the characterization of the paleoclimatic and paleoenvironnmental conditions in which these paleosols formed becomes a major issue. Reliable reconstructions could be performed through detailed micromorphological studies (McCarthy et al., 1998; Hall and Anderson, 2000; Kemp et al., 2006; Srivastava et al., 2010) and whole rock geochemistry, aimed at establishing a quantitative ranking of paleosol development, with reconstruction of provenance, diagenesis, paleotemperature, paleoprecipitation and long-term chemical weathering (Sheldon & Tabor, 2009).

7. Conclusions

(1) Detailed reconstruction of facies architecture in the subsurface of Bologna, focused on 17 continuously-cored boreholes advanced at depths of about 30 m, documents the development of highly heterogeneous alluvial environments at the Apenninic foothills during the last 40 kyr. Close to the fluvial outlets, laterally extensive channel-fill deposits of Late Pleistocene age grade upwards into Holocene floodplain-dominated strata. The gravel-filled paleo-valleys are replaced on the interfluves by extensive overbank facies containing vertically stacked paleosol profiles.

(2) Paleosols represent stratigraphic markers with great lateral extent and correlation potential that can be used on the interfluves to delineate time-equivalent stratigraphic packages. The Late Pleistocene paleosol-bearing succession consists of multiple weakly developed paleosols (Inceptisols) separated by thin (3-5 m) alluvial sediments. Relatively protracted pauses in sedimentation typify the Late Pleistocene paleosols, which represent hiatal surfaces bracketing 3000-4000 years. Incipient weathering only (centuries to one thousand years) is recorded by the more immature Holocene paleosols.

(3) This study demonstrates that paleosols can be used to determine regional accommodation trends even on significantly shorter time scales than previously hypothesized. The Late Pleistocene Inceptisols of the Bologna interfluve are interpreted as having formed under conditions of low accommodation during the final stages of the Late Pleistocene sea-level fall. The most developed paleosol correlates to the abrupt phase of sea-level fall that marks the MIS 3/2 transition. More weakly developed paleosols (Entisols) characterize the post-glacial (transgressive-equivalent) succession, documenting the response of the fluvial system to rapidly increasing accommodation. Late Quaternary paleosol stratigraphy from the Bologna area thus may serve as short-term counterpart to non-marine sequence stratigraphy models developed on time scales of hundred thousand years.

Acknowledgements

This study is based on recent geological investigations undertaken for the construction of the Line 1 of Bologna Underground (AA). We are indebted to Dr. R. Ernione (GeoData, Turin) for supporting this study and for permission to publish data from cores 1-12. Thanks are also due to M. Simoni, for providing stratigraphic and radiocarbon data from the Bologna Municipality area (cores 15-16). We are strongly indebted to GPC reviewers, Freek Busschers and Giovanni Sarti, for their very constructive reviews.

Paper 2. **The value of pocket penetration tests for the high-resolution stratigraphy of late Quaternary non-marine deposits**

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Submitted to *Sedimentary Geology*

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Abstract

Pocket penetrometer measurements, though commonly listed as accessory components of core descriptions, are almost totally ignored in shallow subsurface stratigraphic analysis. In this study, we prove that, if properly calibrated with core data, pocket penetration tests may serve as a quick, inexpensive and powerful tool to enhance high-resolution (paleosol-based) stratigraphy of unconsolidated, late Quaternary non-marine deposits. A paleosol sequence, made up of 12 weakly developed Inceptisols dated to the last 40 ky cal BP, is reconstructed from the subsurface of the southern Po Plain. The individual palaeosols exhibit flat to slightly undulating geometries and can be tracked over distances of tens of km. They show substantially higher penetration values than all other fine-grained, alluvial (floodplain) facies, being typified by a distinct range of penetration resistance. Along the paleosol profiles, A and Bk horizons demonstrate consistent difference in relative compressive strengths, the highest values being invariably observed at the A/Bk boundary. Paleosols are rarely described in conventional stratigraphic logs, and just a small proportion of them is likely to be identified by geologists with no specific sedimentological training. Through core-log calibration techniques, we document that vertical profiles of penetration resistance can be used as a novel approach to identify paleosols, and may represent a strategy for predicting stratigraphic architecture from limited or poor-quality core descriptions. This technique allows to optimize the contribution of all available stratigraphic information, expanding significantly the coverage of well-described, one-dimensional core data.

Keywords: Pocket penetrometer; paleosol; alluvial stratigraphy; Quaternary; Po Plain

1. Introduction

Reconstructing the high-resolution facies architecture of the late Quaternary successions buried beneath the modern alluvial plains is an increasingly important issue for stratigraphic modeling of more ancient successions (Blum and Törnqvist, 2000; Blum et al., 2013). In shallow subsurface exploration programs, however, extensive core data are needed to obtain sufficient stratigraphic information, and drilling commonly represents the most expensive part of the whole exploration campaign. In this regard, the acquisition of a comprehensive dataset including all available stratigraphic information is essential to plan future investigations, and an appropriate level of detail of the stratigraphic description can have far-reaching implications for the success of a project.

In densely populated areas, such as modern alluvial and coastal plains, a large number of core descriptions is commonly available. However, the overall quality of this stratigraphic material may vary appreciably. Geotechnical core logging generally includes simple lithologic descriptions that are hardly suitable for facies interpretation and, consequently, for high-resolution stratigraphy. Delineating subsurface stratigraphy through indirect methods of subsurface investigation, such as those based upon geotechnical engineering properties of soils, may partly compensate for this lack of appropriate stratigraphic descriptions. The high potential of geotechnical data for the high-resolution stratigraphy of unconsolidated Quaternary deposits has been illustrated by Amorosi and Marchi (1999), who showed that piezocone penetration tests can be used for the detailed characterization of distinct coastal plain, deltaic and shallow-marine facies associations. The same technique was successfully applied by Lafuerza et al., (2005), Choi and Kim (2006) and Styllas (2014), proving to be useful for the high-resolution sequence stratigraphic analysis and three-dimensional reconstruction of alluvial to coastal successions.

Based on the same conceptual criteria, we document in this paper that, if proper calibration with core data is carried out, the use of simple pocket penetrometer resistance, a supplementary information normally available from most core descriptions, can be of use to a log analyst for stratigraphic profiling. Pocket penetrometer is a lightweight, handy tool that is commonly used for geotechnical purposes during coring operations. Its primary source of information is for evaluating consistency and approximate unconfined compressive strength. When pushing the loading piston into a freshly cut core, the pin encounters a force. A friction ring is taken along during this operation, which shows on the scale the maximum force that has been encountered. The direct reading scale, commonly ranging between 0 and 5 kg/cm^2 (up to 10), corresponds to equivalent unconfined compressive strength. Pocket penetrometer thus may provide almost continuous record of in situ properties of soils. This tool has been used for a reliable estimate of the effects of compaction on soil productivity (Steber et al., 2007), to estimate threshold friction velocity of wind erosion in the field (Li et al., 2010), and for stratigraphic and geotechnical investigations (Brideau et al., 2010).

Paleosols have long been recognized as key features for subdivision and mapping of continental strata (Joeckel, 1991; Kraus, 1999; Amorosi et al., 2014), and sequence-stratigraphic models have predicted the presumed position of paleosols within non-marine deposits (Van Wagoner et al., 1990; Aitken and Flint, 1996; McCarthy and Plint, 1998; Cleveland et al., 2007). In this paper, we demonstrate that late Quaternary paleosols can be identified on the basis of geotechnical properties generated from simple pocket penetrometer values (Bradford, 1980). The southern Po Plain, for which a paleosol-based stratigraphic framework has been recently made available (Bruno et al., 2013; Amorosi et al., 2014), represents an intriguing opportunity to investigate subsurface stratigraphy based on this approach. To this purpose, we selected a mud-prone, distal alluvial succession between the basin margin and the Po channel belt, with specific focus on the interfluve between Panaro and Reno rivers (Fig. 1). We strategically chose this area because of lack of laterally continuous fluvial bodies that could be utilized as stratigraphic markers.

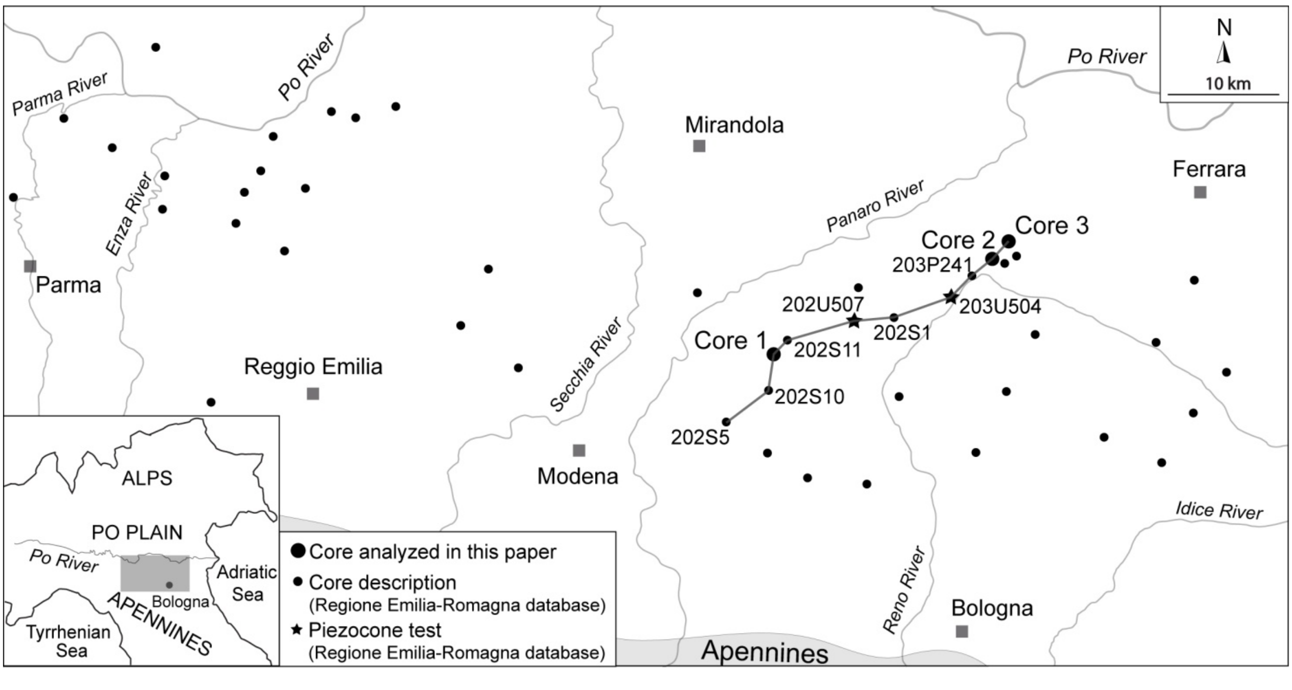

Fig. 1. Location map, with indication of the section trace of Figures 5 and 6. The Regione Emilia-Romagna core database was used for geotechnical characterization in Figure 7.

2. Regional geological setting

The Po Plain is a rapidly subsiding foreland basin, bounded by the Alps to the north and the Apennines to the south (Fig. 1). The formation of the Apenninic fold-and-thrust belt took place since the Late Oligocene (Ricci Lucchi, 1986; Boccaletti et al., 1990) in the framework of the collision of the European plate with the Adria microplate (Boccaletti et al., 1971; Ghielmi et al., 2013), when the sedimentary successions of the subducting margin of Adria were piled up to form the Apenninic accretionary prism (Carminati and Vadacca, 2010). The filling of the Pliocene-Pleistocene Apenninic foredeep has been estimated to exceed 7000 meters in the thickest depocentres (Pieri and Groppi, 1981). The North Apenninic frontal thrust system, buried below the southern margin of the Po Plain makes this area seismically active, as confirmed by the recent M 5.9-6.0 earthquakes of May-June 2012. Several active thrust faults have been recognized, such as the Ferrara and Mirandola growing anticlines, this latter with an uplift of ca. 0.16 mm/y in the last 125 ky (Carminati and Vadacca, 2010).

Extensive subsurface investigations carried out during the last two decades with the aim of establishing a general framework of aquifer distribution have led to accurate reconstruction of the large-scale, subsurface stratigraphic architecture of the Pliocene-Quaternary basin fill (Regione Emilia-Romagna and ENI-AGIP, 1998; Regione Lombardia and ENI-Divisione Agip, 2002). Six depositional sequences were identified south of Po River (Regione Emilia-Romagna and ENI-AGIP, 1998; Molinari et al., 2007) and four north of Po River (Regione Lombardia and ENI-Divisione Agip, 2002). These depositional sequences, recognized on a seismic basis and typically bounded by stratigraphic unconformities of tectonic origin, correspond to 3rd-order depositional sequences in the sense of Mitchum et al. (1977). The lower boundary of the uppermost depositional sequence (Po Supersynthem of Amorosi et al., 2008) has an estimated age of 0.87 My (Muttoni et al., 2003), and is partitioned into eight lower-rank depositional cycles (transgressive-regressive – T-R – cycles of Amorosi and Colalongo, 2005 – see Fig. 2).

Pollen characterization of the youngest two T-R cycles has documented a glacio-eustatic control on facies architecture, with a major influence of Milankovitch-scale eccentricity (ca. 100 ky) cycles (Amorosi et al., 1999, 2004, 2008). The T-R cycles are best recognized beneath the modern coastal plain and the delta, where typical transgressive-regressive coastal wedges form the transgressive and highstand systems tracts (TST+HST in Fig. 2). These shallow-marine bodies are separated by thick packages of alluvial deposits (falling-stage and lowstand systems tracts – FST+LST), the accumulation of which was favored by tectonic subsidence.

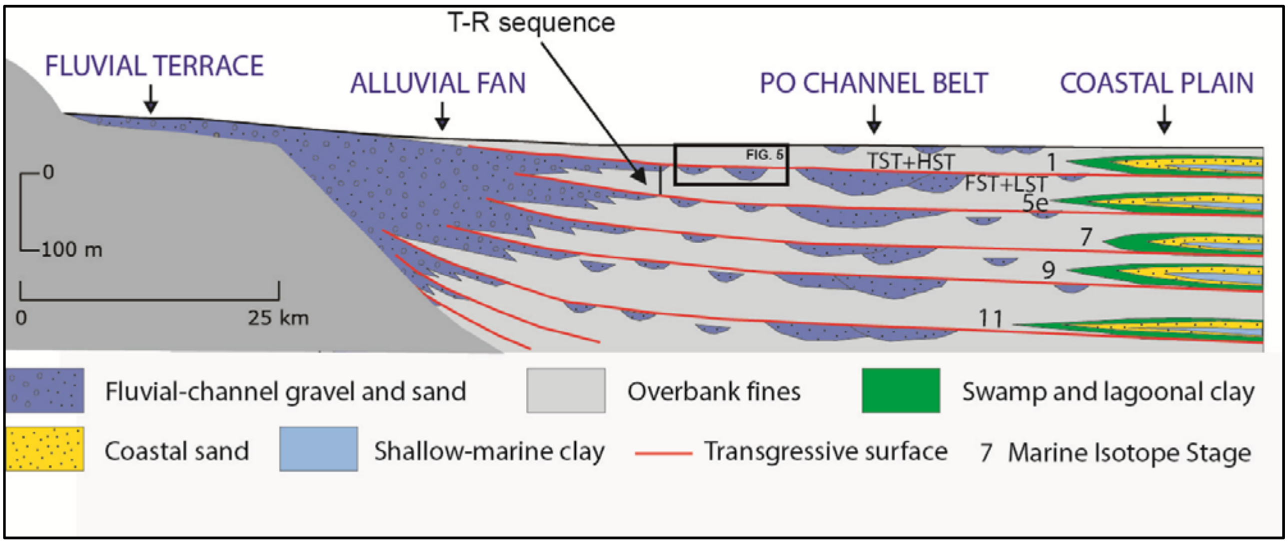

Fig. 2. Transgressive-regressive (T-R) cycles in the subsurface of the Po Plain and their sequence-stratigraphic interpretation. The red lines represent the transgressive surfaces. The lower parts of T-R cycles have a typical interglacial (transgressive/highstand systems tracts - TST+HST) signature, and are marked by diagnostic coastal wedges in lateral transition to mud-prone alluvial deposits. The upper parts of T-R cycles, formed under glacial conditions (falling stage/lowstand systems tracts - FST+LST), display increasingly amalgamated fluvial bodies. The black rectangle shows approximate position of the investigated area in Figures 5 and 6.

In proximal positions, close to the basin margin, the T-R cycles consist of basal overbank facies with isolated fluvial-channel sand deposits. Upwards, the fluvial bodies become increasingly abundant, amalgamated and laterally continuous. Based upon pollen data (Amorosi et al., 2008), the transgressive surfaces (or maximum regressive surfaces of Catuneanu et al., 2009) separate lowstand, glacial deposits from overlying deepening-upward successions formed under interglacial conditions. Landwards, these surfaces can be traced approximately at the boundary between laterally-amalgamated and isolated fluvial bodies (Fig. 2). The lower parts of T-R cycles are interpreted to represent the response of fluvial systems to rapid sea-level rise (equivalent of marine isotope stages 1, 5e, 7, 9 and 11, respectively, in Fig. 2).

3. Methods

In order to test our approach of using penetration tests for paleosol identification and high-resolution stratigraphic reconstructions, we selected a distal, mud-dominated portion of the alluvial plain, away from the influence of the major rivers (i.e., the Po channel belt) and far from the thick gravel bodies of the Apenninic margin (Figs. 1 and 2). Three freshly drilled cores from the Modena and Ferrara alluvial plain (Cores 1-3 in Figs. 1 and 3), 40-50 m long, were used as reference cores for facies analysis and paleosol characterization. We also selected 40 out of 250 detailed core descriptions from the database of Regione Emilia-Romagna Geological Survey from a wider area (Fig. 1). Lithology, color, and accessory components is the typical information available for each borehole. We adopted availability of the following key aspects as decisive for borehole selection: (i) pocket penetration values, (ii) color description, (iii) reaction to HCl, (iv) ^{14}C dating, (v) pollen data, (vi) photographs. Pocket penetration values, available uniquely from fine-grained (silt and clay) stratigraphic intervals, were stored in a specific database and plotted as vertical profiles on the individual logs. We adopted a 40 m cut-off to avoid effects of over-compaction on penetration values and, at the same time, to perform stratigraphic correlations within the time window of radiocarbon dating.

4. Sedimentary facies

In order to evaluate the relationship between depositional facies association and resistance to penetration, detailed facies analysis and pocket penetrometer measurements were undertaken on three cores (Fig. 3). Four facies associations were distinguished on the basis of grainsize trends, transition to the overlying and underlying units, color and consistency.

4.1. Fluvial-channel facies association

Description. This facies association is made up of coarse to medium sand bodies, up to 6 m thick, with erosional lower boundaries and internal FU trends (Fig. 4a). The upper boundary to the overlying muds is either sharp or gradational. Pebble layers and wood fragments are locally abundant in the lower part of the unit. No fossils were observed. Locally preserved sedimentary structures include unidirectional high-angle cross-stratification.

Interpretation. The combination of textural properties, FU tendency, erosional base and sedimentary structures enables interpretation of this facies association as fluvial-channel deposits. This interpretation is supported by the presence of unidirectional flow structures and abundance of floated wood. The sharp boundary to the overlying mud-prone deposits reflects abrupt channel abandonment, whereas transitional contacts suggest gradual abandonment. Simple core analysis does not allow subdivision of this facies association into depositional facies; for this reason, sand bodies are generically interpreted as bar deposits.

4.2. Crevasse and levee facies association

Description. This facies association consists of fine sand bodies, generally less than 1.5 m thick, and silts and silty sands alternating on a cm scale (Fig. 4b). The sand layers exhibit (i) sharp base and gradual top, with internal fining-upward (FU) trends, or (ii) gradual transition from the underlying muds, with sharp top and coarsening-upward (CU) tendency. Compressive strength values derived from pocket penetration tests measured on silt intervals are invariably < 2.5 kg/cm^2.

Interpretation. The high sand/mud ratio of this facies association is interpreted to reflect proximity to a fluvial channel. In particular, sand layers with sharp base and gradual transition to the overlying muds are interpreted to have been deposited in a crevasse channel, while sand layers with gradual base and sharp top are likely to reflect crevasse splays. Heterolithic units made up of silt-sand intercalations are interpreted as natural levee deposits, with sand proportion decreasing with increasing distance from the channel axis.

4.3. Floodplain facies association

Description. This facies association is made up of a monotonous succession, up to 9 m thick, of thoroughly bioturbated, variegated (5YR 8/1, 2.5Y 7/2-5, 5Y 6/1) silts and clays (Fig. 4b). Roots and plant rests are commonly encountered. Iron and manganese oxides are abundant. Sedimentary structures are absent, except for faint horizontal laminations. Concentration of organic matter is locally observed. Thin very fine sand beds with sharp base are occasionally seen. Pocket penetration values for this facies association commonly are in the range of 1.5 and 2.5 kg/cm^2 (average value 2.0 kg/cm^2).

Interpretation. Based on the dominance of bioturbated and oxidized muds, this facies association is interpreted to reflect background deposition of mud from suspension, in a low-energy, subaerially exposed depositional environment (floodplain). Local grey, organic-rich clays are likely to reflect areas of low topographic relief with poor drainage and high water table.

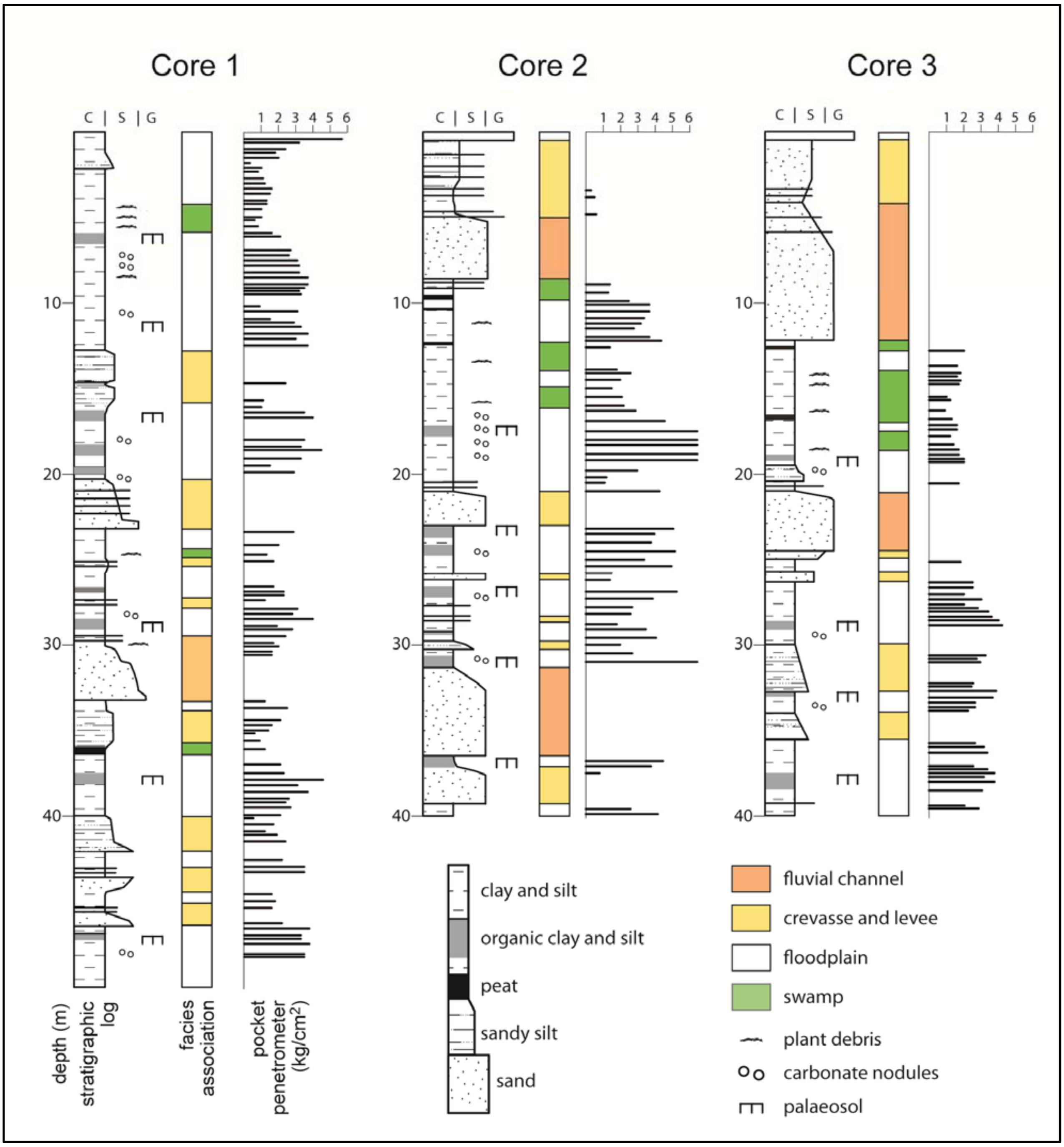

Fig. 3. Detailed stratigraphy of reference cores 1 to 3, with facies interpretation, pocket penetration profiles and stratigraphic position of the 15 paleosols identified.

4.4. Freshwater swamp facies association

Description. Soft gray and dark clay (7.5YR 7/1, 5YR 5/1), with subordinate silts and sandy silts compose this facies association, up to 1.8 m thick. Plant debris, wood fragments and peat layers are frequently encountered (Fig. 4c). Vertical variations in grain size, at a few cm scale, and thin organic-rich layers confer a characteristic horizontal lamination to this facies association. Extremely rare carbonate concretions are encountered. Iron and manganese oxides are absent. This facies association is typified by very low pocket penetrometer values, invariably lower than 1.2 kg/cm^2 (Fig. 3).

Interpretation. Organic soft clays with abundant plant rests are interpreted to have deposited in paludal environments under predominantly reducing conditions. Horizontal lamination is inferred to be the result of the progressive accumulation of organic material, interrupted by occasional flood events. Very low resistance penetration values reflect undrained conditions and submergence. Temporary phases of subaerial exposure, with consequent lowering of the water table, are inferred to have been responsible for the hardening of the clay and the formation of scattered carbonate concretions.

4.5. Paleosols

Description. Visual and manual examination of cores 1-3 with respect to color, texture and plasticity led to recognition of 15 relatively stiff clay horizons, intercalated at various stratigraphic levels within floodplain deposits (Fig. 3). These clay horizons are commonly recognized by their dark, brownish (10YR 3/2, 2.5Y 3/1) color. The organic clay overlies, with gradual transition, lighter (10YR 8/2, 2.5Y 8/2), bioturbated clays and silts, rich in carbonate concretions (Fig. 4d-e). The organic horizons and the associated carbonate-rich clays are typified by substantially higher penetration values than those recorded in the adjacent floodplain clays (Fig. 3). In particular, the darker horizons display average values of compressive strength around 3.5 kg/cm^2, while the underlying carbonate-rich horizons are even more consolidated (average penetration values 3.9 kg/cm^2). An abrupt increase in compressive strength, of at least 1 kg/cm^2, commonly marks the upper boundary of the organic layers (Fig. 3).

Interpretation. The indurated horizons are interpreted as weakly developed palaeosols (Inceptisols of Soil Survey Staff, 1999), marking short-lived phases of subaerial exposure. The indurated, organic dark clays are interpreted as A horizons, while the underlying carbonate-rich clay are inferred to represent Bk or calcic horizons. Overall, pedogenic features suggest that these paleosols were subaerially exposed for periods of a few thousand years.

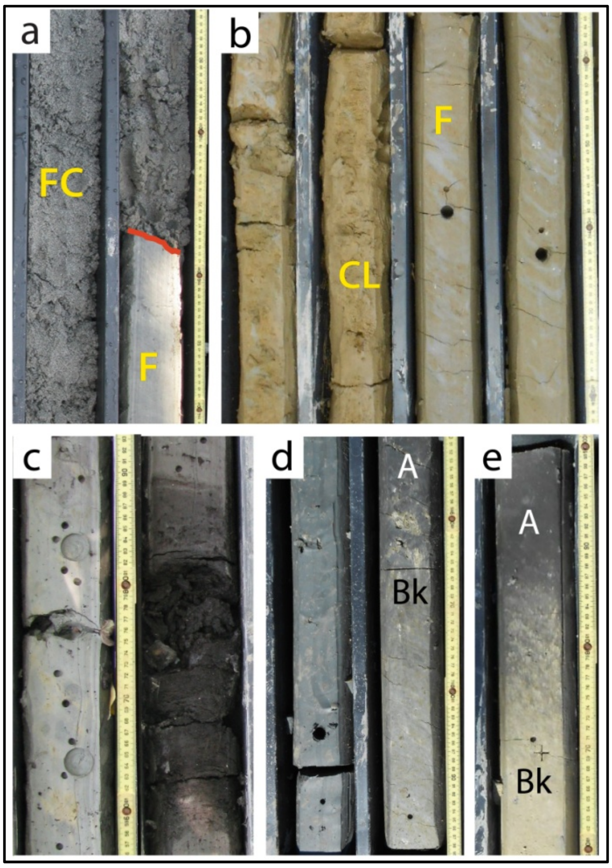

Fig. 4. Representative core photographs of the study succession. A. Erosional lower boundary of a fluvial-channel (FC) sand body above floodplain (F) clays; B. Example of alluvial plain deposits, with differentiation of crevasse/levee (CL) and floodplain (F) facies associations; C. Freshwater swamp clays and peat. D. Inceptisol with diagnostic A/Bk horizons within floodplain silts and clays. Core 2, 17-18 m depth (see paleosol D in Fig. 6); E. Close-up of an Inceptisol. Core 2, 27 m depth (see paleosol G in Fig. 6).

5. Stratigraphic architecture

Reconstructing the stratigraphic architecture of distal alluvial plain successions is a very difficult task. In this context, where the lack of laterally continuous stratigraphic markers represents a strongly inherent limitation to stratigraphic correlations, low data density and poor-quality stratigraphic data may even prevent successful estimation of subsurface alluvial architecture.

Subsurface stratigraphy along an approximately SW-NE oriented, 30 km-long transect was tentatively reconstructed based on accurate facies analysis of three continuous cores (1-3 in Figs. 3 and 5) and with the aid of five basic stratigraphic descriptions. Stratigraphic data from these latter were converted to facies association (Fig. 5) using sedimentological concepts that included the combined interpretation of simple lithologic information and a list of accessory components. Eight radiocarbon dates represent chronologic constraints for stratigraphic correlation.

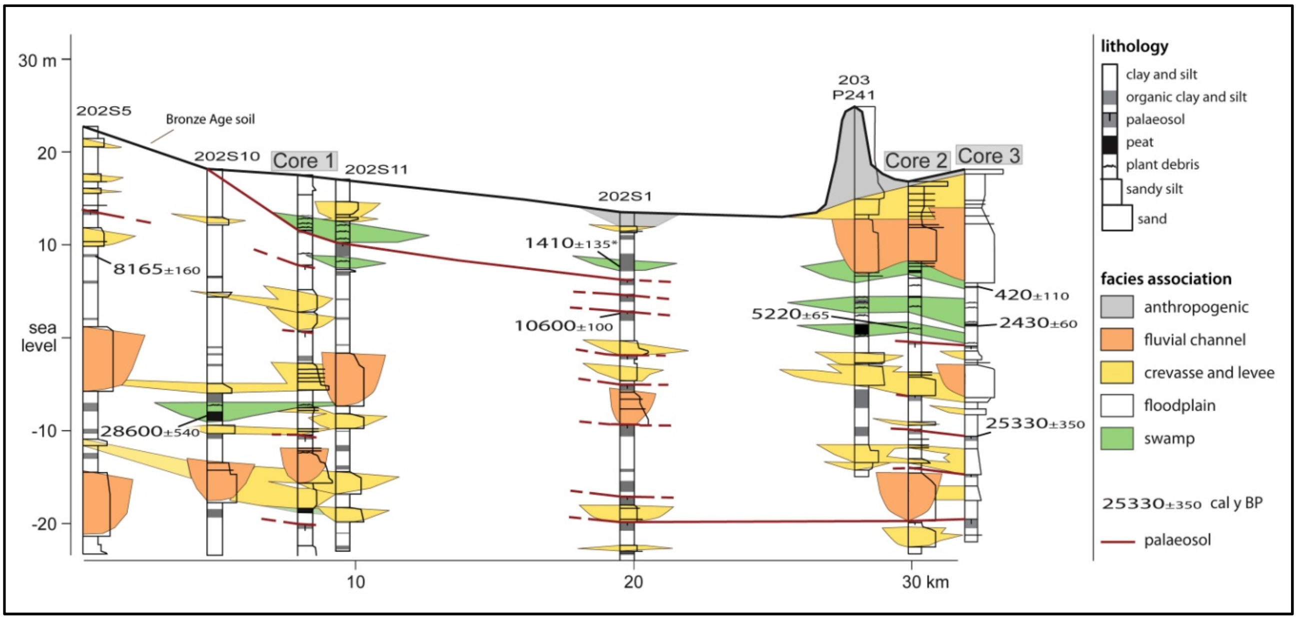

Fig. 5. Stratigraphic correlation panel across the study area (see reference cores 1-3), showing facies architecture of distal alluvial plain deposits. Note that paleosols are poorly identified in standard core descriptions, with the sole exception of core 202S1. For section trace, see Fig. 1.

Strong uncertainties associated with stratigraphic correlation affect the accuracy of facies architecture reconstruction in Figure 5, for which several alternative stratigraphic scenarios could be generated on the basis of the data available.

As a whole, a marked change in fluvial architecture is observed across the Pleistocene-Holocene boundary. The highest proportion of fluvial-channel bodies is recorded in the Pleistocene succession. Individual bodies are generally 3-8 m thick and appear to cluster at distinct stratigraphic levels. Instead, fluvial bodies are mostly isolated in the overlying Holocene section, where they are associated to an abundance of swamp deposits (Fig. 5).

The greater lateral continuity of the late Pleistocene fluvial-channel deposits suggests deposition during phases of increased sediment supply and slowed accommodation. Based on the age of these deposits, roughly embracing the Last Glacial Maximum, we assign the major sand bodies to the lowstand systems tract (LST – see Fig. 2) and late forced-regressive systems tract. However, owing to poor data coverage (average borehole spacing is ca. 4 km, i.e. remarkably greater than the width of the individual channel bodies), we cannot constrain precisely the lateral extension of fluvial sand bodies, neither their hypothetical connectivity. As a consequence, channel-belt geometries in the cross-sections of Figure 5 represent a main uncertainty, and are highly speculative.

Upwards, the abrupt change from laterally amalgamated, sheet-like sand bodies, with possible high degree of interconnectedness, to predominantly muddy units, with mostly isolated, ribbon-shaped sand bodies, reflects a sudden drop in the sediment supply/accommodation ratio (Dreyer, 1993; Shanley and McCabe, 1994; Martinsen et al., 1999), which may testify the sedimentary response to the Holocene sea-level rise (cf. Olsen et al., 1995). In terms of sequence stratigraphy, this part of the sedimentary succession includes the TST+HST (see Fig. 2). The Holocene age of this section and the abundance of wetland deposits, suggesting relative proximity to the shoreline, support this interpretation.

Paleosols, a distinctive stratigraphic feature identified within reference cores 1-3 (see Figs. 3 and 4), appear to have been generated on floodplain muds and seem to alternate rhythmically with non-pedogenized, heterolithic intervals of small channel belts and crevasse/overbank facies. However, owing to limited paleosol identification in pre-existing data, with just one exception (core 202S1 in Fig. 5) paleosols can be traced as highly discontinuous features, and hence they are hardly utilizable as stratigraphic markers.

6. Inferring paleosols from conventional core descriptions

It is readily apparent from the stratigraphic panel of Figure 5 that conventional core descriptions have considerably lower potential for cross-correlations than sedimentological core descriptions (see reference cores 1-3 in Fig. 3), since in the former key features for alluvial architecture, such as paleosols, can be easily missed. In this context, specific physical characteristics and engineering properties that can be extracted from routine core descriptions, including simple analysis of pocket penetration values, appear as a powerful tool to reduce significantly stratigraphic uncertainty. With specific reference to the Inceptisols identified in cores 1-3, attributes that are commonly listed in geotechnical core descriptions, and that could be used for paleosol identification include (Fig. 3):

(i) Color. The immature paleosols identified in the study area have dark colored 'A' horizons underlain by lighter, calcic 'Bk' horizons (Fig. 4d-e). These diagnostic dark/light couplets can often be deduced from conventional stratigraphic descriptions

(ii) Soil reaction to hydrochloric acid. In the Regione Emilia-Romagna classification (0: no reaction to HCl; 4: maximum reaction, i.e., carbonate content > 10%), the 'A' horizons fall invariably in the lowest class (0), while the underlying 'Bk' horizons show the highest values of soil reaction (class 4). When a '0' class directly overlies a '4' class, it is likely that these adjacent layers represent an Inceptisol

(iii) Diagnostic high penetration values. A wide range of strength values typifies the alluvial succession investigated in this study. However, while non-pedogenized floodplain deposits invariably display pocket penetration values lower than 3 kg/cm^2 (average value 2.0 kg/cm^2 - Fig. 3), the 15 paleosols recognized in cores 1-3 display average values of 3.5 kg/cm^2 (A horizon) and 3.9 kg/cm^2 (Bk horizon), respectively (Fig. 3).

Re-examination of pre-existing stratigraphic logs on the basis of the above features, with the aid of sedimentological concepts and special emphasis on vertical pocket penetration profiles, resulted in identification of a significantly higher number of potential paleosols. The correlation panel of Figure 6, which traces out the same cross-section of Figure 5, highlights the influence of penetration test interpretation on well-to-well paleosol correlation. If plotted as vertical profiles, pocket penetration values reveal a clearly defined set of stiff, overconsolidated horizons within alluvial deposits, where compressive strengths are generally > 3 kg/cm^2, and across which penetration values show abrupt increase of about 1 to 2 kg/cm^2 (Fig. 6). Paleosols recognized by pocket penetration values are well correlatable with those identified in cores 1-3 (Fig. 6).

Twelve prominent Inceptisols (A to L in Fig. 6) represent the key stratigraphic features of the study succession: they display relatively flat to slightly undulating geometry and can be tracked tentatively over distances of tens of km on the basis of pedogenic features, stratigraphic position and radiometric dating. In general, paleosols identified via pocket penetration values represent laterally extensive stratigraphic markers that can be used for bracketing packages of stratigraphic significance.

The resulting paleosol-bounded depositional units are approximately 3-5 m thick, and appear to have been developed during time intervals of a few thousand years. In this stratigraphically realistic scenario, where paleosols are used to guide interpretation of facies distribution, channel bodies appear to be clustered at specific stratigraphic intervals (Fig. 6), hence providing the basis for detailed reconstruction of channel migration pathways through time. When traced laterally over lenticular fluvial bodies, paleosols become progressively less pronounced, seem to merge, and finally disappear (Fig. 6). Unfortunately, limited data density hampers the accurate investigation of the relationships between paleosol formation and channel-belt development.

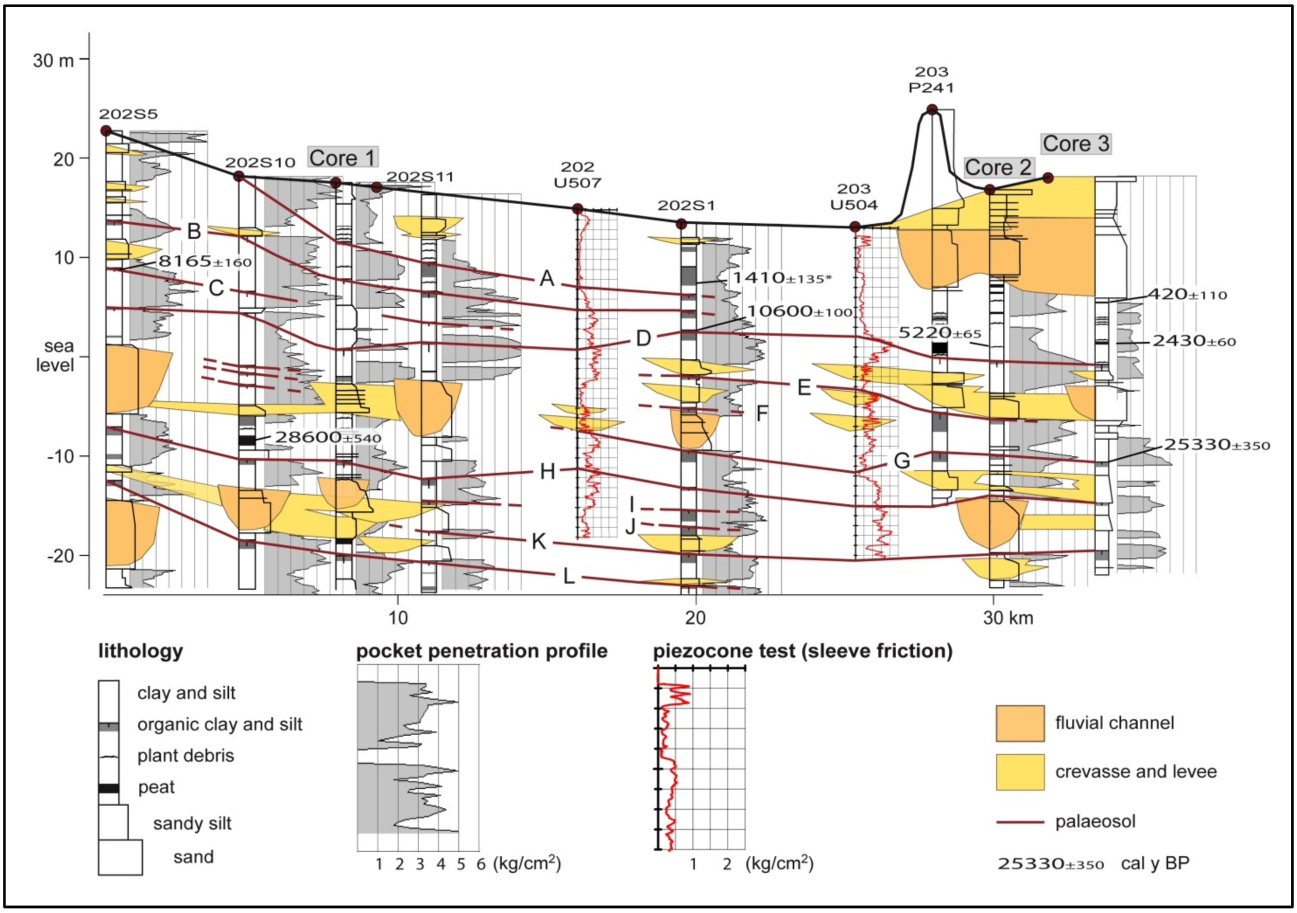

Fig. 6. Example of paleosol-based stratigraphy, following re-interpretation of core descriptions based on pocket penetrometer profiles and eight radiocarbon dates (same cross-section as Figure 5). The asterisk indicates a radiocarbon date projected from outside the section profile. For section trace, see Fig. 1.

Using the same combination of color, carbonate content and distinctive pocket penetrometer signature as diagnostic criteria for paleosol identification, such as shown in Figure 6, we also performed the re-interpretation of 40 core descriptions from the Regione Emilia-Romagna database (see Fig. 1, for cores location), where a total of 39 paleosols had been reported. This re-interpretation led to recognition of 118 (inferred) Inceptisols. Penetration tests across both non-pedogenized floodplain deposits and the interpreted 'A' and 'Bk' horizons display consistent values relative to the values measured in the reference cores 1-3 (Fig. 7). In particular, compressive strength values from organic-rich ('A') horizons are centered at 3.0 kg/cm^2, whereas calcic ('Bk') horizons show a modal value of 3.5 kg/cm^2. The 'normal', non-pedogenized floodplain deposits show remarkably lower compressive strength (average value 2.0 kg/cm^2).

Although we cannot place absolute confidence in our interpretations of the geotechnical dataset, and thus slight paleosol overestimation is possible, the remarkably (three times) higher number of paleosols recognized through our technique suggests that simple re-examination of existing core descriptions in terms of pocket penetration profiles and accessory components might lead to considerable refinement of stratigraphic architecture (compare Fig. 5 with Fig. 6).

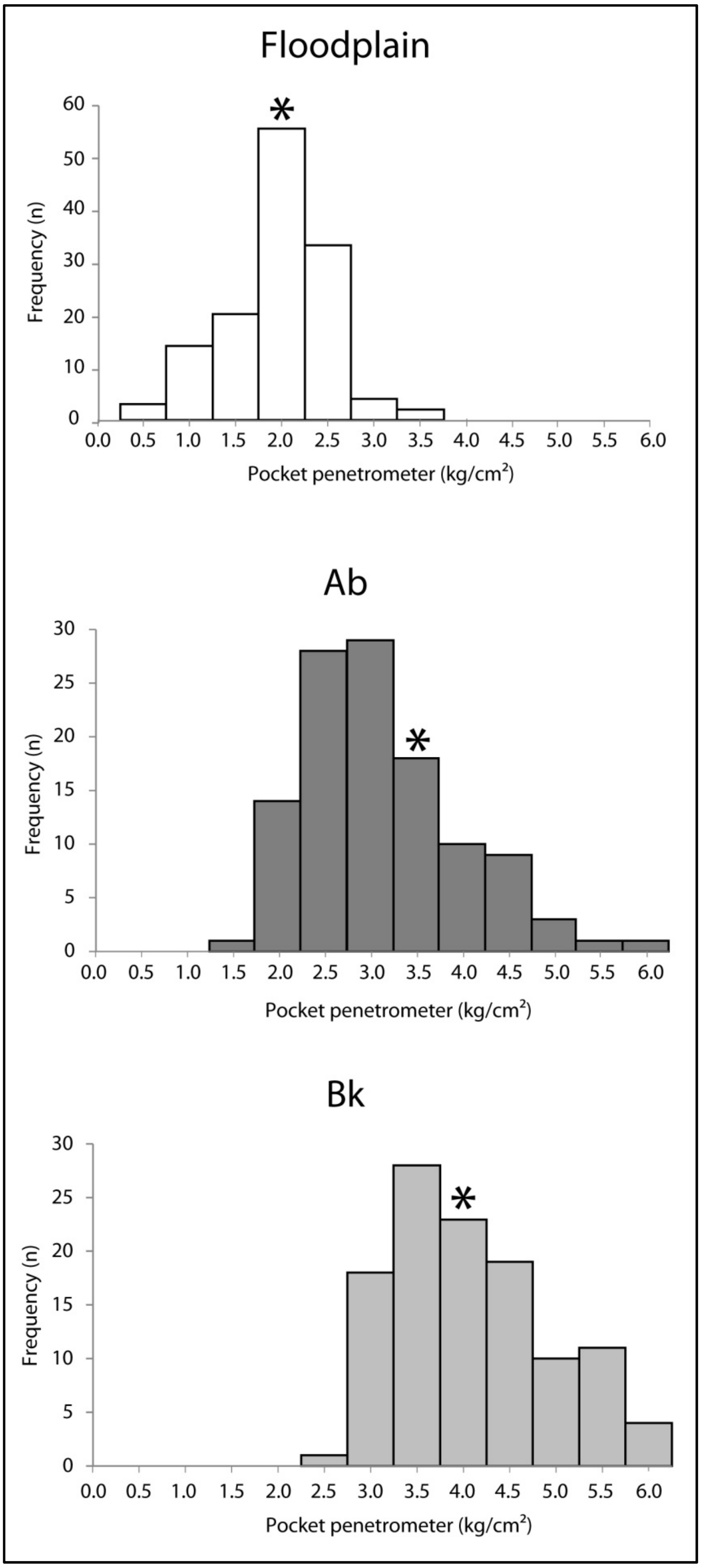

Fig. 7. Histograms of pocket penetration values from 40 core descriptions (see Fig. 1 for cores location), across 120 non-pedogenized floodplain samples (above) and 118 paleosols, subdivided by horizon ('A' – middle, and 'Bk' – below). The asterisks refer to the average pocket penetration values measured from reference cores 1-3.

7. Compressive strength properties of paleosols

We have documented that the late Quaternary Inceptisols of the southern Po Plain exhibit a distinctive geotechnical signature, being characterized invariably by higher penetration values than non-pedogenized floodplain deposits. The sharp increase in penetration values is generally recorded atop the pedogenized horizons: this feature is due to prolonged subaerial exposure, which makes the sediment surface desiccated and unsaturated, resulting in considerable increase in compressive strength.

Pedogenically modified muds with high compressive strengths have been reported from several papers, with values 2-4 times higher than that of the overlying unexposed deposits (Park et al., 1998; Choi and Kim, 2006). In the study area, pocket penetration tests proved to be highly sensitive to paleosol identification, with compressive strengths commonly 1.5-3 times higher than those recorded from the overlying/underlying floodplain deposits (Figs. 3 and 7).

Although, in general, paleosols are easy to identify by their highly consolidated nature, vertical changes in physical properties through individual paleosol horizons appear to follow complex patterns. Previous interpretations of (piezo)cone penetration tests across paleosol-bearing successions have shown that the upper boundaries of paleosols may appear as gradational and defined as zones, rather than sharp surfaces (Amorosi and Marchi, 1999; Choi and Kim, 2006). The same can be said for the pocket penetration signature (compare with Figs. 3 and 6). Despite a certain variability of soil types and wide range of penetrometer resistance, a consistent increase of penetrometer measurements is recorded at the boundary between non-pedogenized and pedogenized deposits (top A horizon – Figs. 7 and 8). The compressive strength, however, is even higher at the boundary between the A horizon and the underlying Bk horizon (Figs. 7 and 8).

Owing to this two-step increase in pocket penetrometer resistance, paleosols are likely to offer two slightly offset images (on the order of 30-50 cm), each representing the different perspective of a distinct viewer. While on one hand a soil specialist would define a paleosol on the basis of its horizonation, thus placing its top at the upper boundary of the A horizon, an interpreter of geotechnical profiles could be inclined to place the top of the same paleosol in a lower position, at the A/Bk boundary (Fig. 8). The lower compressive strengths values invariably recorded in the A horizons relative to the Bk horizons could reflect: (i) temporary re-saturation of the uppermost paleosol at time of burial, (ii) a simple weathering effect, which would contribute to the softening of the soil through an increase in soil moisture and physical disruption (Choi and Kim, 2006), (iii) the presence of diffuse carbonate concretions, which might enhance the resistance values of the Bk horizon.

The overall consistency between penetration profiles recorded under different operating conditions indicates that the inherent quantitative nature of penetration tests can provide reliable constraints to paleosol stratigraphy and, in general, provide comparable results, even when penetration tests are carried out with different equipment and in different time periods (Fig. 7). The robustness of this method suggests that pocket penetrometer values from summary logs can be used as an inexpensive, powerful tool in the alluvial stratigraphy of unconsolidated Quaternary deposits to enhance the detection and successful prediction of paleosols.

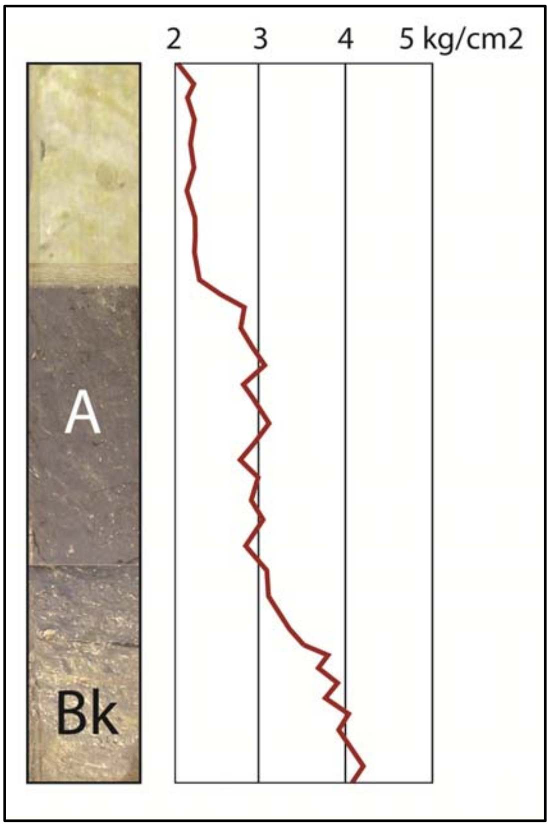

Fig. 8. Idealized penetrometer readings of A and Bk horizons from in-situ measurements in the study area. Note the two-step increase of mean penetrometer resistance atop horizons A and Bk. The highest values invariably mark the A/Bk boundary

Conversely, reliance on correlations based uniquely on pocket penetration profiles can be problematic, and we strongly encourage to carry out detailed calibration with cores before any interpretation of penetration profiles is performed with confidence. It should be kept in mind that a simple increase in pocket penetration values has little objective sedimentological expression, and not all shifts in compressive strength are unequivocally related to paleosol development. In this regard, additional information, such as dark color, occurrence of organic material and carbonate accumulation, should not be overlooked in paleosols estimation.

8. Conclusions

In order to save money and increase research capability, optimizing the contribution of all available data is a primary need for subsurface stratigraphic interpretation. When facies analysis is carried out uniquely through point data (cores, stratigraphic logs) with poor spatial information, re-interpretation under a sedimentological perspective of pre-existing core descriptions may be crucial to increase the accuracy of stratigraphic analysis before a new exploration campaign is undertaken.

Paleosol identification is a critical observation to record when describing a core. However, the presence of paleosols in core descriptions is often neglected by an untrained observer. Descriptive logs can be highly subjective, especially when the geologist's experience is limited. In some instances, stratigraphic descriptions are performed directly by drillers, and are very unlikely to contain information useful for a sedimentologist. In such instances, pocket penetration tests, a set of data normally available from most core descriptions, may provide objective information on sedimentological characteristics not recognized at time of core description.

This study, by focusing on late Quaternary deposits of the southern Po Plain, shows that integration of simple geotechnical (pocket penetrometer resistance) data with accurate facies analysis from even a limited number of cores can be effective in identifying pedogenically modified muds, thus enlarging significantly the number of control points and increasing their value in building a reliable high-resolution stratigraphic framework within unconsolidated alluvial sediments.

Through calibration with facies analysis and radiometric dating from three late Quaternary cored successions of the southern Po Plain, we documented the repeated alternation of 12 pedogenized horizons (Inceptisols A-L) with non-pedogenized, alluvial strata. These paleosol-bounded packages, 3-5 m thick and spanning intervals of a few thousand years, can be physically traced over distances of tens of km, allowing the identification of sedimentary packages of chronostratigraphic significance. Paleosol horizonation plays a fundamental role in shaping the geotechnical response of paleosols to pocket penetration, the maximum increase in penetration resistance being observed at the boundary between the A and Bk horizons.

In spite of simple identification of stiff horizons via pocket penetration tests, the interpretation of penetration resistance profiles is not unequivocal, and this technique should never replace visual inspection of cores. To be of maximum benefit when setting up a comprehensive stratigraphic study, pocket penetration tests should necessarily be calibrated with accurate core descriptions at selected study sites.

Paper 3. **High-frequency depositional cycles within the late Quaternary alluvial succession of Reno River (Northern Italy)**

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Abstract

Palaeosol-based correlations within the Late Pleistocene-Holocene alluvial succession along the Reno River, in the southern Po Plain, enabled the identification of depositional cycles falling in the sub-Milankovitch band. Each cycle, composed of overbank and fluvial facies capped by a poorly to weakly developed palaeosol, is correlatable upstream to a single fluvial terrace in the Reno River valley and to an individual channel belt close to the valley outlet. Four cycles, dated to about 15-10 (c1), 10-5.5 (c2), 5.5-1.5 (c3) and < 1.5 (c4) cal ky BP, respectively, were identified within the Ravenna subsynthem (AES8), an unconformity-bounded unit of the Geological Map of Italy to scale 1:50.000, corresponding to the post-Last Glacial Maximum deposits. This unit, typically wedge-shaped in coastal areas, where consists of retrogradational (coastal plain and estuarine) deposits overlain by progradational (deltaic) facies, at the basin margin is a mud-dominated alluvial succession deposited atop laterally extensive fluvial-channel complexes. The base of AES8, correlatable to the transgressive surface identified in the coastal area, is a palaeosol dated to about 18-15 ky BP. The bounding surfaces of the high-frequency cycles are diachronous along the Reno longitudinal profile, and not necessary associated to remarkable lithological contrasts, but can be detected even in mud-dominated successions. Climate change likely exerted a major control in triggering alternating phases of river aggradation and degradation, with an increasing contribution of anthropogenic factors since the middle-late Holocene.

Based on the correlation of 34 core logs and 33 well descriptions, with the aid of 71 radiocarbon dates, this study highlights to what extent palaeosols can represent powerful stratigraphic tools to identify cyclic patterns in alluvial successions, even at the millennial time scale.

1. Introduction

The concepts and methodologies of sequence stratigraphy, developed for marginal marine and marine strata (Posamentier et al., 1988; Van Wagoner et al., 1990), are not easily applicable in alluvial contexts, where key components of sequences, such as transgressive surfaces, are not well expressed by changes in facies associations as it occurs, instead, in coastal areas (Shanley and McCabe, 1994). A general discussion of sequence stratigraphy in fluvial deposits started, thus, from the early 1990s (Hanneman and Wideman, 1991; Wright and Marriott, 1993). Mature palaeosols are traditionally mentioned as stratigraphic unconformities bounding fourth-order depositional sequences, far from sea-level influence (Gibling et al., 2005). Many authors suggested the subdivision of fluvial-dominated depositional sequences into two or three unconventional systems tracts, based on vertical variations in channel stacking patterns (see Catuneanu et al., 2009; Hanneman and Wideman, 2010; Blum et al., 2013, and references therein): a basal (degradational or low accommodation) systems tract, characterized by laterally continuous fluvial-channel complexes; a transitional, floodplain-dominated systems tract with lenticular, poorly interconnected, ribbon-like fluvial-channel bodies; the upper (aggradational or high accommodation) systems tract, marked by a relative increase in the fluvial to interfluvial facies ratio. The concept of accommodation, originally defined for marine deposits (Jervey, 1988), was redefined as ‘the thickness measured at a specified site and time, of a space which becomes filled with sediments during a specified interval’ (Muto and Steel, 2000). In this perspective, accommodation can be physically measured, even in non-marine sequences, as the thickness of the accumulated and preserved sediments between successive depositional or hiatal surfaces. ‘Parasequence’ is another term, introduced for marine deposits (Van Wagoner et al., 1988, 1990) and extended to lacustrine (Bohacs et al., 2000) and alluvial (King, 1996; Farrell, 2001) environments, where buried soil horizons bracket fifth-order depositional cycles. In uplifting areas, cyclic alluvial architecture is represented by fluvial terraces, often indicated as the geomorphic expression of climate variability (Anderson et al., 2004; Bridgland and Westaway, 2008; Wegmann and Pazzaglia, 2009; Mack et al., 2011; Pierce et al., 2011).

Reno River flows for 90 km across the uplifting Northern Apennines and for 120 km in the subsiding Po Plain (fig. 1), where subsurface stratigraphy is a complex mosaic of floodplain and channel-related facies. The Reno River valley, in Northern Italy has been the object of detailed investigations in the past twenty years, both in the intramontane and in the alluvial plain sectors. Alluvial terraces (Eppes et al., 2008; Picotti and Pazzaglia, 2008) and buried soils in the Bologna interfluve, close to the Reno outlet (Bruno et al., 2013; Amorosi et al., 2014), were mapped and radiocarbon dated, delineating a stratigraphic framework characterized by a distinctive cyclic signature at the millennial temporal scale.

Background stratigraphic information, combined with new data, are used in this work to reconstruct the stratigraphic architecture of the Late Pleistocene/Holocene deposits along the Reno River axis. The aim of this study is to test the potential of palaeosol stratigraphy to improve the temporal and spatial resolution of geological investigations in alluvial settings, far from sea-level influence. The stratigraphic framework delineated along the Reno River profile was used as a basis for correlations at the Po Basin margin, between buried alluvial plain deposits and outcropping fluvial terraces.

2. Geological setting

2.1. Structural setting

The southern Po Plain is a wedge-top basin developed atop a system of blind thrusts that represent the most external structures of the Apenninic chain (Pieri and Groppi, 1981). The boundary between the Po Plain and the Apenninic foothills has been described as either an out-of-sequence thrust fault (Pedeappenninic Thrust Front - PTF of Boccaletti et al., 1985) or the topographic expression of a steep blind ramp, with associated high-angle normal faults in the upper crust (Picotti and Pazzaglia, 2008). Since the early Pleistocene, large parts of the Northern Apennines were involved in a generalized uplift (Ambrosetti et al., 1983; Bartolini et al., 1982) that caused the progressive incision of the drainage network, with formation of steeply cut valleys. GPS data indicate uplifting rates of about 0.7-2 mm/yr for the northern part of the Apennines (Baldi et al., 2009; Cenni et al., 2013), in agreement with long-term velocity estimated through combined geological and topographic investigations (Zattin et al., 2002; Argnani et al., 2003; D'anastasio et al., 2006). Mean subsidence rates of about 15-20 mm/yr, with maximum values of 70 mm/yr, are recorded in the Po Plain (Carminati and Martinelli, 2002; Baldi et al., 2009). These values, however, are affected by human impact (water withdrawal, hydrocarbon extraction), overprinting long-term natural subsidence, estimated to be < 2.5 mm/y (Carminati and Di Donato, 1999).

Reno River flows in the Po Plain in S-N direction, within 40 km long embankments, up to the village of Sant'Agostino (Fig. 1). Downstream, the river course has been modified several times starting from the Middle Ages, due to difficult water flow into the Po River. Finally, in 1724 the Reno River was ultimately driven into the Adriatic Sea through a 30 km-long anthropogenic channel (*Cavo Benedettino*) which flowed into an abandoned distributary channel of the ancient Po delta (*Po di Primaro*).

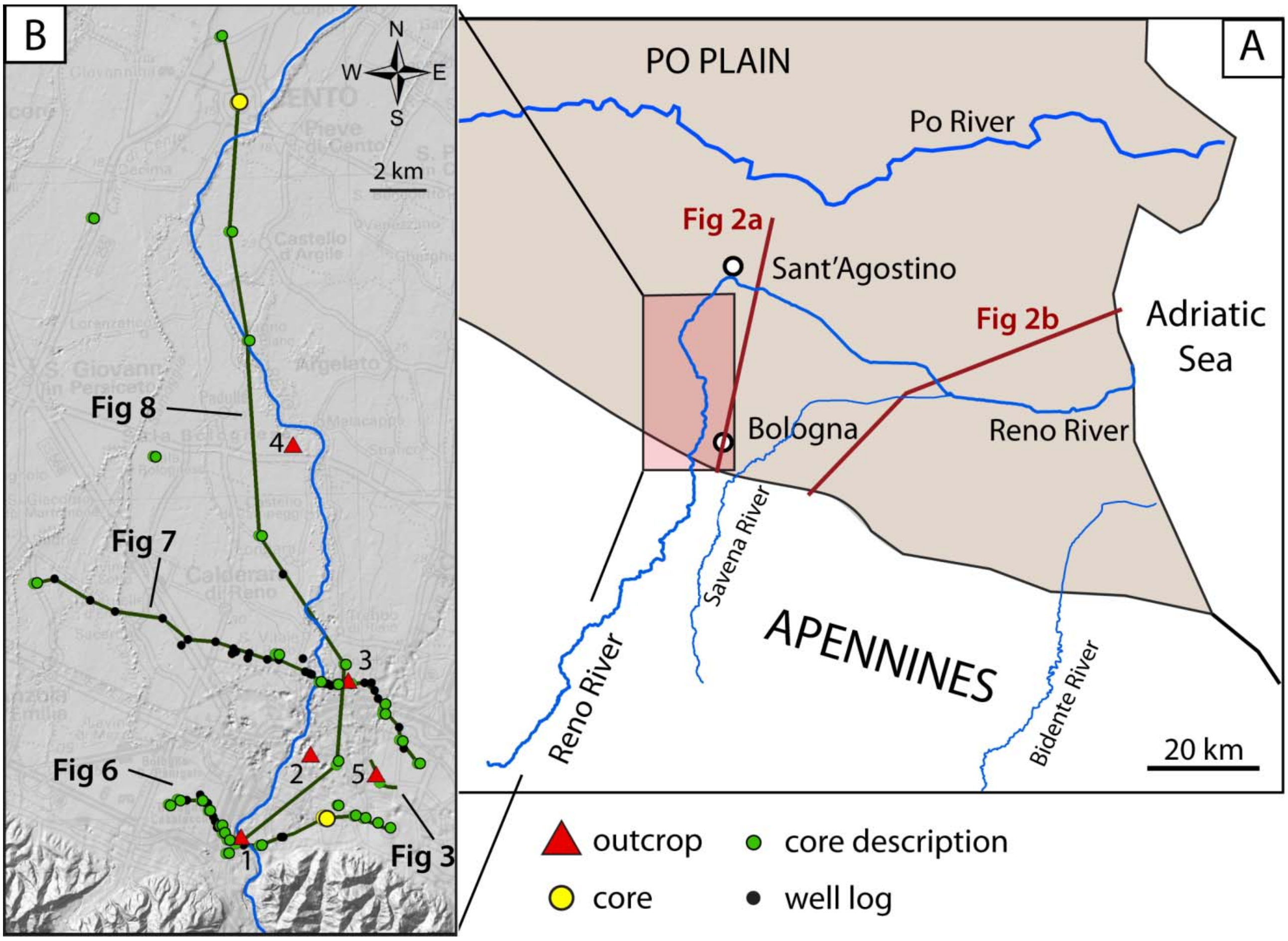

Fig. 1. A. The Reno River course across the Apennines and the Po Plain, with location of the seismic and stratigraphic profiles of Fig. 2; B. A focus on the study area, with location of the stratigraphic cross-sections of Figures 3, 6, 7 and 8.

2.2. Late Quaternary alluvial stratigraphy

2.2.1. The southern Po Plain

Folds and thrusts in the subsurface of the southern Po Plain are sealed by a syntectonic wedge of Plio-Quaternary deep-marine to continental deposits (Pieri and Groppi, 1981), up to 8000 m thick. Alluvial deposits form the topmost portion of the Po Basin fill (Fig. 2a). Their thickness ranges between a few tens of metres close to the basin margin and along the anticline ramps, and several hundreds of metres in the depocentres. On the basis of late Quaternary facies distribution, the southern Po Plain can be subdivided into three sectors: (i) the basin margin, dominated by thick, amalgamated fluvial gravel bodies, with distinctive gravel/mud alternations (Amorosi et al., 1997; 2001); (ii) the central plain, composed by mud-prone floodplain and paludal deposits, with subordinate ribbon-shaped fluvial bodies; (iii) the coastal plain, where alluvial deposits are interbedded with lagoonal and shallow-marine deposits (Fig. 2b). Alternating alluvial and nearshore deposits in the subsurface of the modern coastal plain and the delta define characteristic, fourth-order transgressive-regressive (T-R) cycles. These depositional cycles, each of them covering a time span of about 100 ky, have been related to glacio-eustatic fluctuations (Amorosi et al., 1999; 2004). Based on their diagnostic facies characteristics and correlation of pollen profiles (Amorosi and Colalongo, 2005), the transgressive surfaces can physically be tracked from the coastal plain (where they mark the base of interglacial nearshore deposits) to the basin margin (at the top of glacial, fluvial-channel complexes). Continuous basin subsidence generated the accommodation needed for the formation and the preservation of such cyclic sediment packages, up to 100 m thick. Due to their correlatability at the basin-scale, transgressive-regressive sequences were used as unconformity-bounded units (Salvador, 1994) in the framework of the geological mapping project of Italy to scale 1:50.000. The two topmost cycles are named Villa Verucchio Subsynthem (AES7), and Ravenna Subsynthem (AES8), respectively; AES7 includes the Marine Isotope Sub-Stage (MIS) 5e transgression and the subsequent MIS 4-2 falling-stage and lowstand systems tracts, while AES8 corresponds to the post-LGM transgression and sea-level highstand (MIS 1). An informal lower-rank unit (Modena Unit - AES8a), corresponding to post-Roman deposits, has been identified within uppermost AES8.

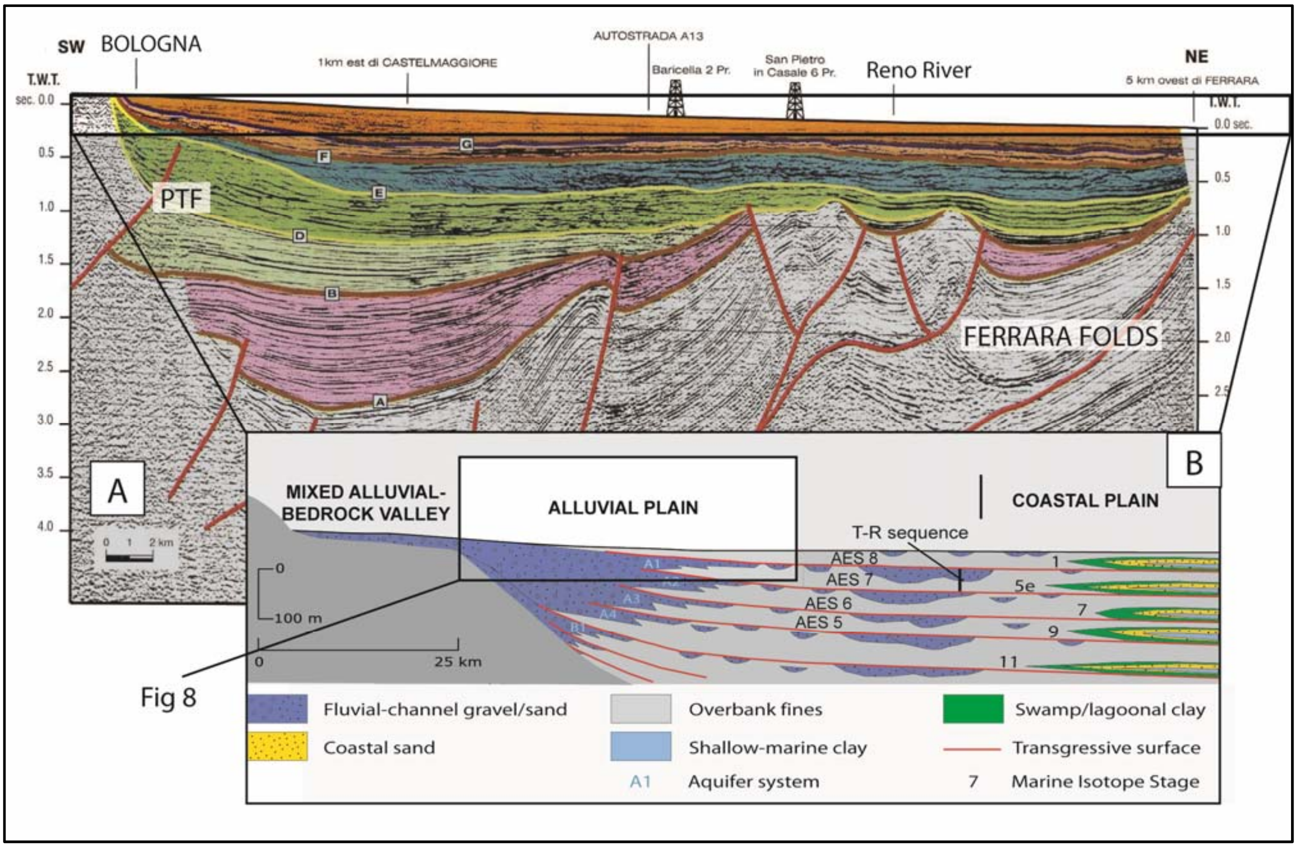

Fig. 2. A. Deep seismic profile transversal to the Apenninic margin (from Regione Emilia-Romagna and Eni-Agip, 1998); B. Schematic cross-section showing the depositional architecture of the Quaternary portion of the Po Basin fill (modified from Amorosi, 2008).

2.2.2. The basin margin

The fluvial-channel complexes at the southern margin of the Po Plain tend to coalesce into a unique gravel sedimentary body elongated parallel to the Apennine chain. Fine-grained, interfluvial areas are commonly found between two successive river outlets. This is the case of the town of Bologna, located on the interfluve between the Reno and Savena river outlets (Fig.1). A characteristic architecture of alluvial depositional cycles at the sub-Milankovitch time scale, bracketed by pedogenized horizons, has recently been documented from the late Quaternary succession of the Bologna interfluvial area (Amorosi et al., 2014). Six laterally-extensive palaeosols exhibit ages within the ^{14}C time window (Fig. 3, Table 1). Particularly, palaesols P1-P3 display a fully glacial, Late Pleistocene age; palaeosol PH marks the Pleistocene/Holocene transition; whereas palaeosols N-EN and IR have Holocene age. The Late Pleistocene palaeosols are more developed and laterally extensive than their Holocene counterparts, as a result of prolonged subaerial exposure during the glacial period. The Holocene phases of soil development correspond to the diffusion of human settlements in the study area, as testified by a vast array of artifacts encountered in the A horizons of these palaeosols (Bruno et al., 2013). A Neolithic to Early Eneolithic Age characterizes palaeosol N-EN, while Iron Age (locally Late Bronze Age) to Late Roman Period artifacts are disseminated in the IR palaeosol. Evidence of human presence during the Late Eneolithic and Bronze Age is almost lacking in the Bologna urban area, while it is documented for the most distal regions (Cattani et al., 2010; Cadeddu et al., 2011; Vinci, 2012).

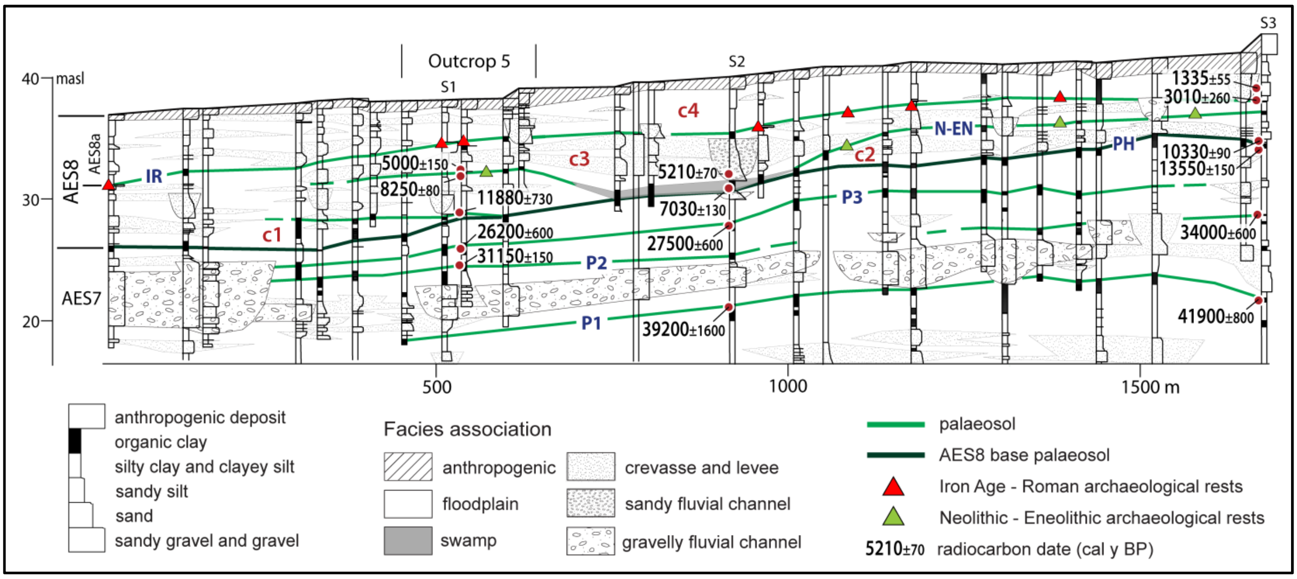

Fig. 3 – High-resolution stratigraphic cross-section, depicting palaeosol stratigraphy of the Bologna interfluve (modified from Amorosi et al., 2014)

2.2.3. Alluvial Terraces

The intramontane Apenninic catchment of Reno River, about 1055 km^2 wide, is composed almost entirely of marine units. For one third it consists of disassembled scaly shales pertaining to the Ligurian domain (Pini, 1999), and for the remaining portion of arenaceous sedimentary rocks. Alluvial deposits can be observed in scattered outcrops along the mountain front (Ricci Lucchi et al., 1982), and in the lower reaches (25 km) of the Reno Valley, where they consist of ten orders (Qt0-Qt9) of fluvial terraces elongated parallel to the present Reno River course (Picotti and Pazzaglia, 2008). The Reno terraces are strath terraces, with thin alluvial fills, capped by soils with different degree of development (Eppes et al., 2008). Terraces Qt5, Qt6, Qt8 and Qt9, radiocarbon dated to about 23, 15-10, 6.5-5.5, and 1.9-1 ky BP (Fig. 4), respectively, are laterally continuous and persistent along the valley. Scattered remnants of Qt7 are mapped and no ^{14}C data are available. An age of about 9 ky is attributed to this terrace, based on the correlation with terraces from the adjacent valleys (Wegmann and Pazzaglia, 2009). Valley slope instability between 6.5 and 3 ky BP is testified by dated colluvial wedges covering the terrace treads (Eppes et al., 2008).

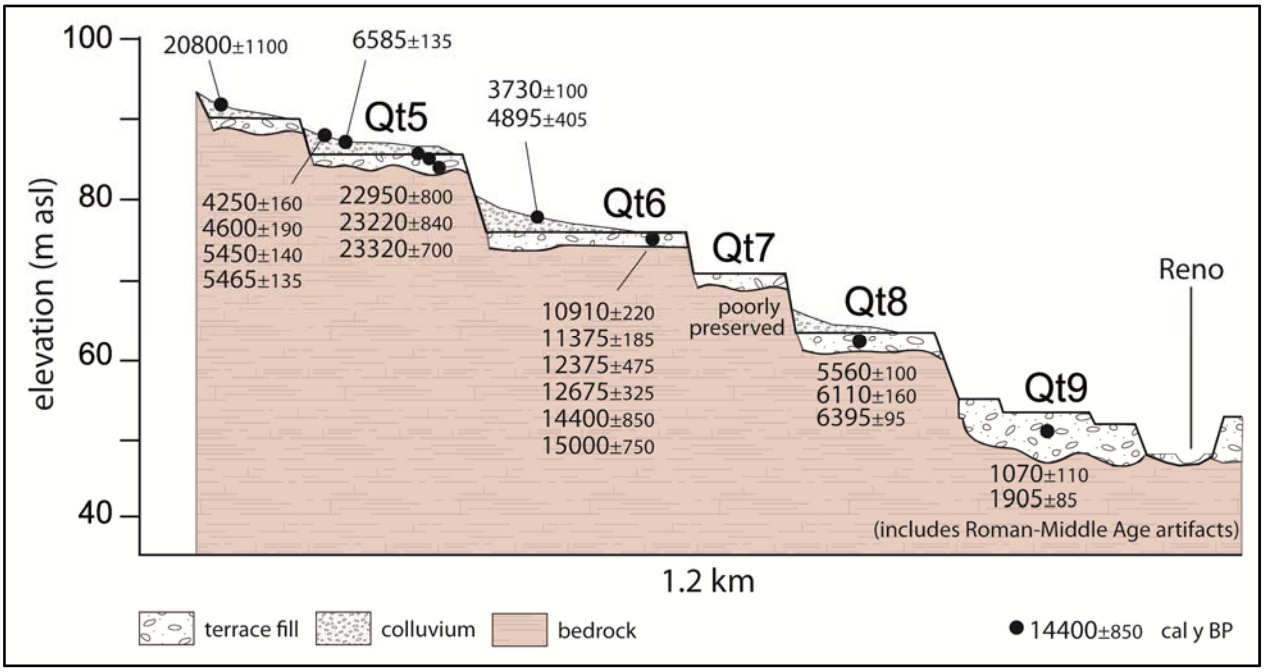

Fig. 4 – Schematic cross-section depicting depositional architecture along the Reno River valley (modified from Picotti and Pazzaglia, 2008).

3. Methods

The stratigraphic architecture of late Quaternary deposits along the Reno River axis was reconstructed through three stratigraphic profiles (Fig. 1b): cross-sections 1 and 2 (Figs. 6 and 7) are 8.2 and 16 km long, respectively, and were traced close to Reno intramontane valley outlet. Cross-section 3 (Fig. 8) is a 31 km-long profile, parallel to Reno River. Sixty-five stratigraphic logs from the database of the Geological Survey of Regione Emilia-Romagna were correlated along the cross-sections. Additional information derived from facies analysis carried out on two continuous cores. The mono-dimensional information supplied by core analysis was implemented by sedimentological investigations of quarries and exposures, which locally allowed the two-dimensional geometry of the sedimentary bodies to be reconstructed.

Nine samples of bulk sediment, wood debris, plant macrofossils or peat were collected from field exposures and cores for ^{14}C dating. All samples were cleaned through acid-alkali-acid pretreatment, to remove secondary calcite and humic acids. Accelerator mass spectrometry measurement at Ion Beam Laboratory (ETH, Zurich) and liquid scintillation counting at ENEA

Laboratory (Bologna, Italy) were used to obtain conventional ^{14}C ages. Calibrated ages (calendar years before present, cal y BP) were obtained using OxCal 4.2 (Bronk Ramsey, 2009), with the Intcal-13 calibration curve (Reimer et al., 2013). The chronological framework is based on these new dates, along with 62 published dates (Table 1) and archeological data archived at the Superintendence to Archaeological Properties of Regione Emilia-Romagna. All ages mentioned in the following text are calibrated years before present.

4. Depositional facies associations

Detailed sedimentological analysis was carried out on six exposures, within quarries and excavations, and on two cores. Outcrops 1, 2 and 3 are located 1, 5 and 10 km downstream of the Reno River outlet, respectively (Fig. 1), and consist predominantly of gravels and gravelly sands. Outcrop 4, mainly composed of sands, is located on the convex side of a meander, west of the modern Reno River course, 16 km downstream of the valley outlet. A predominance of clays and silts characterizes outcrop 5, an excavation for building foundations in the Bologna urban area. Four facies associations were identified on both excavations and cores. These facies associations are described as follows.

4.1. Fluvial-channel facies association.

Gravel and sandy gravel sedimentary bodies characterize this facies association, with width and thickness that may vary considerably with the observation point. Since different facies were observed in the various exposures, the different outcrops are described separately. The sedimentary bodies exposed in the different outcrops are not necessarily at the same stratigraphic level.

Outcrops 1 and 2

Description. In outcrops 1 and 2, this facies association is characterized by massive, imbricated gravel and sandy gravel bodies, with subordinate sand and silt lens-shaped intercalations (Fig. 5a). Gravel bodies exceed the quarry widths (several hundred metres), are commonly amalgamated, and up to 10 m thick. The basal contact on soft, dark clays is erosional, while the top is sharp, or coincides with the present ground surface. Gravels are well sorted, and composed of rounded cobbles with mean diameter of about 8 cm. Sand and silt lenses are either scattered or aligned at the same stratigraphic level.

Interpretation. The massive, imbricated gravels exposed in outcrops 1 and 2 are interpreted as fluvial-channel deposits, typical of braided river systems (Miall, 1985). The remarkable thickness of these deposits is due to the superposition of diffuse gravel sheets and longitudinal bar deposits. Isolated sandy lenses are inferred to be the relict of low-water stage deposits, while sandy lenses aligned at distinct stratigraphic levels are interpreted as laterally correlative to erosion surfaces, through which two distinct channel complexes are amalgamated.

Outcrop 3

Description. A coarse-grained (gravels and gravelly sands) sedimentary body, about 6 m thick, with erosional base and internal fining-up (FU) trend is exposed in outcrop 3 (Fig. 5b). It is characterized by tabular geometry, with lateral extension that exceeds the quarry width. Gravels are imbricated in the lower part of the outcrop, with inclined stratification in its higher part; they are overlain, with both erosional and transitional boundaries, by well-sorted medium and fine sands. Sand bodies with basal gradational contacts are up to 2 m thick, while sand bodies with lower erosional boundaries are lens-shaped, up to 6 m thick, and cut the entire gravel succession. A clay horizon, about 1 m thick, with disseminated wood fragments seals the whole succession. Radiocarbon dating of a wood collected from this horizon gave an age of 3300±150 cal y BP. Tree trunks are abundant at the base of the gravel body; two of these trunks were radiocarbon dated to 5530±90 and 5660±90 cal y BP.

Interpretation. The facies observed in outcrop 3 are typical of a gravel point bar. Similar facies have already been described in detail from the Bologna area (Ori, 1979). The basal massive imbricated gravels are interpreted as channel floor-bar toe facies (fb), while the overlying sandy gravels are inferred to be the bar body facies (bb), showing epsilon bedding. Point bar deposits are gradually overlain by sands, which are interpreted to represent the progressive abandonment of the channel (ca), with temporary reactivation during higher magnitude flood events. Sands locally cutting the point bar facies are interpreted as chute channels deposits, while sands cutting the entire point bar facies succession are argued to be the result of either chute or neck cut-off. The organic clays that cap the entire succession are inferred to reflect the ultimate abandonment of the channel belt.

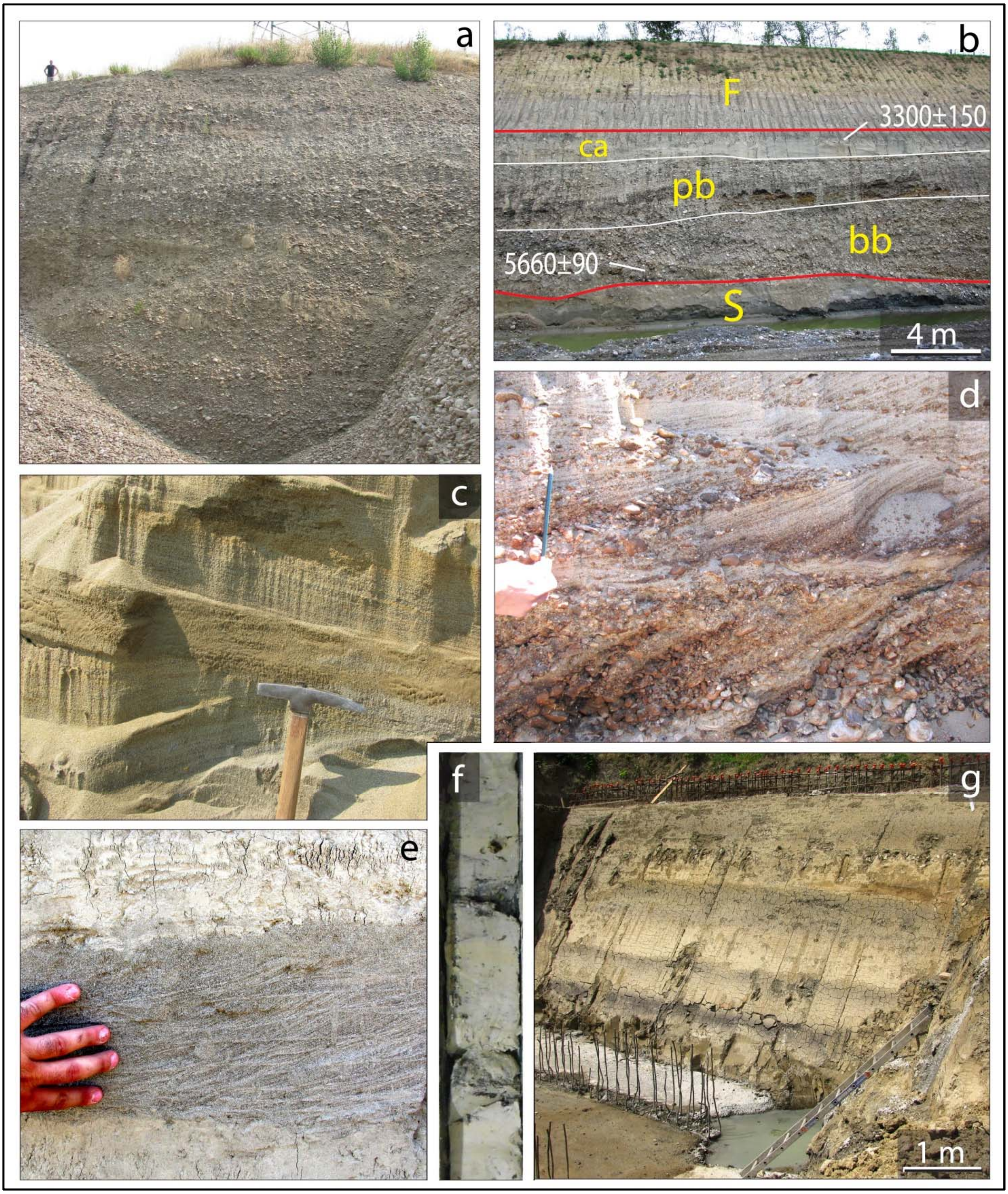

Fig. 5. Representative photographs of the major facies associations from field exposures and cores. A. massive, imbricated fluvial-channel gravels; B. gravelly point bar facies association (fb: channel floor-bar toe; bb: bar body; ca: channel abandonment) between swamp (S) and floodplain (F) deposits; C. cross-stratification in sandy fluvial-channel deposits; D. high-angle cross-stratification and fining-upward trend in fluvial-channel deposits; E. sand layer between massive bioturbated clays in levee deposits; F. soft, organic, paludal clays (core length in the photograph is 50 cm); G. floodplain deposits with vertically stacked palaeosols.

Outcrop 4

Description. Outcrop 4 is dominated by a sand body, up to 8 m thick, with lateral extension greater than the quarry width. These sands overlie silt and clay deposits through an erosional contact; *in situ* tree stumps are visible on the top surface of the silt-clay unit, where exposed. The age of one of these trunk, collected in the western part of the quarry, is 830±140 cal y BP. The top of the sand body is the ground surface. Small scale, high-angle cross stratification is the most evident sedimentary structure (Fig. 5c). Scattered wood fragments are encountered in the sands. A sub-rounded wood clast (max axis of 7 cm) was dated to 8370±170 cal y BP.

Interpretation. Sands exposed in outcrop 4 were likely deposited in a laterally migrating channel (Allen, 1963). Although no evidence of lateral accretion is visible due to the orientation of the exposed surface, these deposits are interpreted as a point bar facies assemblage based on the highly sinuous plan geometry of the quarried deposit. The age obtained from the tree stump should be related to the activation of the channel, since the sample has been collected in the western part of an eastward migrating meander. The stratigraphically inverted age obtained from the wood clast has been interpreted as the result of the erosion of older fluvial channel deposits at the basin margin, into which the clast was incorporated.

Outcrop 5

Description. Fluvial-channel deposits in outcrop 5 consist of lenticular, coarse-grained (sandy gravel to sand) sedimentary bodies, occurring at various stratigraphic levels, between two soil horizons, or between a buried soil and the modern ground surface. The basal contact is erosional, while the top is either sharp or gradual. The thickness ranges between 2.5 and 7 m; width is between 10 and 30 m. Gravels are matrix-supported and composed of sub-rounded pebbles, about 3 cm in diameter; the gravel/sand ratio decreases upwards. Sand bodies have internal FU trends and basal pebble layers. Horizontal and high-angle cross stratification is frequently encountered (Fig. 5d). Tree trunks are locally present at the base of these sedimentary bodies.

Interpretation. Based on their geometry, grain size, lower contacts, and accessory components, the sedimentary bodies exposed in outcrop 5 are interpreted as fluvial-channel deposits. Their vertical and lateral extension and the location on map of the outcrop, enable the attribution of these deposits to tributaries of the Reno River.

4.2. Crevasse facies association

Description. This facies association, showing lateral transition to fluvial-channel deposits, includes sandy lensoid to sheet-like bodies, up to 3 m thick. Sandy lenses are up to 10 m wide and exhibit concave-up, erosional lower boundaries, with internal FU trends and either sharp or gradational boundary with the overlying muds. Sandy sheets are laterally extensive and show gradational base, internal coarsening-up (CU) tendencies and faint convex-up top surfaces. Horizontal and cross- stratification is commonly observed in the sandy lenses.

Interpretation. The combination of two-dimensional geometry, internal diagnostic sedimentological characteristic, and stratigraphic position relative to the fluvial-channel facies, allows interpretation of these deposits as crevasse facies association. Particularly, lens-shaped deposits, with erosional or sharp base and internal FU trends are interpreted as crevasse channels; sheet-like deposits with gradational lower boundaries and internal CU trends are likely to reflect crevasse splays.

4.3. Levee facies association

Description. This facies association consists of laterally extensive sedimentary bodies, up to 5 m thick, made up of alternating sand and silt layers, 5-20 cm thick. These sedimentary bodies, laterally contiguous to the fluvial-channel facies, display typical plano-convex geometry. Sand and silt layers are horizontal (i.e., parallel to the base) in the lower part of this facies association, whereas upwards they show progressively convex-up geometries. Sand layers have erosive or sharp base and are cross-stratified close to the channel axis (Fig. 5e); a few metres away they become progressively thinner, with sharp base and internal flat lamination. The contact with the overlying massive and bioturbated silty layers is gradational.

Interpretation. Based on stratigraphic position, contiguous to the fluvial-channel facies, grain-size tendencies and sedimentary structures, these sediments are argued to represent proximal overbank deposits: the coarser part of the suspended load was deposited close to the channel axis, while the finer portion accumulated in more distal position. The progressive accumulation of coarse-grained material close to channel axis resulted in the formation of a topographically elevated area (natural levee).

4.4. Freshwater swamp facies association

Description. These deposits were identified in core 2 and in the lower part of outcrops 2 and 3, where their base was not observed. In core 2 (Fig. 5f), the thickness of this facies association attains 4.5 m. This unit consists of soft, organic clays, with abundant plant macrofossils and rare freshwater mollusks. Peat layers occur at various stratigraphic levels. Iron and manganese oxides and carbonate concretions are absent. These clays are generally overlain through either sharp or erosional contacts by crevasse or fluvial-channel deposits.
Interpretation. Soft, dark clays, with peat layers and no traces of oxidation and pedogenesis are argued to have been deposited in low-energy environments, characterized by stagnant water and reducing conditions (swamps). These environments represent topographically depressed areas that acted as preferential sites for channel occupation, as testified by the common upward transition to crevasse or fluvial-channel deposits.

4.5. Floodplain facies association

Description. This facies association is exposed in outcrops 1, 3 and 5, where consists of variegated clays and silts, with very subordinate silty sands. In outcrop 5, with the exception of fluvial-channel deposits, this facies association forms the whole exposure. Palaeosols are easily identifiable at various stratigraphic levels (Fig. 5g) owing to well-developed horizonation, with brownish (2.5Y 4/1), indurated, carbonate-free organic clays that overlie lighter (2.5Y 8/2) clays and silts, rich in carbonate nodules and tubules. Palaeosols with poor horizonation (outcrop 1) are hardly recognizable. They are characterized by brown clays (7.5YR 5/6), slight reaction to HCl, desiccation cracks, polygonal structures and rootlets. Iron and manganese oxides are commonly observed.
Interpretation. The abundance of mud and the occurrence of vertically stacked palaeosols indicate that this facies association was deposited on a floodplain, characterized by prolonged phases of subaerial exposure, with oxidation conditions and soil development, separated by phases of intense and frequent flood events. Carbonate-free horizons overlying carbonate-rich clays and silts are interpreted as weakly developed palaeosols (Inceptisols), consistent with phases of subaerial exposure in the range of a few thousands of years. Calcic horizons with faint evidence of soil development are interpreted as immature palaeosols (Entisols), marking shorter periods of subaerial exposure (a few hundred years).

5. Late Pleistocene-Holocene depositional architecture along Reno River

In this section, we illustrate the stratigraphic architecture of the Late Pleistocene-Holocene succession along a 35 km-long Reno River transect, downstream of the valley outlet: this transect is subdivided into two distinct morphological segments: the upper alluvial plain (upper 5 km) and the lower alluvial plain (between 5 and 35 km).

In the upper alluvial plain, characterized by low subsidence rates, fluvial-channel deposits consist of amalgamated gravel bodies laterally associated to pedogenized horizons with slightly aggradational pattern (Fig. 6). Soil horizons in the interfluves occur at various stratigraphic levels, allowing identification of at least six depositional cycles composed of overbank deposits capped by a laterally extensive palaeosol. These cycles are dated to about 31-26.5, 26.5-15, 15-10, 10-7, 7-1.5, (locally 7-4 and 4-1.5), and < 1.5 y BP, respectively. Despite strong limitations in precise dating of channel deposits, a tentative chronological attribution of the individual channel belts can be performed based on the geometric relationships with the adjacent palaeosols. The most laterally extensive channel belt, overlain by an Inceptisol exposed from about 18 to 15 ky BP, is likely older than 18 ky BP. Channel belt C1, cutting the 18-15 ky Inceptisol and covered by organic clays dated to about 10 ky BP, was deposited between 15 and 10 ky. Channel belts C3 and C4 exhibit younger ages, since they both cut an Entisol exposed between about 8 and 7 ky. C3 is overlain by an Entisol bearing Iron Age (about 3 ky BP) and Roman artifacts (2.5-1.5 ky BP). This palaeosol is cut by C4. Consequently, C3 accumulated between about 7 and 3 ky BP, while C4 has post-Roman age.

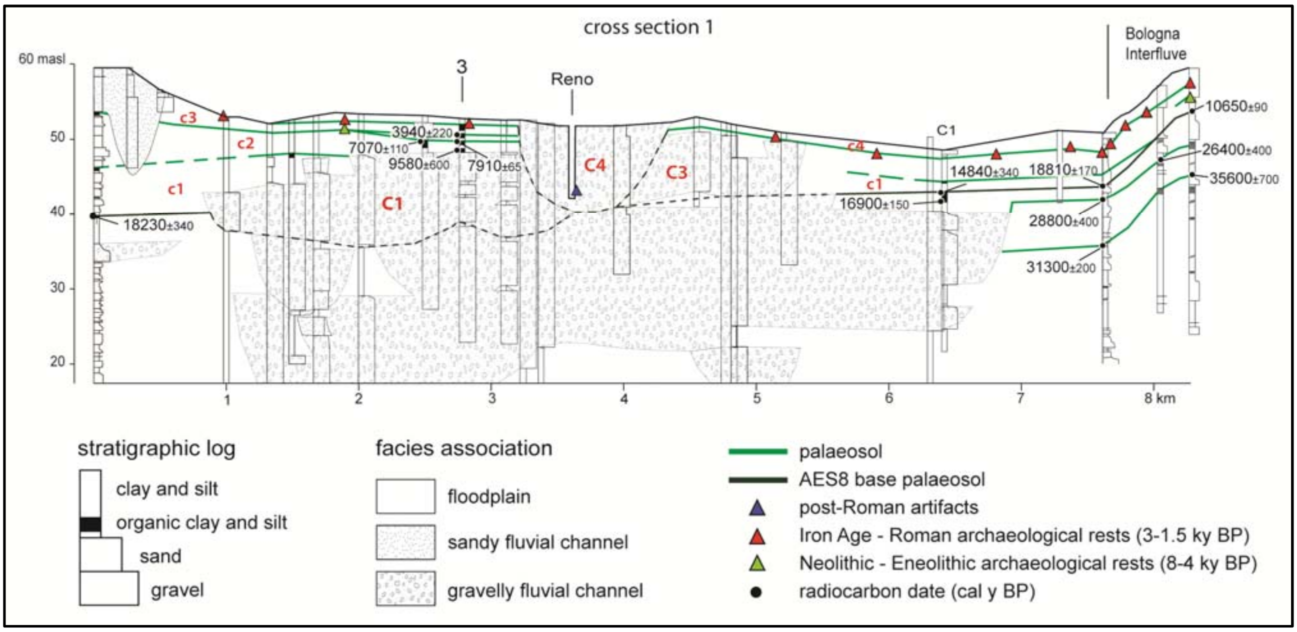

Fig. 6. Stratigraphic cross-section depicting the stacking pattern of fluvial-channel deposits close to the Reno valley outlet. For codes c1, c4 and C1-C4, see text.

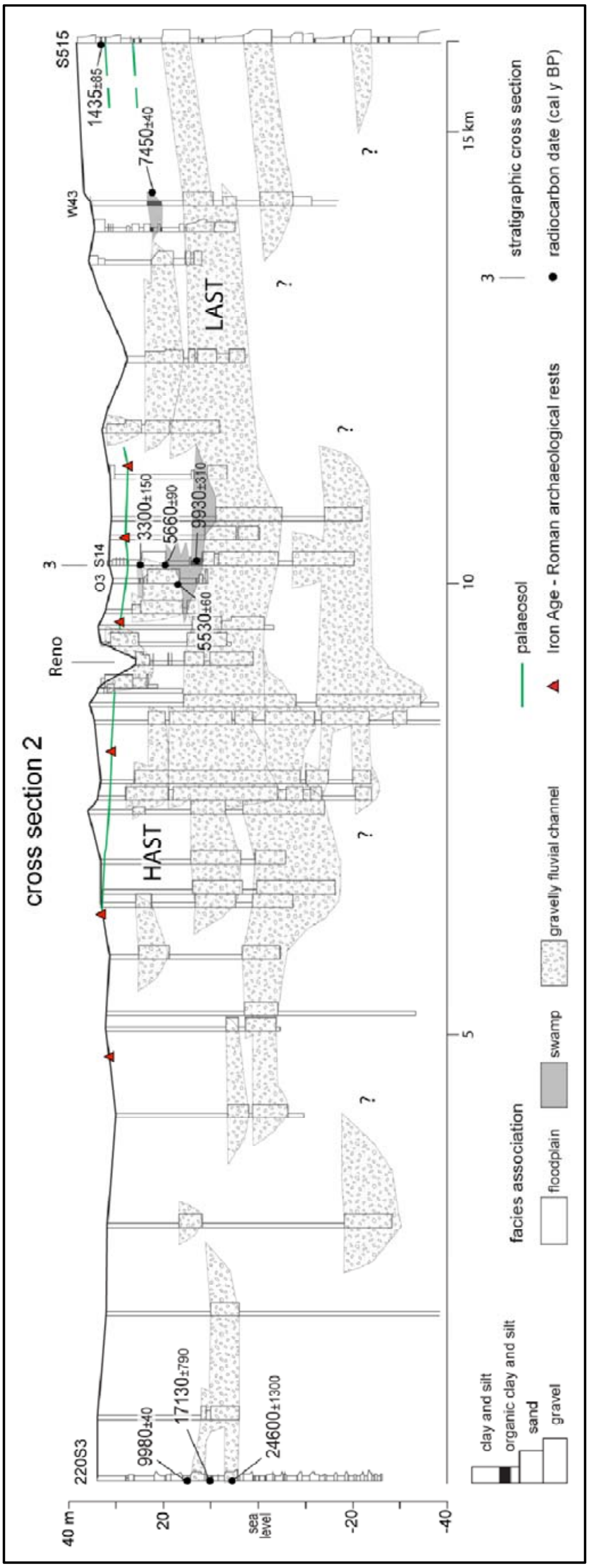

Fig. 7. Stratigraphic cross-section, 15 km north of the Apenninic foothills, highlighting the distinctive depositional architecture of glacial versus interglacial fluvial-channel deposits. LAST: low accommodation systems tract. HAST: high accommodation systems tract.

In the lower alluvial plain, where maximum subsidence is recorded, fluvial-channel deposits are mostly concentrated at two stratigraphic levels (Figs. 7 and 8). The lower sedimentary body consists of a laterally extensive (> 10 km) gravel complex that propagates 25 km downstream of the valley outlet. This channel belt is less than 40 ky old and is sealed by swamp deposits dated to 14-10 cal ky BP. Isolated gravel bodies, replaced by sands 15 km downstream of the valley outlet, are observed at higher stratigraphic levels. Vertically stacked palaeosols allow the identification of four palaeosol-bounded depositional cycles dated to about 15-10, 10-5.5, 5.5-1.5, and < 1.5 ky BP, respectively.

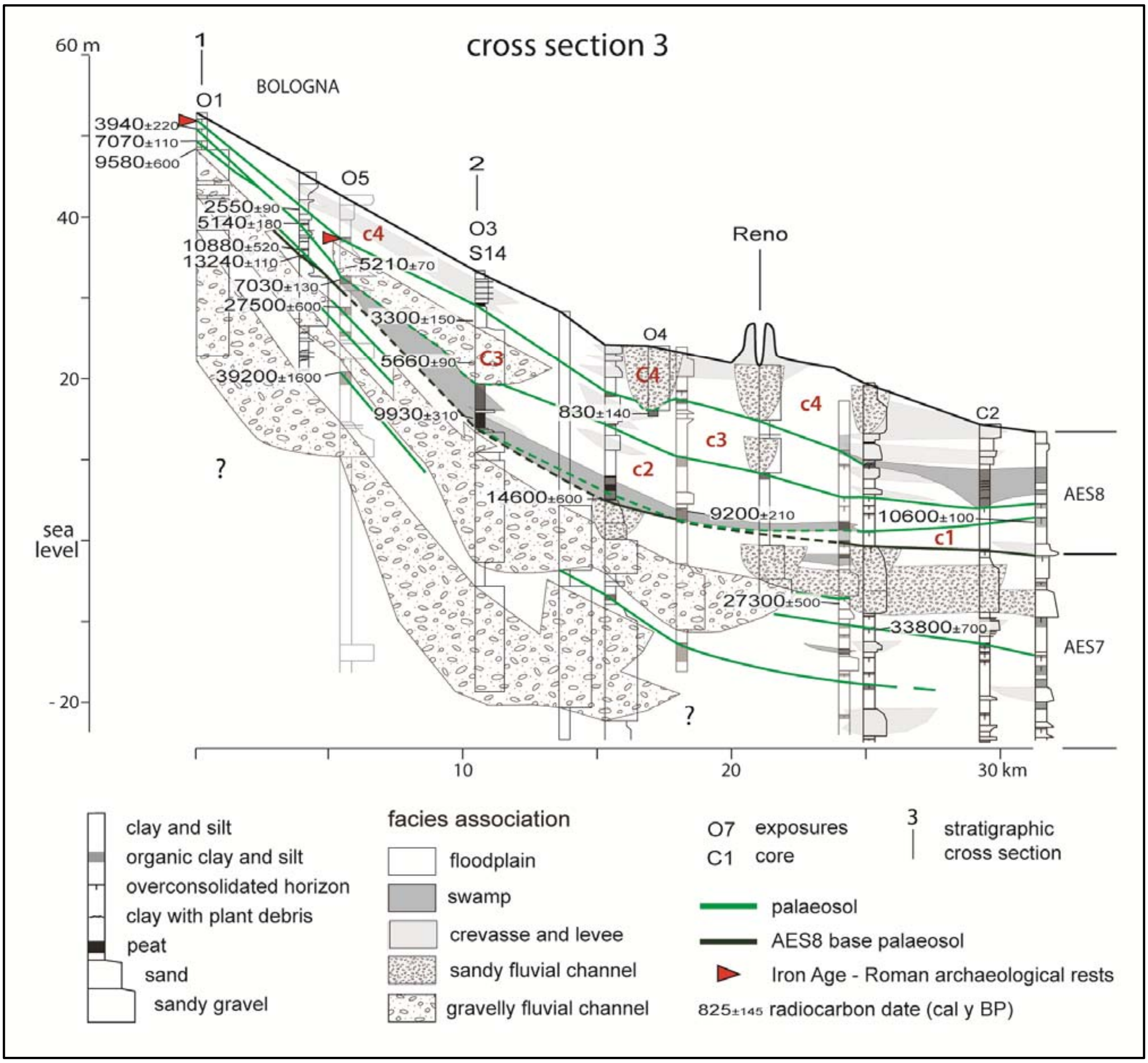

Fig. 8. Stratigraphic cross-section transversal to the Apenninic chain, showing vertical variations in depositional architecture and high-frequency depositional cycles. For codes c1-c4 see text.

6. High-frequency depositional cycles and their correlation with fluvial terraces

Palaeosol-based correlations along the Reno River axis delineate a stratigraphic framework, consistent with previous studies, characterized by vertical variations in channel stacking patterns (Amorosi et al., 1997) and soil development (Amorosi et al., 2014) that allow identification of two unconventional systems tracts within the Late Pleistocene-Holocene alluvial succession (Fig. 9): a basal low accommodation systems tract (LAST), characterized by laterally extensive fluvial-channel deposits laterally connected with weakly developed palaeosols, and a high accommodation systems tract (HAST) consisting of a mud-prone succession, with isolated lens-shaped fluvial channel bodies, marked by poorly to weakly developed palaeosols. With reference to the Geological Map of Italy, HAST coincides with AES8, while LAST corresponds to the upper portion of AES7.

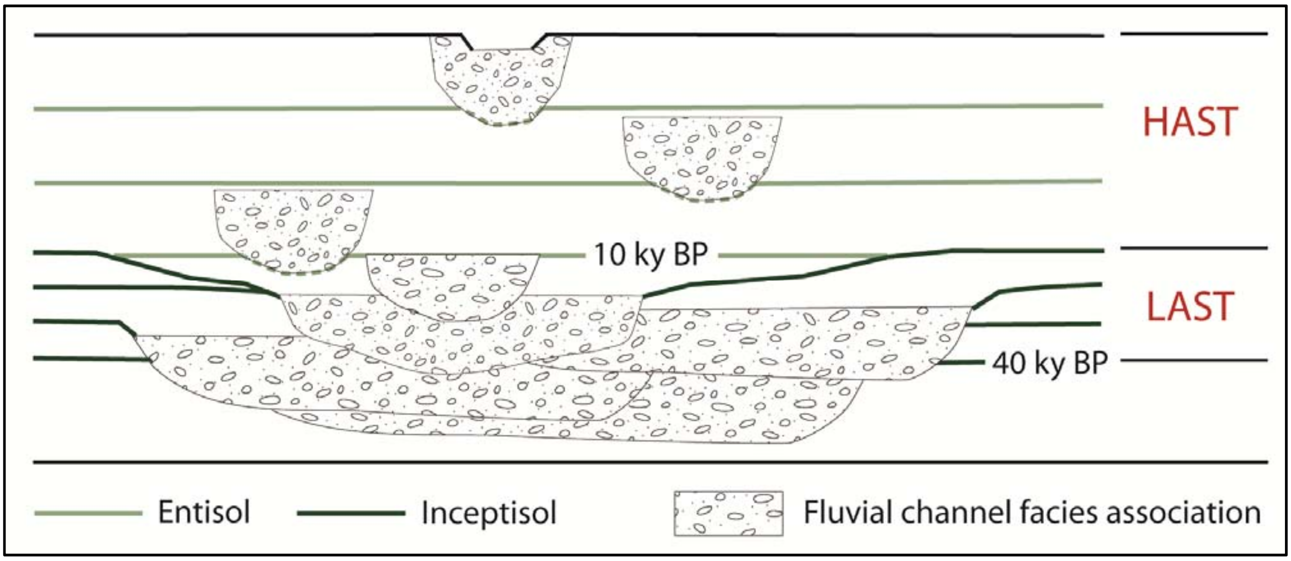

Fig. 9 - Schematic cross section highlighting contrasting facies pattern between glacial, low accommodation and interglacial high accommodation depositional architecture.

The transition from LAST to HAST is paralleled in terms of pollen spectra by the abrupt change from a herbaceous or *Pinus*-dominated vegetation cover (typical of glacial climate conditions) to a predominance of thermophilous (*Quercus, Corylus, Carpinus*) forests (Holocene Thermal Maximum) (Fig. 10).

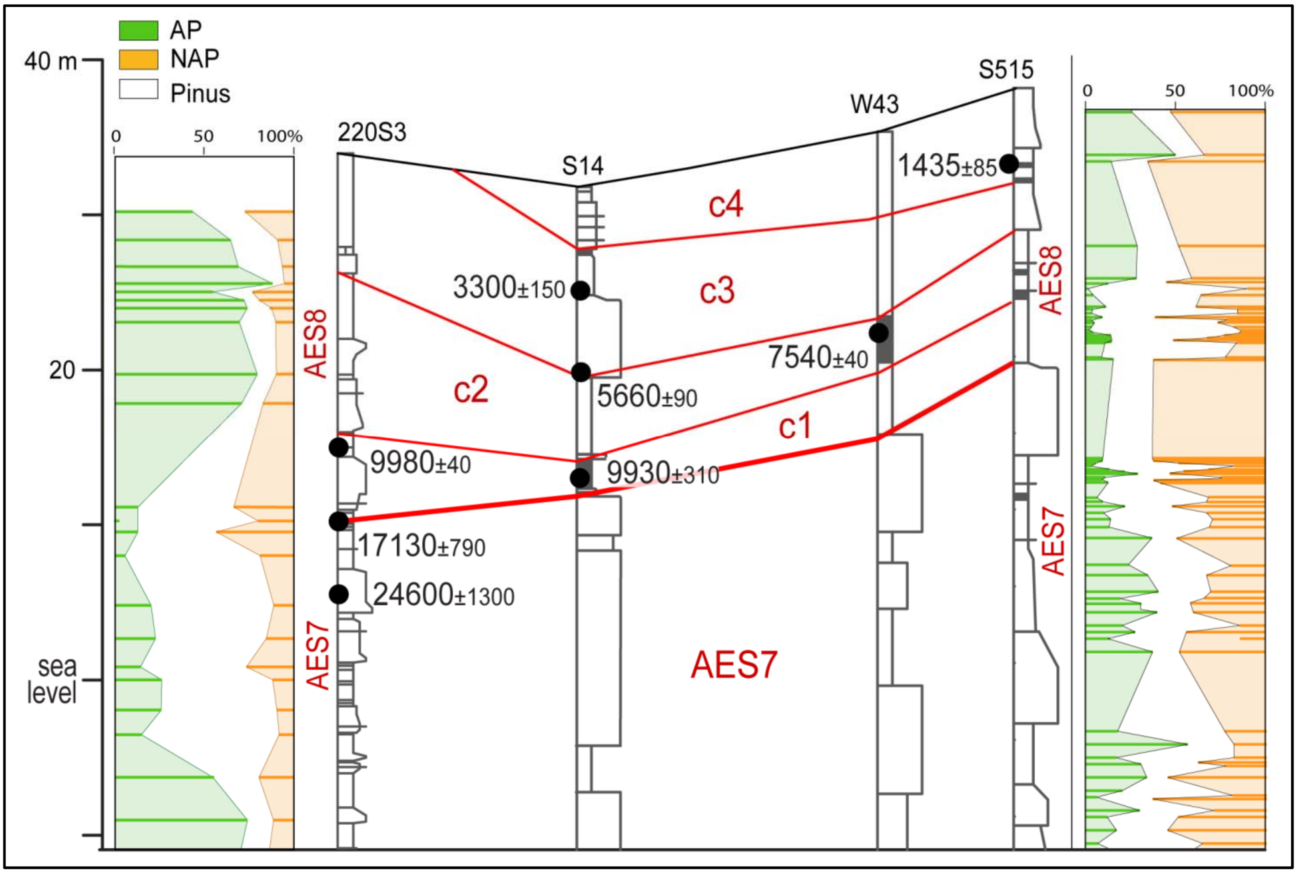

Fig. 10. Correlation of the late Quaternary fluvial-channel deposits along Reno River with pollen profiles from cores P515 (Amorosi et al., 2001) and 220S3 (Martelli et al., 2008). For horizontal scale, see Fig. 7. For codes c1-c4, AP and NAP see text.

Four depositional cycles (c1-c4) were identified within AES8 and dated to about 15-10 (c1), 10-5.5 (c2), 5.5-1.5 (c3), and < 1.5 ky BP (c4) (Figs. 6 and 8). Each cycle records an early aggradational phase, consisting of overbank and fluvial deposits, followed by a degradational phase, represented by a soil horizon. The base of each aggradation/degradation cycle is the sharp contact between the top of the soil horizon and the overlying overbank deposits. This surface is laterally correlative with the erosional lower boundary of fluvial-channel deposits onto floodplain muds (Figs. 6 and 8). Key surfaces for stratigraphic subdivision thus can be identified within seemingly homogeneous floodplain successions through palaeosol-based correlations. In contrast, facies changes marked by obvious lithological variations do not necessarily represent suitable surfaces for bracketing high-frequency depositional cycles.

Radiocarbon dates on palaeosols and fluvial-channel deposits compose a stratigraphic framework consistent with the one obtained from the fluvial terraces of the Reno intramontane valley (Table 1). In particular, cycles c1, c2, c3 and c4 are correlatable with terraces Qt6, Qt7, Qt8 and Qt9, respectively.

Cycle c1 marks the transition from the low accommodation to the high accommodation systems tract. Close to the basin margin, this depositional cycle was observed only in the Reno palaeovalley, while it is generally lacking in the Bologna interfluve (Fig. 6). In this area, for which sediment was supplied by small creeks draining the nearby Apenninic hills, c1 is likely restricted to narrow fluvial incisions, hardly detected through simple log correlations. In more distal areas, c1 consists of predominant swamp deposits, with subordinate fluvial-channel and floodplain facies.

No numerical ages are available for Qt7 and for the related fluvial-channel bodies in the alluvial plain (with the exception of a reworked wood sample collected from outcrop 4, Table 1). However, palaeosol stratigraphy clearly indicates the presence of aggradational-degradational cycle c2 (see S1, Fig. 3). Radiocarbon dates from river terraces of the Bidente valley (Wegmann and Pazzaglia, 2009), 70 km east of Bologna, and especially from the Savena River (Amorosi et al., 1997), just 9 km east of Reno River (Fig.1), indicate ages around 8-10 cal ky BP, in agreement with the dated palaeosols (Table 1).

Cycle c3 corresponds to the activation of an eastern branch of Reno River (Fig. 7) and of a tributary river system in the Bologna area, with the consequent burial of several Early-Eneolithic villages (Fig. 3). The aggradational phase likely lasted until 3 ky BP, as pointed out by colluvial wedges covering the terrace treads, dated to about 6.5-3 ky BP (Fig. 4), and by the absence of late Eneolithic and Bronze age settlements in the Bologna area. Locally, a poorly developed palaeosol dated to 4 ky (Fig. 6) divides the aggradational interval in two distinct sub-phases. The degradational phase started from the Iron Age (and locally the Late Bronze Age) and lasted until the Late Roman Period, culminating in the surface separating c3 from c4.

Cycle c4 corresponds to the informal unit AES8a of the Geological Map of Italy. The aggradational phase, starting in the Late Antiquity (Cremonini et al., 2013), likely lasted until the beginning of the last century, when sediment extraction, dams and channelization led to a progressive narrowing of the Reno riverbed (about 60% from 1884 to 1979 – Viel et al., 2005), and to the transition to a single tread channel (Pellegrini et al., 2008; Surian and Rinaldi, 2009).

The correlation on a millennial time scale of alluvial plain deposits with fluvial terraces enables the lateral tracking of the lower boundaries of late Quaternary high-frequency depositional cycles across the Apenninic margin, from the top of soil horizons to the strath of fluvial terraces. Radiocarbon dates and the distribution of archaeological findings suggest that such bounding surfaces are not necessarily synchronous along the river longitudinal profile (Fig. 11): for example, cycle c3 started at 6.5 ky BP in the Apenninic valley, while avulsion of Reno River and its tributary occurred around 5.5 ky BP, in agreement with the abandonment of numerous early-Eneolithic sites. Cycle c4 started with valley aggradation at 1.9 ky BP, which led to river avulsion and subsequent burial of the Late-Roman and Early-Medieval settlements at about 1 ky BP. Diachronous is also the transition from an aggradational to a degradational style within a single depositional cycle, as testified by the pattern of distribution of the archeological findings. The rests of Bronze Age settlements have been documented in an area 20 km NW and NE of Bologna (Cattani et al., 2010; Vinci, 2012), while those of late Bronze Age are restricted to the northern part of the Bologna urban area, and the Iron Age rests are concentrated in the historical part of Bologna. The diachroneity in the onset of pedogenesis and soil burial is reflected by lateral variations in the degree of soil evolution (from poorly to weakly developed).

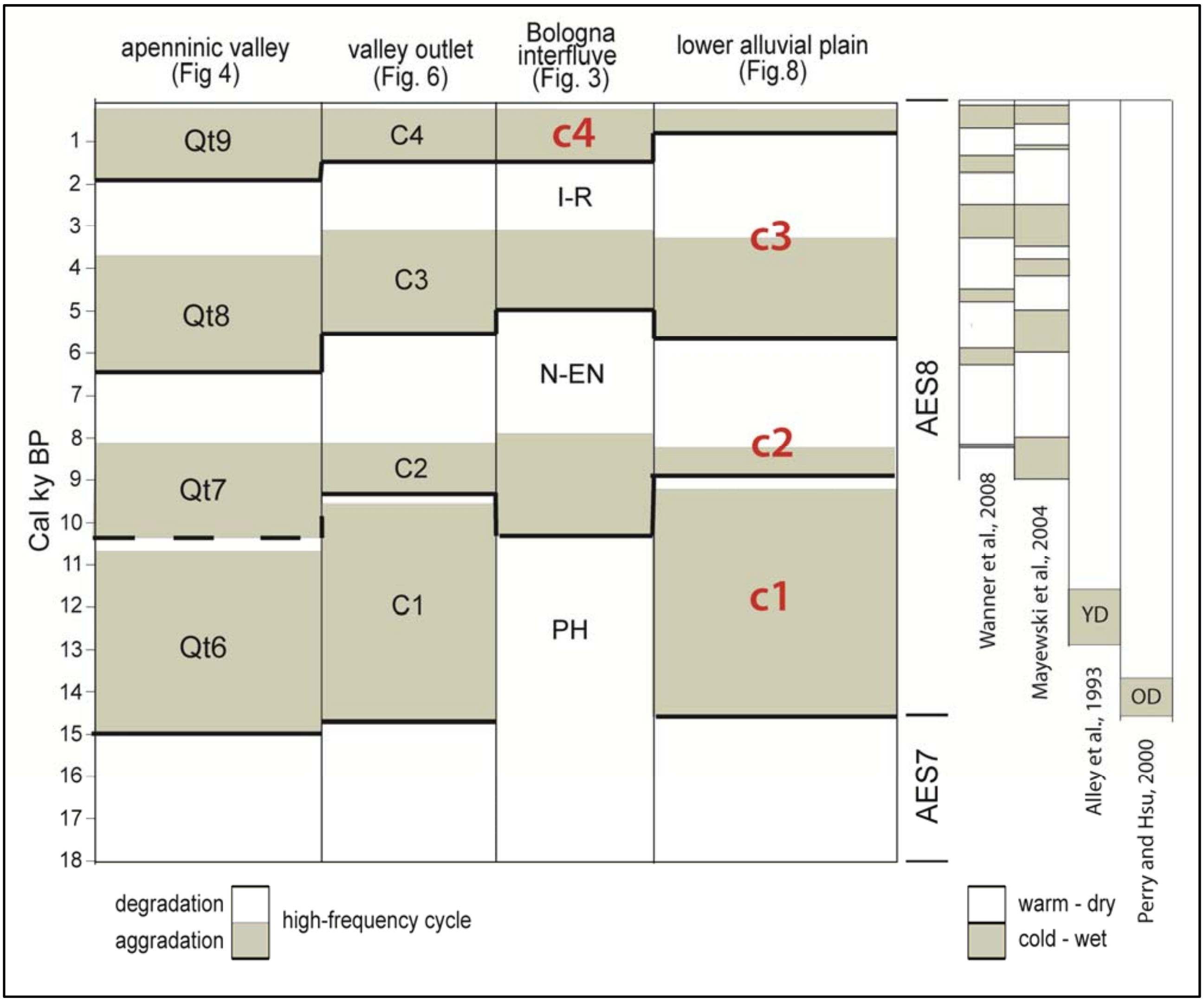

Fig. 11. Diagram depicting the high-frequency depositional cycles detected in distinct sectors of the Reno River and their correlation with cold-humid periods (on the right). YD: Younger Dryas; OD: Oldest Dryas

Progressively younger ages of fluvial flooding surfaces downstream (with the exception of the Bologna interfluve) suggest an “upstream control” on fluvial processes, due to two possible main factors: differential tectonic movements, which could have locally modified the steepness of the river profile, and rapid climate changes, influencing the sediment supply/discharge ratio (Catuneanu et al., 2009). The good correlatability of Reno River terraces with other valley systems of the Romagna and Marche Apennines (Wegmann and Pazzaglia, 2009) suggests a predominant allogenic control on the confined Apenninic valleys. The aggradational phases of depositional cycles c2, c3 and c4 show a good match with the main post-glacial cold-humid phases (Fig. 11), such as the 8.2 (c2), 6 and 4 (c3) cold events, Dark Ages and the Little Ice Age (c4) (Mayewski et al., 2004; Wanner et al., 2008). Samples from terrace Qt6, on the other hand, exhibit ^{14}C ages covering almost entirely the time window of the Lateglacial, between Oldest Dryas and Younger Dryas (Fig. 4 and Table 1).

In the alluvial plain, local factors such as palaeotopography can further complicate the picture. A palaeotopographic reconstructrion of the Iron-Age palaeosol (top of cycle c3) in the Bologna area, combined with the isopach map of the post-Roman deposits (cycle c4), depict the influence of inherited morphology on the thickness of these deposits, spanning between 0 and 9 m (Bruno et al., 2013).

Anthropogenic factors became increasingly important from the mid-late Holocene, due to radical changes in land use. The first important attested phase of deforestation in the Po Plain and in the adjoining Apennines, was contemporaneous with a drastic change in land exploitation at the Neolithic/Eneolithic transition: during the Neolithic, agricultural practices had minimal impact on the vegetation mantle and were exerted in limited portions of the alluvial plain. By contrast, during the Eneolithic, transhumant pastoralism led to intense and widespread deforestation through slash and burn techniques (Cremaschi and Nicosia, 2012). During the Bronze Age and the Iron Age, hydraulic techniques improved parallel to deforestation. Wells for water supply, drainage ditches and embankments are frequently encountered in archaeological surveys close to the Iron Age settlements (Bruno et al., 2013). Water control was ultimately institutionalized during the Roman Empire (Svetonio, *Augustus*, 37). The reactivation of fluvial dynamics from the 3rd century AD, recorded in several areas of the southern Po Plain (Cremaschi and Gasperi, 1989; Bruno et al., 2013, Cremonini et al., 2013), was paralleled by a generalized crisis of human societies and the decline of the Roman Empire, coupled with a dramatic climate deterioration (Büntgen et al., 2011; Dermody et al., 2012).

Sample Code	14C Age	Calibrated 2s	Material	Deposit	Source	Figs	Cycle	Synthem
AA54506	1150±35	1170-970	charcoal	terrace fill	Eppes et alii, 2008	4		
AA54513	1150±40	1180-960	charcoal	terrace fill	Eppes et alii, 2008	4		
LTL-8270A	1410±45	1395-1275	root	floodplain	Cremonini et alii, 2013	3	c4	
LTL-3196A	1530±35	1525-1350	root	floodplain	Cremonini et alii, 2013	7-9		
AA54505	1945±35	1990-1820	shell	terrace fill	Eppes et alii, 2008	4		
ENEA-982	920±90	970-675	wood	floodplain	This work	8		
Ter1	2480±80	2740-2360	charcoal	archeao site	SAER	8		
StBO	2840±130	3275-2747	organic clay	floodplain	Cremonini et alii, 2006	3		
ENEA-929	3090±70	3450-3140	organic clay	swamp	This work	7-8-9		
ENEA-930	3180±90	3635-3210	wood	swamp	This work	7-8-9		
AA54511	3440±30	3830-3630	charcoal	colluvium	Eppes et alii, 2008	4		
AA58316	3840±40	4410-4090	Snail shell	colluvium	Eppes et alii, 2008	4		
ENEA-955	3640±80	4160-3720	charcoal	floodplain	This work	6-8		
AA58315	4040±40	4790-4410	charcoal	colluvium	Eppes et alii, 2008	4		
AA54510	4495±30	5300-4990	weather. shell	colluvium	Eppes et alii, 2008	4	c3	
POZ-35947	4565±35	5190-5055	wood	fluvial channel	Amorosi et alii, 2014	3-8		
AA58317	4695±50	5590-5310	seed shell	colluvium	Eppes et alii, 2008	4		
ENEA-945a	4760±30	5590-5465	wood	fluvial channel	This work	7-8		
AA58318	4785±40	5600-5330	charcoal	colluvium	Eppes et alii, 2008	4		
ENEA-945b	4890±70	5755-5570	wood	fluvial channel	This work	7-8-9		
AA54504	4840±45	5660-5460	charcoal	terrace fill	Eppes et alii, 2008	4		
AA61344	5325±45	6270-5950	charcoal	terrace fill	Eppes et alii, 2008	4		
AA61346	5630±45	6490-6300	charcoal	terrace fill	Eppes et alii, 2008	4		AES8
AA61343	5775±45	6720-6450	charcoal	colluvium	Eppes et alii, 2008	4		
ENEA-956	4410±80	5145-4850	charcoal	archeao site	Amorosi et alii, 2014	3		
Ter2	4540±80	5335-4960	organic clay	floodplain	SAER	8		
POZ-36012	6110±50	7160-6890	organic clay	swamp	Amorosi et alii, 2014	3-8		
LTL-2436A	6310±50	7335-7157	charcoal	floodplain	Ferrari et alii, 2006	6-8		
ETH-45299	6505±35	7485-7410	plant frag	swamp	Amorosi et alii, 2014	7		
ETH-48055	7090±35	7975-7845	organic clay	floodplain	Amorosi et alii, 2014	6-8		
ETH-48056	7385±30	8325-8160	organic clay	floodplain	Amorosi et alii, 2014	3	c2	
221090P513	7490±60	8395-8185	wood	fluvial channel	Amorosi et alii, 2014	Text		
ENEA-983	7580±85	8545-8200	wood	fluvial channel	This work	Text		
202S7	8190±80	9410-8995	plant frag	swamp	Molinari & Pizziolo, 2009	8		
220120A513	8450±220	10175-8980	organic clay	floodplain	Martelli et alii, 2009b	6-8		
220080P476	8820±120	10190-9560	organic clay	swamp	Martelli et alii, 2009a	7-8-9		
220S3_1	8820±300	10715-9235	organic clay	floodplain	Martelli et alii, 2009b	7-8-9		
ETH-46107	9180±30	10420-10240	organic clay	floodplain	Amorosi et alii, 2014	3		
202S1	9360±40	10695-10495	organic clay	floodplain	Molinari & Pizziolo, 2009	8		
ETH-45313	9400±40	10735-10550	organic clay	floodplain	Amorosi et al., 2014	6		
AA64285	9560±55	11130-10690	charcoal	terrace fill	Eppes et alii, 2008	4	c1	
ENEA-931	9600±200	11410-10365	organic clay	floodplain	Amorosi et alii, 2014	8		
AA64287	9920±55	11560-11190	shells	terrace fill	Eppes et alii, 2008	4		
ENEA-924	10170±270	12615-11145	organic clay	floodplain	Amorosi et alii, 2014	3		

Sample Code	14C Age	Calibrated 2s	Material	Deposit	Source	Figs	Cycle	Synthem
AA64286	10405±55	12850-11900	shells	terrace fill	Eppes et alii, 2008	4	c1	AES8
AA64284	10700±80	13000-12350	shells	terrace fill	Eppes et alii, 2008	4		
ETH-45848	11680±35	13685-13390	organic clay	floodplain	Amorosi et alii, 2014	3		
AA54508	11960±60	15250-13550	shell	terrace fill	Eppes et alii, 2008	4		
220S9	12510±200	15270-13940	wood	swamp	Martelli et alii, 2009b	8		
AA54512	12690±50	15750-14250	weathered shell	terrace fill	Eppes et alii 2008	4		
ETH-45328	11375±45	13360-13130	organic clay	floodplain	Amorosi et alii, 2014	8		AES7
ETH-48057	12570±40	15175-14490	organic clay	floodplain	This work	6		
ETH-48058	13800±45	17075-16745	organic clay	floodplain	This work	6		
220S3_2	13930±300	17920-16335	organic clay	floodplain	Martelli et alii, 2009b	7-8-9		
220S6	14970±120	18570-17895	organic clay	floodplain	Martelli et alii, 2009b	6		
ETH-45320	15960±40	18985-18640	organic clay	floodplain	Amorosi et alii, 2014	6		
AA64283	17470±330	21850-19750	Shells	colluvium	Eppes et alii, 2008	4		
AA61345	19320±120	23750-22150	shell frags	terrace fill	Eppes et alii, 2008	4		
QT5	19470±330	24060-22385	Wood	terrace fill	Picotti & Pazzaglia, 2008	4		
AA54503	19670±90	24050-22650	Shell	terrace fill	Eppes et alii, 2008	4		
ENEA-925	21550±180	26300-25080	organic clay	floodplain	Amorosi et alii, 2014	3		
202S13	22600±100	27830-26810	organic clay	floodplain	Molinari & Pizziolo, 2009	8		
POZ-35948	22870±160	28100-26900	organic clay	floodplain	Amorosi et alii, 2014	3		
ETH-45321.2	23930±90	29220-28370	organic clay	floodplain	Amorosi et alii, 2014	6		
ETH-45650	26640±100	31310-31000	organic clay	floodplain	Amorosi et alii, 2014	3		
ETH-45326	27030±90	31500-31140	organic clay	floodplain	Amorosi et alii, 2014	6		
202S2	29040±200	34500-33120	organic clay	floodplain	Molinari & Pizziolo, 2009	8		
ETH-45303	29310±200	34590-33350	organic clay	floodplain	Amorosi et alii, 2014	3		
ETH-45315	30925±250	36300-34890	organic clay	floodplain	Amorosi et alii, 2014	6		
POZ-36013	34200±600	40850-37580	organic clay	floodplain	Amorosi et alii, 2014	3		
ETH-45305	36960±500	42660-41100	organic clay	floodplain	Amorosi et alii, 2014	3		

Table 1. List of radiocarbon dates of Figures 3-10

7. Conclusions

Stratigraphic reconstructions along the Reno River profile, based on the correlation of laterally extensive palaeosols, enabled the identification of a cyclic facies alternation at the millennial scale within the Late Pleistocene-Holocene alluvial succession. The major outcomes of this research can be summarized as follow:

(1) vertical variations in channel stacking patterns and soil development allowed the identification of (i) a low accommodation systems tract, characterized by laterally-extensive

fluvial-channel deposits connected to weakly developed palaeosols, and (ii) a floodplain-dominated high accommodation systems tract, with lens-shaped fluvial channel deposits and poorly to weakly developed palaeosols. The high accommodation systems tract coincides with the unconformity-bounded stratigraphic unit of post-LGM age, named AES8 after the Geological Map of Italy.

(2) Four high-frequency depositional cycles, composed by overbank and fluvial deposits, and capped by soil horizons, were identified within AES8, and dated to about 15-10, 10-5.5, 5.5-1.5, and <1.5 ky BP, respectively. The base of each cycle is the contact between a soil horizon and overlying overbank deposits. This surface can laterally be traced into the erosional base of fluvial-channel bodies and to the strath of alluvial terraces cropping out in the Apenninic valley.

(3) The bounding surfaces of small-scale depositional cycles are identifiable within seemingly homogeneous floodplain successions, and do not correspond necessarily to marked lithological changes.

(4) The transition from aggradation to degradation phases within each cycle was not synchronous along the river longitudinal profile. This diachroneity is reflected by lateral variations in the development of soil horizons.

(5) River aggradation and degradation were likely triggered by rapid climate changes, aggradational phases taking place during cold-humid periods. The impact of anthropogenic factors became progressively more important since the middle-late Holocene, following the development of agricultural techniques. Widespread deforestation during the early Eneolithic Age enhanced aggradation, whereas improved hydraulic techniques starting from the Iron Age favoured the onset of pedogenesis.

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Paper 4. **Human-landscape interactions in the Bologna area (Northern Italy) during the middle-late Holocene with focus on the Roman period**

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Abstract

Integrated sedimentological and archaeological investigations of mid-late Holocene deposits from the subsurface of Bologna elucidate the complex relationship among urban settlement, human society, geomorphology and climate change at the southern margin of the Po Plain. Above the Pleistocene-Holocene unconformity, the Holocene succession forms an intricate mosaic of alluvial deposits. Two palaeosols, spanning between about 8000-5000 cal yr BP and 3200-1500 cal yr BP, respectively, represent the most prominent stratigraphic markers across the study units. A huge amount of archaeological remains from the younger palaeosol enables the identification of an uninterrupted sequence of settlements from the Early Iron Age to the Late Roman period. The first permanent settlements of Iron Age took place in a topographically elevated region protected from flooding. The onset of pedogenesis during this period reflects the radical transformation of the environment by human settlements through widespread control of the river network and setting of regular patterns of irrigation channels. A period of exceptional climate stability characterized the expansion of the Roman Empire. This phase is testified by a wealth of exceptionally preserved archaeological material including buildings, cemetery sites, streets and irrigation channels. Subsurface correlations of the Roman palaeosol enable detailed reconstruction of the Roman topography, with special focus on fluvial paths and communication routes. The decline of the

Roman Empire, hit by a devastating epidemic and the barbarian invasions, was paralleled by a phase of climatic deterioration, resulting in the abandonment of rural lands and degradation of the river network, which ultimately favoured the burial of Roman settlement.

Keywords: Geoarchaeology, Urban geology, Alluvial system, Human settlement, Iron Age, Roman period, Italy

1. Introduction

Alluvial and coastal plains are densely populated regions that store beneath their surface detailed archives of late Holocene environmental changes and their relationship with human settlements (Brown, 2008). Conventional geoarchaeological studies in these areas rely upon the integration of historical documentation, archaeological surveys and detailed geomorphological mapping. The common geomorphological approach, however, is strongly limited in highly urbanized areas, owing to strong anthropogenic disturbance. On the other hand, modern urban areas commonly benefit from high density stratigraphic information, mostly derived from foundation drillings.

In Mediterranean urban areas, the abundance of stratigraphic data due to massive processes of urbanization and construction is generally coupled with cultural prominence and a wealth of archaeological documentation. All these data are typically clustered in the historical centres. Towns and cities thus represent intriguing sites where the evolution of human societies can potentially be framed into a context of changing palaeoenvironments. Geoarchaeological investigations of Holocene deposits from urban areas of the European Mediterranean based upon integrated stratigraphical, archaeological and historical data are those of Marseille (Mohrange et al., 2001; 2003), Rome (Giraudi et al., 2009; Di Rita et al., 2010, 2011; Bellotti et al., 2011), Pisa (Benvenuti et al., 2006; 2011; Rossi et al., 2012), Ferrara (Stefani and Zuppiroli, 2010), Cyprus (Butzer and Harris, 2007) and Thessaloniki (Fouache et al., 2008; Ghilardi et al., 2012).

The town of Bologna, located at the northern foothills of the Apennines (Fig. 1), represents an excellent test site to perform a geoarchaeological study focused on stratigraphy, for a number of reasons: (i) the high level of geological knowledge, derived from both subsurface (Amorosi et al., 1996) and outcrop (Picotti et al., 2009) studies; (ii) the large availability of stratigraphic data beneath the historical centre, with average density of about 80 data/km^2; (iii) an almost constant human presence since the middle Holocene, which provides the basis for the identification of repeated phases of human occupation. The Bologna area was already an important urban centre under the Etruscans, between the 7th and the 6th century BC (Taglioni, 1999). The Romans, one of the most advanced and enduring societies, founded the colony of Bononia (Roman name for Bologna) in 189 BC. Two years later, they built the *Via Aemilia*, a road that runs along the boundary between the Apenninic chain and the Po Plain (Fig. 1).

This study relies on a huge stratigraphical and archaeological dataset (Fig. 1), stored at the Geological, Soil and Seismic Survey of Regione Emilia-Romagna and at Superintendence to Archaeological Properties of Emilia-Romagna, respectively. The aim of this paper is to provide stratigraphical evidence of distinct phases of human occupation in the Bologna area during the middle-late Holocene, through reconstruction of subsurface facies architecture and physical tracking of ancient soil horizons. Specific objective is to document the Late Bronze Age to Roman palaeoenvironments and address the issue of the relationships between historical settlement, climate variability and palaeoenvironmental evolution in the Bologna area in terms of natural versus anthropogenic forcing.

2. Geological setting

The Po Plain is the superficial expression of a foredeep basin bounded by two mountain belts (the Apennines to the south and the Alps to the north), which developed during the Pliocene and the Quaternary (Ricci Lucchi, 1986). The Quaternary succession displays a strong wedge-shaped geometry at the southern basin margin. In the depocentre, south of modern Po River, it is several hundred metres thick, with minimum values (about 100 m) in the Ferrara area (Regione Emilia-Romagna and Eni-Agip, 1998).

At the southern margin of the Po Basin, the Quaternary deposits consist of coalescing fluvial-channel complexes, resulting from the lateral migration of the Apenninic rivers into the alluvial plain (Amorosi et al., 1996; 1997). Due to the short distance between adjacent Apenninic valleys, these fluvial systems tend to coalesce into a unique composite sedimentary body, elongate parallel to the basin margin. Because of the point-sourced feeding systems, at most proximal location fine-grained strata may occur between successive river outlets.

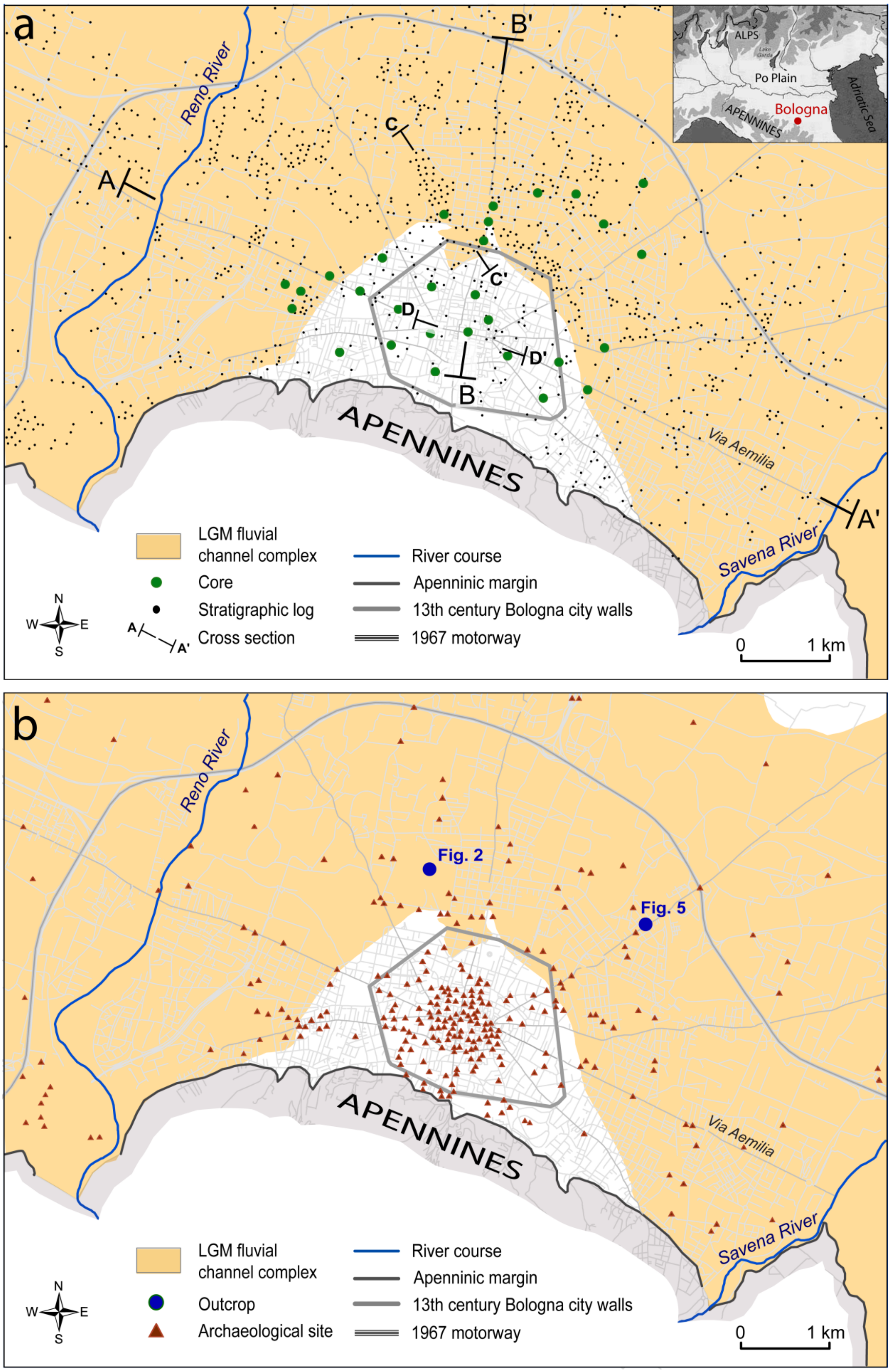

Fig. 1. Study area, with location of: A. about 3000 stratigraphical core drillings (black and green dots) and the section traces of Figures 3 and 4; B. 500 archaeological sites of interest (red triangles) and outcrops of Figures 2 and 5 (blue dots). LGM: Last Glacial Maximum. The reconstructed areal extent of the two LGM fluvial channel systems is from Amorosi et al. (1997), modified.

The town of Bologna is bounded by two rivers with characteristic torrential regime (Fig. 1): Reno River to the west and Savena River to the east. During the Last Glacial Maximum, lateral migration of these two rivers affected a large part of the area, as documented by the coalescence of gravel bodies north of the historical centre (Fig. 1). A predominance of silt-clay deposits has been instead reported from beneath the town centre (Amorosi et al., 1997). This is due to the particular position of the Bologna area, in the middle of a triangle-shaped, interfluvial area between the Reno and Savena outlets (Fig. 1).

The Pleistocene-Holocene boundary, which typically separates over-consolidated stiff (glacial) clays from overlying, relatively soft ("transgressive-equivalent") deposits, has been clearly identified in cores and on the basis of piezocone penetration tests (see Amorosi and Marchi, 1999, for a review). This surface, which commonly separates Pleistocene gravel-dominated deposits from an overlying, Holocene mud-prone succession, represents a key stratigraphic boundary used for allostratigraphic subdivisions.

3. Methods

More than 2000 stratigraphic data compose the geological dataset. In particular, we used 29 continuous cores as reference for facies analysis. Stratigraphic data from drillings and cone penetration tests were used as additional tools to obtain information about lithology, accessory materials and physical properties of the study units. Key outcrops were used to predict the extent of sediment body geometries. Sixteen samples of charcoal, wood, and organic-rich clay were radiocarbon dated. All samples were cleaned from contaminations through acid-alkali-acid pre-treatment and dated through liquid scintillation counting at Bologna ENEA Laboratory (Italy) or AMS technique at Poznan Radiocarbon Laboratory (Poland) and Laboratory of Ion Beam Physics (ETH, Zurich, Switzerland). The ^{14}C dates were calibrated with Oxcal 4.1 (Bronk Ramsey 2009), using the Intcal-09 calibration curve (Reimer et al., 2009). Six previously published radiometric dates were used to refine the chronological framework (see Supplementary material).

About 750 archaeological profiles were used to reconstruct the Roman topographic surface: (i) 450 profiles from local studies carried out between the end of the 19th century and 1980, (ii) 300 profiles from recent reports, where detailed successions of settlements are documented. All these reports where re-interpreted under a geoarchaeological perspective, marking for each reference point elevation (above sea-level) and depth (below ground surface) of the Roman topographic surface. These data where were georeferenced and contoured using ArcGis. The map was then re-drawn by hand. Calibration of stratigraphic data with archaeological documentation and radiocarbon dates allowed the lateral tracking of the Roman palaeosol. To reconstruct the palaeoenvironmental conditions in which the settlements took place, additional data (type of settlement, evolution of the construction techniques, stratigraphy, hydraulic information) were collected from the archaeological reports.

4. Depositional facies associations

Detailed sedimentological analysis was carried out on both cores and outcrops. This enabled identification of the main facies associations on the basis of lithology, vertical trends in grain-size, thickness, type of stratigraphic contact, and geometry of sedimentary bodies.

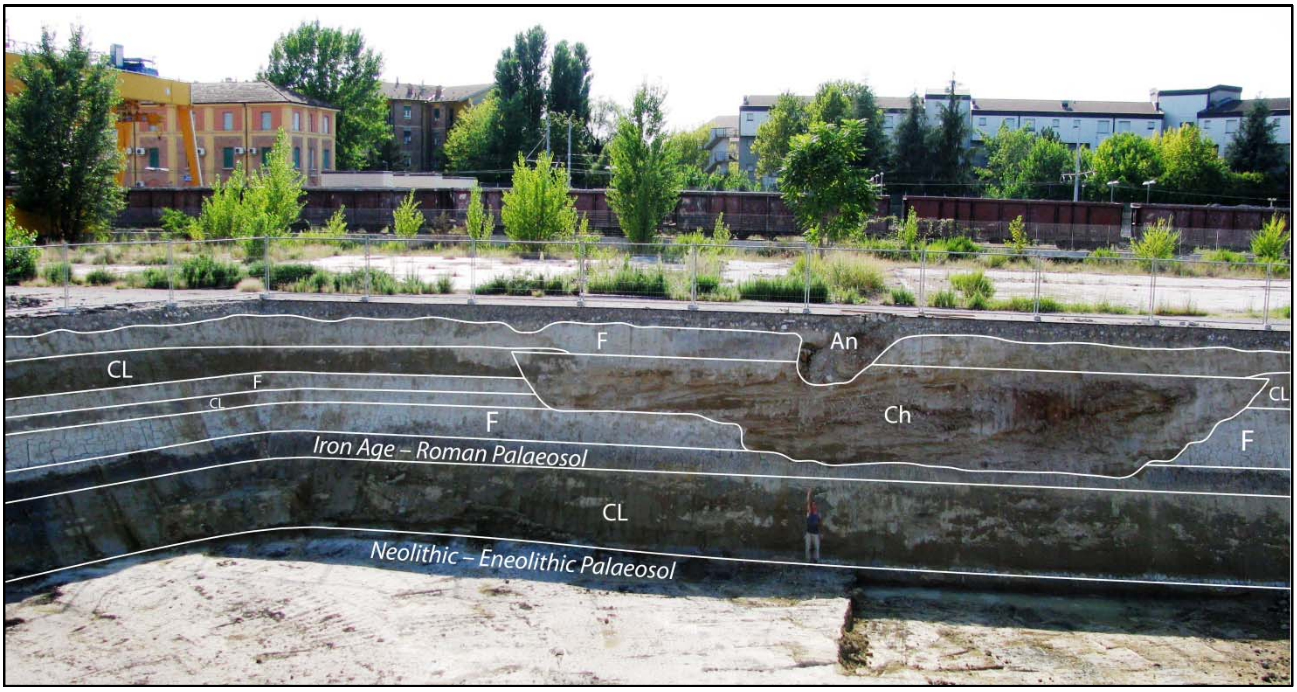

Fig. 2. Example of facies interpretation from outcrop (see Fig. 1, for location), showing stratigraphic location of the two Holocene palaeosols. Ch: Fluvial channel, CL: Crevasse-levee, F: Floodplain, An: Anthropogenic.

4.1. Fluvial-channel facies association

Description. This facies association is made up of coarse-grained (gravel and sand) sedimentary bodies, with erosional lower boundaries and either sharp or gradual transition to the overlying muds. Gravel bodies are commonly matrix-supported, with an upward increasing proportion of sand and silt. The gravel/mud ratio decreases with the distance from the Apenninic chain. In the most proximal outcrops, gravel bodies are poorly sorted and disorganized, while moving downstream they consist of vertically stacked sets with horizontal and high-angle cross-stratification. Gravel bodies are commonly amalgamated, with overall thickness that may exceed 10 m. Their lateral extension generally exceeds the maximum visible width in quarries (several hundred metres). Tree trunks are commonly found in the lower part of these bodies. In contrast, sand bodies are markedly lenticular, thinner (2-6 m) and significantly narrower (15-40 m). Inclined bedding is a common feature (Fig. 2), although high-angle cross-stratification is frequently found. Basal pebble layers are frequently encountered. Organic-rich layers are common atop this facies association. Fossils are absent.

Interpretation. On the basis of its sedimentological characteristics (erosional lower boundary, fining-upward trend and diagnostic sedimentary structures) this facies association is interpreted to reflect fluvial-channel fills. The alternation of massive, horizontally stratified and cross-bedded gravels is a characteristic feature of longitudinal bars within a braided stream network (Rust, 1972; Miall, 1977). A clear separation between bed load and suspended load is indicated by the abundance of traction structures, whereas mass transport processes associated to high magnitude flooding events are suggested by poor sorting. Inclined bedding within highly lenticular sand bodies is likely to reflect lateral accretion features (epsilon bedding) within high-sinuosity, ribbon-shaped meandering rivers (Allen, 1963). Vertical and lateral amalgamation of gravel bodies resulted from lateral channel migration within an overall subsiding (aggrading) system. The vertical transition from coarse-grained to overlying mud-prone deposits through sharp or gradual contacts reflects either abrupt or gradual channel abandonment, respectively.

4.2. Crevasse and levee facies association

Description. This facies association is characterized by two depositional facies, with distinct lithologies. One facies consists of sand bodies, 0.5-2 m thick, made up of very fine to medium sand. These bodies exhibit abundant high-angle cross-stratification and may show either coarsening-upward (CU) tendencies, with gradual transition to underlying mud deposits, or (less commonly) fining-upward (FU) trends, with erosional lower boundaries. Another facies includes a rhythmical alternation of very-fine sand and silt layers, on a few cm to 20 cm scale. Horizontal lamination and small-scale cross-lamination are the most common sedimentary structures. In outcrop, this facies shows transition to the upper portion of fluvial-channel bodies and thins out rapidly away from the channel axes (Fig. 2)

Interpretation. Sedimentological features and the diagnostic stratigraphic relationships with the adjacent fluvial bodies (see section CC', Fig. 4) suggest that this facies association represents a variety of "channel-related" deposits. The relatively thicker sand bodies are inferred to represent crevasse deposits. Specifically, sharp-based bodies with internal FU tendencies are thought to have been formed in crevasse channels, while CU sand successions with gradational lower boundary should be representative of crevasse splays. Sand-silt alternations are instead characteristic features of natural levee, overbank deposits. Their particular stratigraphic position, contiguous to the upper part of fluvial-channel bodies, makes them interpretable as channel wings (Friend et al., 1979).

4.3 Floodplain facies association

Description. This facies association, up to 20 m thick, consists of a monotonous succession of silts and clays, locally interrupted by pedogenized horizons. Palaeosol profiles range in thickness between 70 and 180 cm, and generally display sharp tops and gradual lower boundaries. The upper horizons, 40-80cm thick, are readily recognizable by their characteristic brownish to black colour (Hue 10YR-2.5Y, Value 3-5, Chroma 2-4), weak or strong reaction to HCl, and common anthropogenic material. These horizons are locally underlain through gradual contacts by lighter (Hue 2,5Y, Value 4-5 e Chroma 2-4) and strongly indurated horizons, 30-100 cm thick, showing very strong reaction to HCl. Sedimentary structures are lacking along the palaeosol profile, owing to intense bioturbation, whereas root traces, vegetal remains, Fe and Mn oxides, polygonal structures and slickensides are common. Rare freshwater gastropods were encountered. Organic-rich clays, grey to black in colour, were also observed. These clays typically have soft consistency and contain abundant freshwater macrofossils, wood and plant fragments. Peat layers are common. Carbonate concretions and iron oxides are absent.

Interpretation. Massive silt and clay deposits are interpreted as the result of deposition of fine overbank suspended load. The abundance of plant material, concurrently with oxidation and rare freshwater molluscs, is consistent with a floodplain environment, contiguous to fluvial channels. Palaeosols with thin upper (A) horizons, showing strong reaction to HCl and no well-developed horizonation are interpreted as immature (Entisols). Palaeosols with dark, indurated A horizons, slightly reacting to HCl and overlying $CaCO_3$-rich deposits are inferred to represent weakly developed palaeosols (Inceptisols), with characteristic A-Bw-Bk profiles. The Inceptisols indicate phases of subaerial exposure on the order of a few thousands of years, with calcium carbonate dissolution and accumulation in the underlying horizon. The abundance of archaeological remains documents the presence of human settlement in the area. Dark, soft clays with abundant freshwater molluscs and plant fragments are interpreted to have formed in paludal (backswamp) environments.

4.4 Anthropogenic facies association

Description. This facies association is made up of chaotic, unconsolidated and unsorted deposits of different provenance. The coexistence of materials of both human (bricks, charcoal, plastic and iron fragments) and natural (sediment, wood, bones) origin is the diagnostic feature of this unit. Blocks and cobbles generally have undifferentiated origin and exhibit angular, sub-angular or rounded shapes. No sedimentary structures are detectable. In outcrop, rests of manufactures and building structures are commonly encountered. Lens-shaped bodies, 1 to 3 m wide and up to 1.5 m thick, with erosional base and dark to black, massive clayey fills are locally observed.

Interpretation. Lack of sedimentary structures and the presence of dateable, man-made materials, enable the attribution of this facies association to human activity. In particular, the unsorted and unconsolidated deposits are generally related to landfill activities, whereas higher levels of clast organization often reflect building foundations. The lens-shaped bodies with dark clayey fills are interpreted as channels of anthropogenic origin in which low-energy flow conditions were maintained. Since recent fluvial channels may include bricks as bed-load, but at the same time fluvial, sub-rounded pebbles may have been utilized for building foundations and roads, the distinction between fluvial and anthropogenic material from cores can be a difficult task.

5. Late Quaternary stratigraphy and archaeology

The high-resolution stratigraphical study carried out in this work is consistent with previous investigations from the Bologna area (Amorosi et al., 1996, 1997), showing a strikingly contrasting facies architecture between the town centre and the contiguous, periurban areas (Fig. 3, cross-section AA'). Laterally extensive fluvial channel complexes, made up of amalgamated gravels and sands, are the distinctive stratigraphic feature beneath modern Reno and Savena rivers. These sedimentary bodies reflect fluvial activity within two separate palaeovalleys that were active during the Last Glacial Maximum (Amorosi et al., 1996 - see Fig. 1). The two fluvial depositional systems typically merge north of Bologna into a laterally extensive gravel-sand body (Figs. 1 and 3, cross-section BB'), while no coarse-grained deposits are recorded beneath the historical centre, which acted invariably as an interfluve. Indeed, at this location, the late Quaternary succession consists almost entirely of thick silt-clay floodplain deposits, with rare thin sand intercalations (Fig. 3).

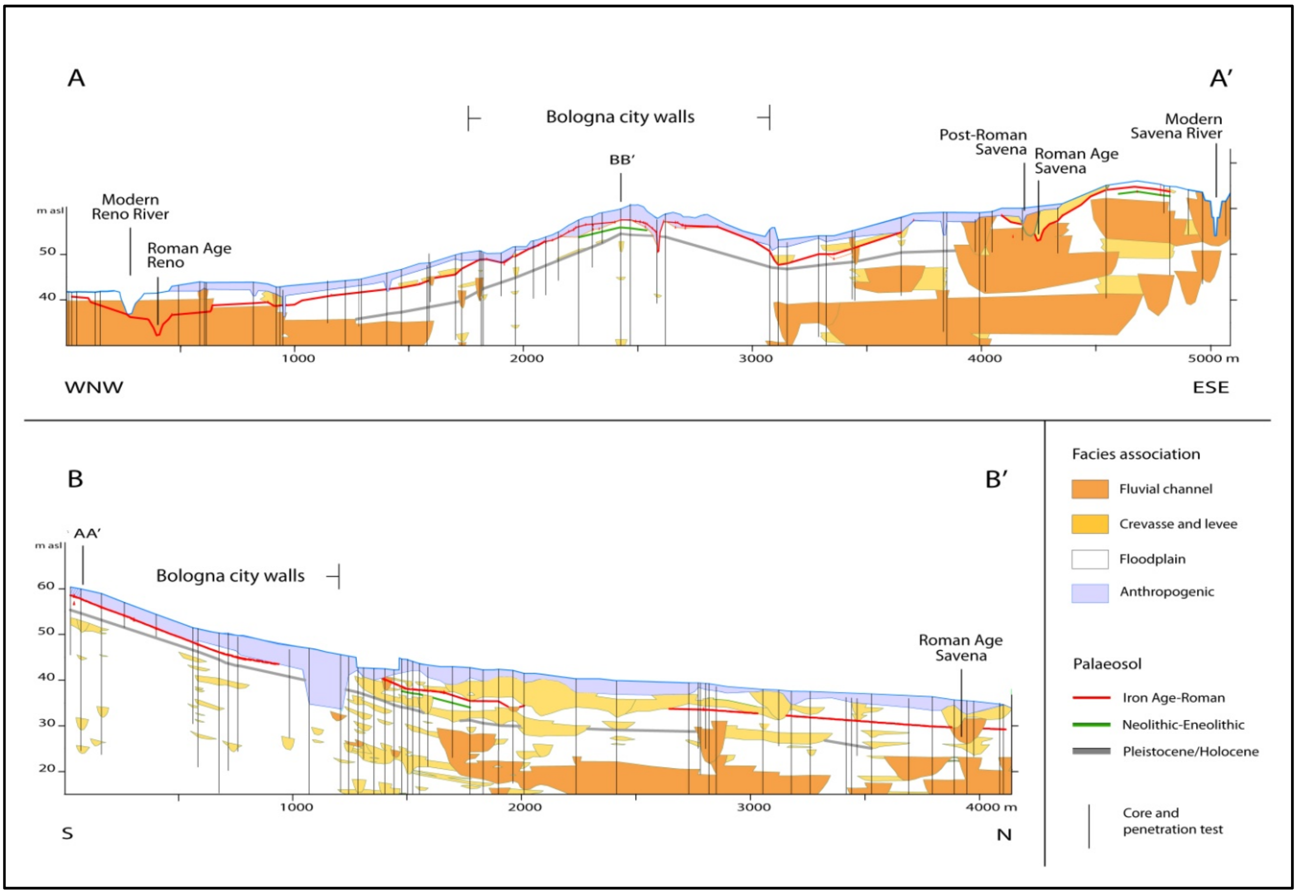

Fig. 3. Stratigraphic cross-sections (for section traces, see Fig. 1) depicting the late Quaternary facies architecture in the Bologna area.

5.1. Holocene stratigraphy

The stratigraphic unconformity close to the Pleistocene-Holocene boundary represents the most valuable stratigraphic marker within the study succession (Fig. 3). This surface is a characteristic indurated horizon associated to a remarkable depositional hiatus (Fig. 4).

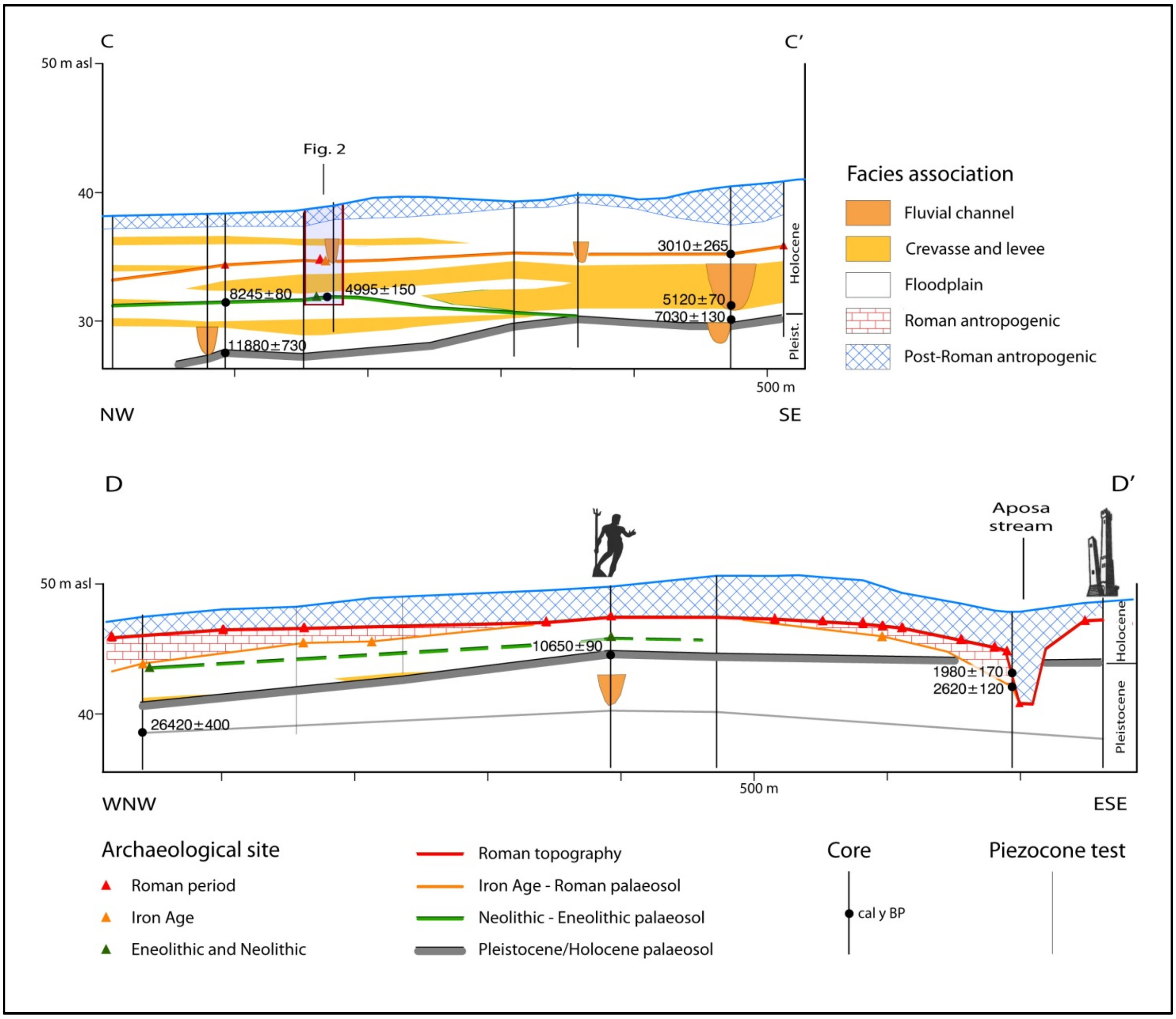

Fig. 4. Stratigraphic cross-sections (for section traces, see Fig. 1) showing contrasting facies architecture between the periurban (section CC') and urban (section DD') Bologna areas. Anthropogenic units are amalgamated beneath the town centre, whereas they are separated by overbank deposits north of the urban area.

Two closely-spaced palaeosols represent additional stratigraphic markers within the Holocene succession of the Bologna area (Figs. 3 and 4). Given their stratigraphic position, just few metres below the ground surface, these palaeosols can be identified using not only core data, but also deep excavations (Fig. 2). The lower palaeosol, commonly encountered 5-7 m below the ground surface, is highly discontinuous (Figs. 3 and 4). A variable thickness (commonly about 2 m) of overbank and crevasse deposits separates this palaeosol from the upper one (Fig. 2), which exhibits instead significantly greater lateral continuity (Figs. 3 and 4). Based upon existing and new radiocarbon dates (see Supplementary material) we were able to establish a precise chronological attribution for these two palaeosols. Particularly, the older palaeosol was radiocarbon dated to about 8000-5000 cal yr BP, while an age of about 3200-1500 cal yr BP was assigned to the upper palaeosol, based upon combined ^{14}C dates and archaeological evidence (see Section 6.2).

Archaeological digs and excavations in the subsurface of Bologna unearthed an abundance of archaeological remains associated to the Holocene palaeosols. The older palaeosol bears evidence for human settlements and artifacts of Neolithic and Early Eneolithic age. Late Eneolithic rests, dated to 4100-3800 cal yr BP, were documented uniquely close to the Reno outlet and in the small town of Castenaso, 10 km east of Bologna (Cadeddu et al., 2011). The younger palaeosol contains material from the Late Bronze Age to the Roman period (Fig. 5).

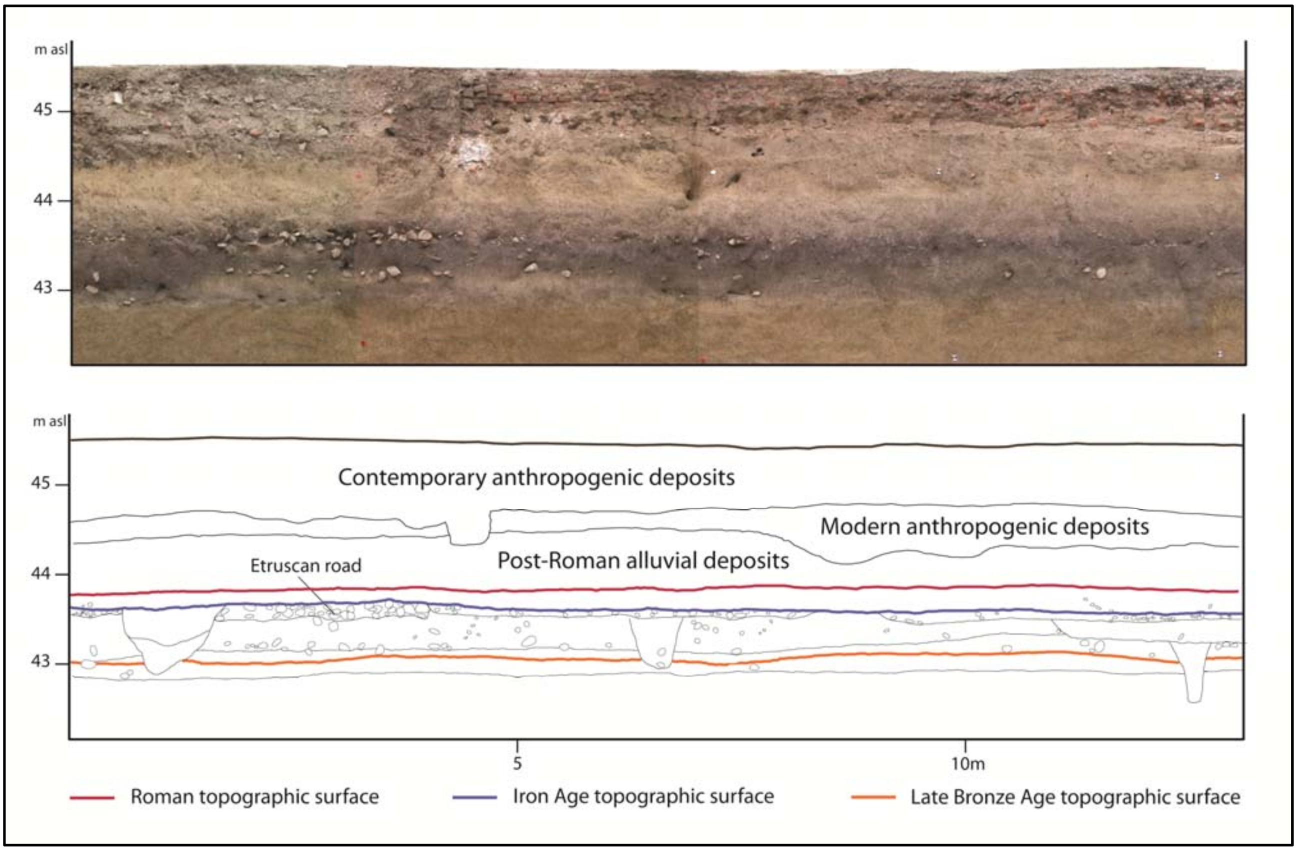

Fig. 5. Examples of composite palaeosol recording distinct stages (Late Bronze, Iron Age, Roman) of human occupation (see Fig. 1, for location).

However, remains of Late Bronze Age are relatively uncommon, and the palaeosol can be regarded as developed almost entirely during the Iron Age-Roman period. There is no evidence in the Bologna area of earlier (Early-Middle Bronze Age) settlements, such as the *terramare* culture, which are instead well documented in other sectors of the Po Plain (Greig, 1984; Barfield, 1994; Cardarelli, 1997; Cremaschi et al., 2006).

The next sections explore the archaeological characteristics of the Iron Age-Roman palaeosol, for which a wealth of archaeological material is available (Fig. 6).

5.2. Types of archaeological material

The abundance of archaeological remains from the Iron Age-Roman palaeosol and their stacking at distinct stratigraphic levels provide evidence for a sequence of settlements indicative of different cultures and traditions (Fig. 5). Each culture was identified by particular architectural styles and death rituals. Archaeological dating of coins and ceramics enabled the attribution of distinct anthropogenic units to specific phases of human settlement. The archaeological material can be classified in four classes. These are summarized below.

5.2.1. Buildings

On the basis of the material used and construction techniques employed, five distinct cultural stages were distinguished: Early Iron Age (Villanovan Culture, 9th–8th century BC), Etruscan Age (7th – 6th century BC), Roman Republican Age (5th–1st century BC), Roman Imperial Age (1st century BC – 3rd century AD), and Late Antiquity (3rd–4th century AD). Documentation of the Early Iron Age dwellings derives mainly from depictions on urn burials by the Villanovans in Latium, where they are represented as gabled huts. Because of the low preservation potential of the material used (timber, wattle and clay), only traces of the bottom of these huts were detected. The oldest buildings made of stone are attributed to the Etruscan culture. The transition to the Roman building techniques is invariably marked by the occurrence of baked bricks. Large availability of clay ensured their preferential use relative to other types of stone, which however continued to be used as building material. Standard size and different types of concrete enabled attribution of the archaeological remains to distinct phases of Roman occupation (Marta, 1986; Pavia and Caro, 2008). Stone and baked bricks were used to build masonry foundations less than one metre high, while the rest of the masonry was made of sundried bricks (Marta, 1986). For this reason, only the foundation of Roman dwellings are generally preserved, with sparse tiles and accessory material made of stone, concrete or baked clay (Fig. 6a). Distinct types of dwellings typify the urban and rural areas. Rural houses in the subsurface of the periurban area of Bologna are generally farms (*villae rusticae*) with associated productive areas, storehouses and gardens (Fig. 6a). The *domus* or private home, and the *insula* or multi-storey tenement are the typical findings of the urban centre. The existence of temples, marketplaces, government buildings, theatres and public baths has been attested in the subsurface of the ancient urban area (Ortalli, 1986, 1989, 1999).

5.2.2. Street, bridges and communication routes

The most notable archaeological rests are roads of Roman period, with only subordinate roads of Etruscan age. Roman roads allowed rapid diffusion of the materials and methods of construction (Berechman, 2003), which for these reason represent temporal markers throughout the Roman Empire. The current knowledge of road construction techniques derives mainly from archaeological surveys, while rare notes are present in the Roman historiography (*Statius, Silvae, IV, 3, 40 segg.; Vitruvium, De architectura, VII, 1 segg.; Plinius, Naturalis Historia, XXXVI, 186 segg.)*. Findings of Roman roads are frequent in the Roman urban area, where a network (partly inherited by the Etruscans) of W-E and N-S oriented streets has been reconstructed (Bergonzoni and Bonora, 1976). The two major roads, the *Cardine maximum* (N-S oriented) and the *Decumanus maximum* (W-E oriented), subdivide the urban area into four sectors, and represent the link between urban and rural communication route networks (Fig. 7). Only sparse evidence of Roman roads is available from rural areas (Fig. 6b).

5.2.3 Cemetery sites

Death rituals have chronologically specific role in the distinct cultures. Cremation was preferentially used during the Early Iron Age by the Villanovans (this term derives from the town of Villanova, a few km from Bologna), whose necropolis are fingerprinted unequivocally by the typical bi-conical urn (Fig. 6c). On the other hand, inhumation was common in the Etruscan and Celtic burials. Both Etruscan and Celtic tombs were dug into the ground, but the Etruscan tombs had a more complex architecture than simple pit graves. Both inhumation and cremation rites are present in the Roman funeral complexes unearthed in the Bologna area, generally along the major rural roads. During the Late Antiquity, inhumations returned to be the preferential rite and the tombs (Fig. 6d), identifiable by their characteristic gabled shape (*tombe alla cappuccina*), are generally the topmost archaeological unit in the Late Bronze Age–Late Antiquity sequence. Although the type of sarcophagus (in case of inhumation) or cinerary urn (in case of cremation) may allow attribution of a specific type of burial to a particular culture, the grave goods can be used to refine chronological attribution: coins (Fig. 6e), jewellery, clothes, utensils and weaponry may serve as efficient chronological markers, with even centennial temporal resolution.

5.2.4. Anthropogenic channels and hydraulic features

Archaeological reports attest the existence of drainage ditches and irrigation channels since already the Early Iron Age. Ducts exposed in outcrops during the archaeological surveys (Fig. 6f, g), appear lens-shaped in cross-section and rectilinear in plan view. They are generally filled with brownish clays, testifying to low-energy conditions, with subordinate clasts and artifacts, which indicate its period of activity. Multiple channels can be present in the same archaeological site: dating of channel-fills proved that ducts W-E and N-S oriented generally predate the construction of the *Via Aemilia*. Starting from the 2^{nd} century BC, forested and swampy areas were progressively reclaimed and organized in a regular square grid of agricultural plots (*centuriae*) that were allocated to the Roman Army veterans (Marchetti, 2002). These plots were delimitated by roads and ditches parallel and perpendicular to the *via Aemilia*. The subsequent channel network had the same orientation of the centuriation. Among other hydraulic features, embankments, drywalls and palisades have been found close to the Etruscan and Roman urban Area (Ortalli, 1993).

Fig. 6. Types of archaeological findings in the subsurface of Bologna: A. rests of a Roman farm (*villa rustica*) in plan view, discovered during the excavation for the construction of the new Municipality of Bologna, north of the historical centre (Archive of the Suprintendence of Archaeological Properties of Regione Emilia Romagna - SAER); B. Roman road (*glareata*), N-S oriented, along the N prolongation of the *cardine maximum* (see R5 in Fig. 7) (SAER); C. Villanovan double (bi-conical) cinerary urn (Civic Archaeological Museum of Bologna); D. typical Late Antiquity inhumation (SAER); E. coin from the grave goods of a Roman inhumation assigned to the 3rd century BC (SAER); plan view (F) and cross-section (G) of an anthropogenic channel dated to the Iron Age (SAER).

6. Human settlements and the development of the Iron Age-Roman palaeosol

6.1 Reconstruction of the Roman landscape

The Roman colony of Bononia was located close to the Apenninic foothills, in a topographically elevated area particularly favourable for human settlement, bordered on the west and on the east by two river incisions (c3 and c4, Fig. 7). Archaeological evidence indicates the existence of stable human settlements in this area since already the Iron Age. Archaeological data, integrated with historical documentation and stratigraphic (palaeosol) correlations (Figs. 3 and 4), enable the accurate reconstruction of the Roman landscape in the Bologna area. Particularly, three major features of the Roman topography are outlined (Fig. 7): (i) surface morphology, depicted by means of 2 m-spaced topographic contours; (ii) the river network; (iii) communication routes.

In the Bologna area, the modern alluvial plain still preserves traces of the ancient Roman topography. Centuriation, for example, is identifiable from the modern road layout, which is partially organized according to the typical 700-m square grids (Fig. 7). An Inceptisol of Roman period, with partly decalcified ‘A’ horizon (up to 80 cm thick), crops out patchily at the Apenninic foothills and in N-S elongated rural areas, W and E of Bologna. In these areas, archaeological rests of Roman period can simply be unearthed by deep plowing. In contrast, in the town centre the Roman topography is buried beneath about 5 m of alluvial deposits (Fig. 4, section CC’) or is part of a complex succession of stacked anthropogenic units (Fig. 4, section DD’).

The contour map reconstructed for the Roman period shows an overall N-dipping topographic surface (Fig. 7). Higher gradients are observed close to the Apenninic chain, around the town centre (Bologna interfluve), whereas low-angle dip slopes are reconstructed from relatively more distal positions. The Reno and Savena rivers flowed in significantly different position compared to the modern paths (Fig. 1), and merged about 5 km north of Bologna. Five short creeks draining the adjacent Apenninic chain and flowing in S-N direction (c1-c5 in Fig. 7) acted as tributaries of Savena River. Contour lines at the basin margin suggest the existence of small, coalescing alluvial fans, the deposition of which likely preceded the formation of the Iron Age-Roman palaesol. These landforms are cut by river incisions which most likely induced soil development.

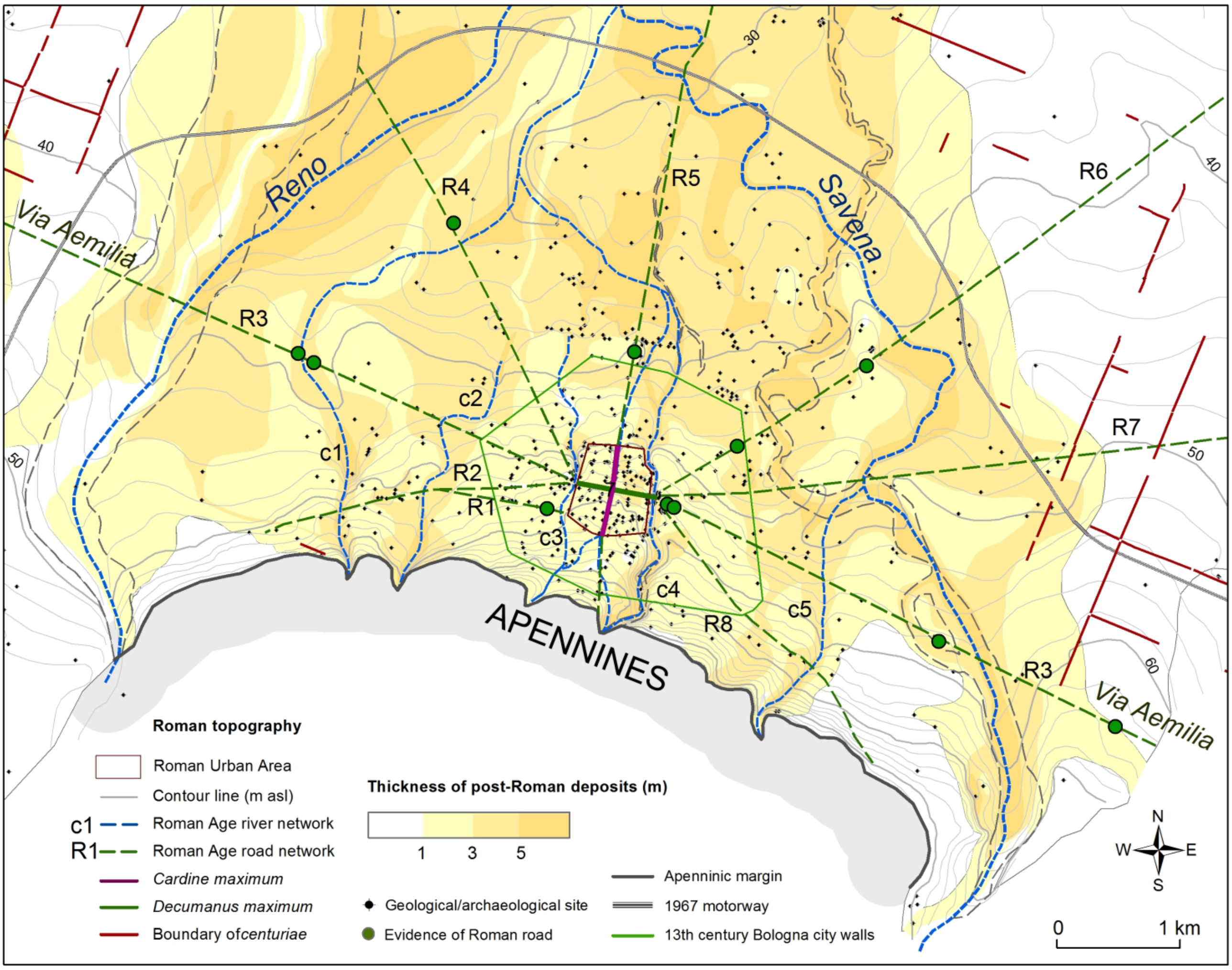

Fig. 7. Reconstruction of the Roman landscape by integrated archaeological, historical and stratigraphical documentation.

Significant modification of the river network by human activities is documented close to the Roman urban area. For example, Aposa creek (c4 in Fig. 7) is rectilinear and narrower near the ancient urban centre, where it flowed confined by walls. Vallescura creek (c3 in Fig. 7), which was active during the Iron Age, was deactivated during the Roman Empire and filled with landfill material. During the Roman Republican age, up to the fall of the Roman Empire, an anthropogenic c3, running through the urban area became active along the *Cardine maximum* (Curina et al., 2010).

The Roman road layout, partly inherited by the Etruscans, was made up of long, rectilinear stretches connecting the colony of Bologna with the main towns of the Roman Empire. The *Via Aemilia* (Fig. 7) is probably the best example, with a straight stretch 450 km long. The layout of the main Roman roadways displays strong similarities with the modern road network and was significantly influenced by the river network. Roman roads were designed in order to cross the rivers perpendicularly in as few points as possible, and for this reason their layout provides additional information about the ancient fluvial paths. A striking example is the *Decumanus maximum* (Fig. 7), which just off the Roman urban area (after crossing channels c3 and c4) splits in three roads (R2, R3 and R4) on the west, and four roads (R3, R6, R7 and R8) on the east (Fig. 7). The anomalous cross-cutting relationships between R1 and c3 confirm that during the Roman period channel c3 was at least partially filled.

6.2 Development and burial of the Iron Age-Roman palaeosol

The combination of sedimentological, archaeological and historical data into a high-resolution stratigraphic framework enables us to trace the late Holocene palaeoenvironmental evolution of the Bologna area. With respect to the development and burial of the Iron Age-Roman palaeosol, for which the most detailed stratigraphic information is available, two distinct phases can be reconstructed: (i) 9th century BC-3rd century AD phase, characterized by high floodplain stability, expansion of human settlements, and onset of the Iron Age pedogenesis; (ii) post-3rd century AD phase, characterized instead by high fluvial activity, crisis of the human society, contraction of the urban area, mass abandonment of rural areas, and burial of the Iron Age–Roman palaeosol.

The first permanent settlements during the Iron Age took place in a topographically slightly elevated tract of land between two rivers. The Iron Age populations started to control the river network and to protect their settlements from flooding, probably also through widespread erection of artificial levees. Stable settlements were also associated to the development of agriculture and the setting of regular patterns of irrigation channels in which flood waters were conveyed (Ortalli, 1993, 1995). Soil development likely started in this context.

During the ensuing Roman period, the control of the river network was pervasive (Fig. 7) and human influence on fluvial dynamics prevailed over other factors (Marchetti, 2002). Wide areas of the Po Plain were reclaimed and subdivided into regular square grids of *centuriae*. River courses in the proximity of the urban area were strictly controlled, maintained and kept cleaned from sediments, preventing channels from silting up. The continuous expansion of human settlements in the town centre area, documented by archaeological material spanning the Iron Age-Late Antiquity period, was favoured by the slightly raised, interchannel location (Fig. 7), less susceptible to flooding than the adjacent regions. Distinct topographic surfaces, attributable to the Roman period, the Iron Age, and even the Late Bronze Age are locally identifiable in the Bologna periurban area (Fig. 5), whereas in the historical centre they merge into a complex occupational sequence (Fig. 4, section DD').

Starting from the 3rd century AD, the Po Plain experienced a generalized crisis of human society that was controlled by two major events: (i) a widespread plague epidemic led to strong depopulation of the area (Gilliam, 1961; Fears, 2004), as testified by the contraction of the major cities along the *Via Aemilia*. Some of these once flourishing cities, such as *Claterna*, a few kilometres east of Bologna, disappeared in this period, to be rediscovered in archaeological surveys only during the last centuries (Brizio, 1892); (ii) from northern Europe, which was instead experiencing generalized overpopulation (Pauli Diaconi, *Historia Longobardorum*, book 1), many groups moved to the Po plain. This stage, known as "barbaric invasions", was probably one of the most important causes in the crisis of the Roman Empire (Anderson and Lewit, 1988). Several towns at the southern margin of the Po Plain where besieged, and the population abandoned the countryside to take refuge in fortified towns, with subsequent loss of control of the river network and degradation of the water flow system (Castaldini et al., 2007).

In the geo-archaeological record of the Bologna area this period is well documented. During the Late Antiquity, periurban and rural houses were abandoned and partially disassembled to obtain construction materials. The latter stages of use of these dwellings are dated, based on associated coins, to the 3rd–4th century AD and testify to a decline in the construction techniques, with abundant use of recycling material.

The burial of the Roman settlement by overbank sedimentation realistically took place during the Early Medieval Age, consistent with the coeval phase of fluvial aggradation recorded a few km south of Bologna in the Reno River valley (Eppes et al., 2008). In this period Bologna was a fortified town (Foschi, 1992), reduced to one fourth of the Roman town. Outside the Early Medieval city walls, extremely rare rests of Early Medieval Age are documented. In several excavations, the youngest inhumations in the uppermost part of the Roman palaeosol, just below the overbank facies, are confidently dated to the 4th century AD based on the associated grave goods. The oldest archaeological material above the overbank facies is attributed to the Late Medieval Age.

Although historical events clearly played a major role in controlling the burial of the Roman settlements in the Bologna area, a contributing effect of climate cannot be ruled out. The possible impact of climate change on the expansion and fall of Rome has long intrigued historians, and it is widely established that exceptional climate stability (i.e., climate warmer than in later centuries) characterized the centuries of the Roman Empire's rise, especially between 100 BC and 200 AD

(Desprat et al., 2003; McCormick et al., 2012; Wang et al., 2012). Recent studies from the adjacent Apenninic and Alpine regions show a good match between the burial of the Roman settlement in the study area and regional climate proxies. For example, advance/retreat reconstructions for the Alpine glaciers during the last three millennia (Holzhauser et al., 2005) indicate that glaciers were larger than today around the 6th century BC (Iron Age) and after the Roman Empire decline, with major advances during the course of the 6th century AD (Early Medieval Age) and around the 16th century AD (Little Ice Age). A synchronous sharp increase in climatic humidity between 1800-1500 yr BP has been documented across the central Mediterranean (Alps, Italy and Turkey) and Central Europe, using a vast range of proxy archives and model simulations (Dermody et al., 2012; Büntgen et al., 2011). This is also confirmed by several historical notes (Pauli Diaconi, *Historia Longobardorum*, book 3).

In the light of these remarks, it is apparent that overbank deposition atop the Iron Age-Roman palaeosol took place under increasingly cooler and wetter conditions. The burial of the Roman settlements soon after 500 AD can thus be viewed as the result of combined historical events and disadvantageous climate conditions. Climatic deterioration increased the incidence of large floods (Macklin and Lewin, 2003), whose devastating effect was enhanced by the sudden black out in the control of the river network, resulting in the widespread flooding of previously protected interfluvial areas.

7. Conclusions

An integrated sedimentological and stratigraphical study from the subsurface of Bologna, in northern Italy, enabled detailed reconstruction of facies architecture and environmental changes at the southern margin of the Po Plain during the Holocene. Owing to an astonishing number of artifacts, a laterally extensive palaeosol of Iron Age-Roman period highlighted the relationships between changing environments and human societies, documenting at the same time a combined anthropogenic and natural impact on the landscape. The major outcomes of this study can be summarized as follows:

(1) Two laterally extensive palaeosols, of Neolithic-Eneolithic and Iron Age-Roman period, respectively, form prominent stratigraphic markers within the late Quaternary interfluve

succession of the Bologna area. In the adjacent Reno and Savena river systems, laterally extensive gravel-sand bodies of late Pleistocene age are overlain by a mud-prone succession of floodplain deposits with ribbon-shaped fluvial bodies.

(2) A vast array of artifacts (buildings, streets, cemetery sites, channels) from the younger palaeosol testify to distinct stages of uninterrupted occupation between the Iron Age (and locally, the Late Bronze Age) and the Late Antiquity. Integration of archaeological data with historical documentation and stratigraphic correlations based on palaeosol stratigraphy enable an accurate reconstruction of Roman topography, including the palaeo-river network and communication routes.

(3) A combination of human activities, geomorphic processes and climate change appears to have exerted a major control on the development and burial of the Iron Age-Roman palaeosol. Human modifications of the landscape, likely including erection of artificial levees and bank protection, are inferred to have favoured the onset of pedogenesis during the Iron Age and the subsequent Roman period. With the fall of the Roman Empire, the degradation of the river system superposed to disadvantageous climate conditions led to the ultimate burial of the Roman settlements.

(4) This study documents the central role of historic urban areas for interdisciplinary geoarchaeological studies. At these specific locations, anomalously high concentration of stratigraphical, historical and archaeological data may help unravel, better than in any other site, the complex relationships among urban settlement, environmental evolution and climate change.

Acknowledgements

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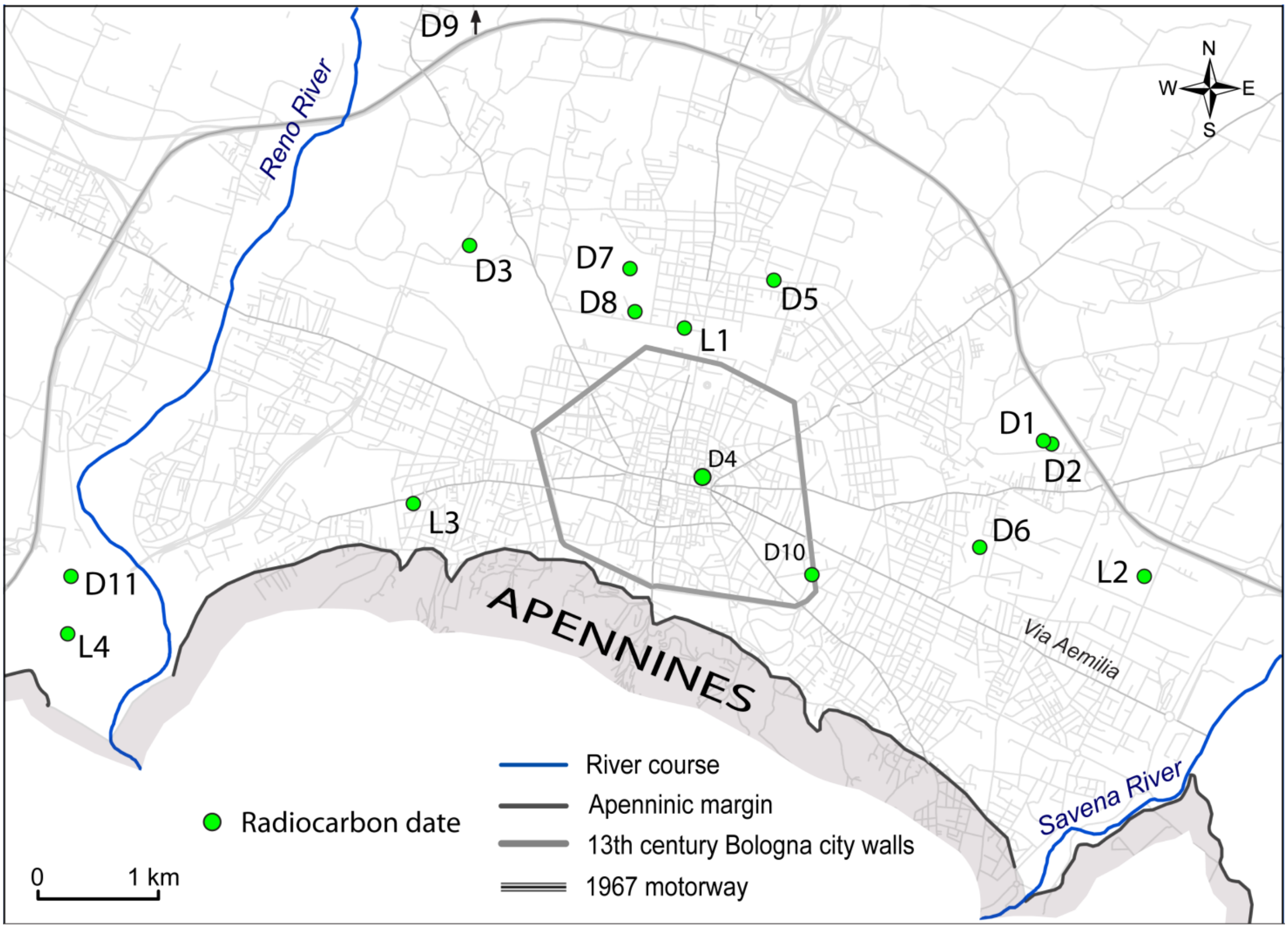
Supplementary material

site	Cal years (2σ) BP	Cal years (2σ) BC/AD	dated material	environment	Historical Timescale
D1	1420-1125 (91,8%)	533-828 AD	wood	swamp	Late Antiquity
D2a	1395-1290 (95,4%)	555-660 AD	wood	swamp	
D3a	1880-1555 (95,4%)	71-393 AD	wood	fluvial channel	Roman Age
D4a	2145-1810 (94,2%)	195 BC -140 AD	charcoal	urban area	
D2b	2745-2150 (95,4%)	794-203 BC	wood	swamp	Iron Age
D3b	2735-2359 (95,4%)	786-410 BC	charcoal	floodplain	
D4b	2720-2455 (92,2%)	775-505 BC	charcoal	urban area	
D5a	2740-2490 (95,4%)	790-540 BC	TOC	swamp	
D6	3080-2750 (93,7%)	1130-800 BC	TOC	floodplain	Bronze Age
L1 [1]	3275-2745 (92,0%)	1326-798 BC	TOC	floodplain	
D7a	5145-4850 (69,5%)	3200-2900 BC	charcoal	floodplain	Eneolithic
D3c	5335-4960 (83,6%)	3385-3010 BC	TOC	floodplain	
D8a	5325-5260 (37,3%) 5190-5055 (49,2%)	3375-3310 BC 3240-3105 BC	wood	fluvial channel	
L2 [2]	5480-5285 (88,1%)	3530-3335 BC	charcoal	floodplain	
D9	5755-5570 (77,5%)	3805-3620 BC	wood	fluvial channel	
D10	6570-6310 (91,8%)	4620-4360 BC	wood	swamp	Neolithic
L3a [3]	6910-6665 (95,4%)	4960-4720 BC	bone	floodplain	
D8b	7160-6890 (95,4%)	5215-4930 BC	TOC	swamp	
L4a [4]	7180-6960 (95.4%)	5230-5010 BC	bone	floodplain	
L3b [3]	7255-6995 (95,4%)	5310-5050 BC	bone	floodplain	
L4b [4]	7335-7155 (95,4%)	5385-5207 BC	bone	floodplain	
D5b	7485-7410 (62,0%)	5535-5460 BC	charcoal	swamp	
D11	7975-7845 (95,4%)	6030-5895 BC	TOC	floodplain	
D7b	8325-8160 (93,0%)	6375-6210 BC	TOC	floodplain	

List of (published and new) radiocarbon dates in chronological order related to the Neolithic-Eneolithic and (Late Bronze) Iron Age-Roman palaeosols: (1) from Cremonini et al., 2006; (2) from Cremonini, 1980; (3) from Ferrari and Steffé, 2006; (4) from Ferrari et al., 2006.



Location of the radiocarbon dates listed in the previous tab

6. CONCLUSIONS

Palaesols are characteristic features of alluvial plain deposits that can be used efficiently for high-resolution stratigraphic interpretation and basin-scale correlations. Through the analysis of more than 5000 stratigraphic logs and 750 archaeological information, supported by 60 new radiocarbon dates, we reconstructed a detailed picture of palaeosol-based stratigraphic architecture between Bologna and the Po River. We documented in this work to what extent palaeosols can represent a suitable tool for high-resolution stratigraphic correlations within highly heterogeneous non-marine sedimentary successions, and we explored the potential use of palaesols on different time scales.

The traditional approach to alluvial stratigraphy, focused on the detailed characterization of fluvial bodies in terms of lithology and geometry, fails to obtain reliable results in areas far from the influence of the major fluvial systems. Wide interfluvial sectors of the Po Plain, between the Apenninic margin and the Po River, remained virtually unexplored due to the lack of stratigraphic markers, fundamental for reliable correlations. Palaeosol stratigraphy introduces methods and observations that can readily fill this gap. We demonstrate in this work how this technique can be performed on seemingly monotonous mud-prone interfluvial successions, even at the millennial time scale.

This research was carried in three main sectors: (i) the Bologna interfluve, between Reno and Savena fluvial systems (paper 1 and 4), characterized by an exceptionally high concentration of stratigraphic information (about 20 data/km^2); (ii) a 6750 km^2 wide portion of the alluvial plain between Bologna and the Po River (paper 2), composed in the subsurface of a complex patchwork of lens-shaped sediment bodies within predominant floodplain muds; (iii) the area beneath the modern Reno River, extending 30 km downstream of the valley outlet (paper 3), in which the geometric relationships between fluvial and interfluvial facies are well expressed. The very high density of data, clustered in the Bologna urban area allowed the definition of an extremely detailed interfluvial stratigraphic framework (paper 1), supported by about 30 radiocarbon dates. Unfortunately, the coverage of high-quality stratigraphic information drastically drops down out of the major urban centres. Additionally, since palaeosol stratigraphy is a poorly used technique within late Quaternary deposits, and the available dataset mainly derives from geotechnical investigations, palaeosols are rarely mentioned in core descriptions. Thus, to improve the coverage of observation points, up to a density adequate to carry out reliable palaeosol-based correlations, we tested a method of palaeosol identification even from poor lithologic core descriptions. This method was based on the analysis of pocket penetration profiles, calibrated with a limited number of core observation (paper 2). The framework of interfluve stratigraphy, consistent with the one obtained for the Bologna area, was traced up to a fluvial-dominated context (paper 3), in order to define a preliminary model of palaeosol formation and burial, related to fluvial incision and aggradation, respectively. Finally, the availability of a large archaeological dataset was used to map the most recent palaeosol of the Bologna interfluve, and to evaluate the impact of increasing human intervention on soil development and burial (paper 4).

The major issues of this thesis are summarized as follow:

(1) Palaeosols represent stratigraphic markers with great correlation potential, identifiable over distances of 40-50 km. Stratigraphic correlations of closely-spaced continuously-cored boreholes in the subsurface of Bologna, close to the Apenninic margin, highlighted how palaeosol can continuously be traced across interfluvial areas allowing the link between previously disconnected adjacent fluvial systems. In more distal position, where subsurface depositional architecture is dominated by markedly lenticular sediment bodies, palaeosols revealed to be the unique reliable stratigraphic markers within the Late Pleistocene-Holocene alluvial succession.

(2) A sequence of five vertically-stacked palaeosols was identified within the late Quaternary succession of the Bologna interfluve. The most prominent stratigraphic markers beneath the mud-dominated strata are three closely-spaced Inceptisols (P1-P3), dated to the Late Pleistocene (from 42 to 26 ky BP). These palaeosols record relatively protracted pauses in sedimentation (3-4 ky) that occurred during the final stages of the Late Pleistocene sea-level fall. A fourth laterally extensive Inceptisol, encompassing the Pleistocene-Holocene boundary (PH), marks the major post-LGM phase of soil development. More weakly developed and laterally discontinuous palaeosols (Entisols) characterize the Holocene highstand succession. This upward decrease in soil development and correlatability was interpreted as the result of post-glacial increasing accommodation. Moving toward the Reno and Savena river systems, the Late Pleistocene Inceptisols are replaced by laterally extensive fluvial-channel complexes deposited during MIS 2 under conditions of high sediment supply/accommodation ratio. These sedimentary bodies grade upwards in a mud dominated succession, with less extensive

and less interconnected fluvial channel bodies, documenting the response of the fluvial system to rapidly increasing accommodation.

(3) Pocket penetrometer measurements on cores document that palaeosols are overconsolidated horizons characterized by resistance higher than the other alluvial facies, with penetration values ranging between 3 and 6 kg/cm^2. Along an individual A-Bk-C palaeosol profile the highest values in compressive strengths commonly mark the Bk horizons. This peculiar signature, calibrated with facies analysis on a limited number of cores, allows the identification of palaeosols even from low-quality core descriptions, thus enlarging significantly the number of control points for a stratigraphic research, without increase in costs.

(4) Weakly developed palaeosols in the subsurface of the southern Po Plain are the bounding surfaces of high-frequency (5^{th}-order) depositional cycles. Each cycle is composed by a lower aggradational interval, consisting of overbank facies, and an upper degradational, condensed interval, represented by a palaeosol. The lower boundaries of the aggradational/ degradational sequences can physically be traced at the base of the main fluvial channel complexes. Such bounding surfaces identifiable even within homogenous mud-prone successions, can be intended as an interfluve 5^{th}-order sequence boundary. The subdivision of the Late Pleistocene-Holocene alluvial succession in 5^{th}-order depositional cycles allows the correlation at the basin scale of heterogeneous facies associations. Particularly, four depositional cycles identified beneath the modern Reno River were correlated with fluvial terraces in the intramontane valley, across the Apenninic margin, which marks the transition from uplifting to subsiding conditions. The result of these correlations is the definition of a strong relationship between fluvial incision and soil development. High-frequency depositional cycles, and thus the main phases of soil development and burial are tentatively linked to millennial-scale climate variation occurred during the Late Pleistocene-Holocene. However, geochemical and micromorphological analyses are required to precisely document the control of climate change on alluvial sedimentation.

(5) The impact of human activities on soil development and burial became progressively more important during the middle-late Holocene. A prolonged phase of floodplain stability

characterized the period between 3000 and 1500 y BP. This phase is represented in the subsurface of Bologna by a palaeosol into which hundreds of artifacts of Iron Age and Roman Age were found. Numerous hydraulic features documenting both Iron Age and Roman settlements suggest that the onset of pedogenesis could have strongly been enhanced by a strict control on the river network. Accurate reconstruction of the Roman topography, including the palaeo-river courses and communication routes, indicates intense landscape modification by human activity. With the fall of the Roman Empire, the degradation of the drainage network superposed to disadvantageous climate conditions led to the ultimate burial of the Late Roman settlements.

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APPENDIX. The geo-archaeological map "*Bologna sotto Bologna*"

The geo-archaeological map "*Bologna sotto Bologna"* aims to divulge to the scientific and non-scientific local community the knowledge acquired on the shallow subsurface of the town after more than twenty years of geological and archaeological investigations. In this regard, through collection and re-interpretation of dishomogeneous and poorly organized data the research carried out during this PhD program contributed to achieve a generally accepted stratigraphic and geoarchaeological framework for the town of Bologna.

In the grid of the Geological Map of Italy to scale 1:50.000, the town of Bologna was cut in two by the boundary between sheets 220 and 221, and geological investigations on late Quaternary deposits carried out in the last decades were mainly focused close to the Reno and Savena Rivers, where the contrast between fluvial-channel and floodplain facies was clearly expressed. Geological maps to scale 1:10.000 were produced by the Geological, Seismic and Soil Survey of Regione Emilia-Romagna, only for the Apenninic sector, south of Bologna. The historical part of the town thus remained basically unstudied.

On the other hand, archaological surveys carried out by the Superintendence to archaeological properties of Regione Emilia-Romagna in the last thirty years were mainly concentrated on the historical centre. With the exception of extremely detailed reconstructions of the Roman urban area, these archaeological data have never been overviewed to create a comprehensive framework for the Bologna territory. Finally, excluding investigations on single archaeological sites, a geo-archaeological study, unraveling the mutual relationship between alluvial processes and human presence during mid-Late Holocene, was lacking for the Bologna area.

Through the integrated analysis of more than 3000 stratigraphic logs and 750 archaeological reports, the geo-archaeological map of Bologna aims to fill this gap. A particularly detailed documentation on the Iron Age and Roman archaeological rests, combined with large availability of shallow (< 10 m deep) subsurface stratigraphic data, has addressed the research on the late Holocene (last three millennia). "*Bologna sotto Bologna"* is the result of the collaboration between University of Bologna (Department of Biology, Earth and Environmental Sciences), Regione Emilia-Romagna (Geological, Seismic and Soil Survey and *Istituto Beni Culturali*) and Superintendence to Archaeological properties of Regione Emilia-Romagna. The flyer, in landscape orientation, is two-sided: in side A, two maps and the related explanatory notes outline the major aspects of the Roman landscape, including morphology and depth of the topographic surface, the river network and the main road layout. A stratigraphic cross-sections depicts the methodology used to reconstruct all these features. Side B focuses on the concept of soil in a geo-pedologic and archaeological perspective, with particular reference to the Iron Age-Roman soil, its development and burial. A geological map and a cross-section parallel to the Apennines depict the distribution of the alluvial and anthropogenic deposits overlying the Iron Age-Roman palaeosol.

2013

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La carta geo-archeologica di Bologna è il risultato di una collaborazione tra la Regione Emilia-Romagna (Servizio Geologico, Sismico e dei Suoli e Istituto per i Beni Artistici, Culturali e Naturali), la Soprintendenza per i Beni Archeologici dell'Emilia-Romagna e il Dipartimento di Scienze Biologiche, Geologiche e Ambientali dell'Università degli Studi di Bologna.

Si compone di cartografie e immagini relative all'area urbana bolognese durante il periodo romano e post–romano. Sul fronte, due carte e una sezione illustrano l'andamento morfologico del piano romano e lo spessore dei sedimenti che lo ricoprono. Sul retro, ci si sofferma su concetti quali il suolo, gli ambienti deposizionali del passato e la distribuzione dei sedimenti che separano il piano romano da quello attuale.

La carta geo-archeologica vuole rendere di dominio comune alcune delle conoscenze acquisite in anni di studi del sottosuolo di Bologna che conserva importanti testimonianze delle diverse fasi di sviluppo della città nella storia.

Siti visitabili

1. piazza del Nettuno 3. **Biblioteca Sala Borsa** area archeologica con i resti della basilica civile e altre strutture
2. via Rizzoli sottopasso. Decumano massimo
3. Strada Maggiore 11. **Palazzo Lupari** basolato della via Emilia
4. via Carbonesi 5. Teatro romano
5. via Parigi 5. **Complesso di San Colombano** resti di edificio romano e cripta altomedievale
6. via dell'Indipendenza 8. **Hotel Baglioni** basolato stradale di un decumano e resti del foro commerciale
7. via Rizzoli. **Canale Aposa** ponte romano
8. via dei Gombruti. **Sinagoga** resti di *domus* con pavimenti a mosaico
9. via Matteotti 7. **Liceo Sabin** resti di pavimento in esagonette e pozzo
10. Museo Civico Archeologico via dell'Archiginnasio
11. Museo Civico Medievale via Manzoni 4
12. Museo della Storia di Bologna via Castiglione 8

Bologna sepolta

La città di Bologna offre agli occhi di un forestiero di passaggio numerose suggestioni del passato. All'interno di quel che resta delle mura del XIII secolo coesistono testimonianze di età medievale, moderna e contemporanea; ciascun elemento architettonico racconta un preciso momento storico, consuetudini, usi, costumi e progresso tecnologico. Quello che il visitatore non può desumere, da una seppur attenta osservazione del centro storico, è che sotto i propri piedi c'è un'altra storia della città.

Le indagini archeologiche, fortuite o programmate, condotte nel corso dell'ultimo quarantennio dalla Soprintendenza per i Beni Archeologici dell'Emilia-Romagna, hanno permesso di riconoscere quanto ancora si conserva nel sottosuolo facendo emergere una realtà diacronica che ci restituisce in modo sufficientemente approfondito l'evoluzione urbanistica della città di Bologna, dall'età del ferro fino al rinascimento. Le informazioni più significative e meglio documentabili si desumono tuttavia per la città romana di cui è emerso, a tratti, il tessuto urbano ben definito fin dal momento della sua fondazione come colonia, avvenuta nel 189 a.C., due anni prima della costruzione della *via Aemilia*. L'impianto cittadino si estendeva, secondo una preordinata pianificazione, in un areale compreso tra gli attuali assi di via Marconi-piazza Malpighi a ovest, via Castiglione a est, via Farini-Carbonesi a sud e via Riva Reno-Augusto Righi a nord. Il limite cittadino era definito da due corsi d'acqua, il rio Vallescura a occidente e il torrente Aposa a oriente; gli altri due lati erano invece delimitati da due fossati che furono colmati nel corso del tempo. Il reticolo di strade ortogonali tra loro, suddivideva il tessuto urbano in isolati regolari, incentrati sulle due vie principali – il *cardo* e il *decumanus maximi* – e sulla piazza principale, il foro, racchiuso tra gli edifici pubblici civili e religiosi. All'interno degli isolati si trovavano le abitazioni private, talune con elementi architettonici e pavimentali di grande pregio formale; nei carrobbi principali si attestavano tracciati viari che collegavano la colonia ad altre città distribuite nel territorio. Nell'immediato suburbio, lungo le principali vie, erano collocate le aree sepolcrali caratterizzate dalla presenza di sepolture di varia tipologia tra cui anche grandi sepolcri e segnacoli di notevole impatto visivo e architettonico.

Bologna romana nella ricostruzione di Riccardo Merlo, con la consulenza di Jacopo Ortalli. Il disegno è stato realizzato immaginando di osservare la città da nord.

Le carte e la sezione

L'analisi di circa cinquecento relazioni di scavo e di oltre mille sondaggi a carotaggio continuo ha permesso, in primo luogo, la ricostruzione della morfologia del *paleosuolo romano*.

Per *paleosuolo romano* si intende il suolo sepolto, che si rinviene generalmente tra 2 e 5 metri al di sotto della città di Bologna, all'interno del quale sono presenti testimonianze delle diverse fasi di occupazione del territorio, dall'età del ferro alla caduta dell'Impero Romano. La scelta di definire questo suolo sepolto come *paleosuolo romano* dipende dal fatto che in esso sono prevalenti i rinvenimenti archeologici relativi al periodo romano.

Le carte e la sezione illustrano l'andamento del *paleosuolo romano* nel sottosuolo, lo spessore di sedimenti che lo separano dal piano topografico attuale e la ricostruzione della ipotetica rete viaria romana e delle modificazioni subite dal reticolo idrografico dall'età romana a oggi. In vaste aree della pianura bolognese un drappo di sedimenti, spesso fino a 9 metri, ricopre il *paleosuolo romano*.

In carta, il *paleosuolo romano* mostra una leggera inclinazione verso nord con pendenze che diminuiscono allontanandosi dalle colline fino a diventare quasi impercettibili verso la pianura, ed è solcato da pronunciate incisioni fluviali. I dati analizzati hanno permesso di elaborare una ipotetica ricostruzione del reticolo idrografico di età romana. Il fiume Reno e il torrente Savena, per il quale vengono proposti due percorsi distinti, seguivano tracciati diversi da quelli odierni e scorrevano più vicini alla città, con una probabile confluenza a nord di questa.

La profondità cui si rinviene nel sottosuolo il *paleosuolo romano* dipende dallo spessore dei sedimenti che lo ricoprono ed è massima proprio in corrispondenza delle antiche incisioni fluviali e nelle aree attualmente occupate dal Reno e dal Savena. In queste aree l'attività fluviale ha letteralmente asportato il *paleosuolo romano* e tutte le evidenze archeologiche ad esso associate. Al contrario, a nord-ovest e a nord-est di Bologna, il *paleosuolo romano* è sepolto poche decine di centimetri al di sotto del piano topografico attuale. Si noti, quindi, come lo spessore dei sedimenti che ricoprono il *paleosuolo romano* sia funzione delle dinamiche fluviali, raggiungendo i massimi valori nelle aree, esterne alla città, in cui i processi fluviali (avulsioni, migrazioni, alluvioni) si sono esplicati in un contesto quasi del tutto naturale. La sezione geologica, tracciata grosso modo lungo la via Emilia, evidenzia la variabilità dello spessore dei sedimenti che hanno sepolto il *paleosuolo romano* (linea rossa) e la migrazione laterale dei corsi d'acqua, avvenuta dall'età romana a oggi. La sezione illustra inoltre la distribuzione dei rinvenimenti archeologici, di cui sono riportati alcuni significativi esempi, e mostra come questi siano estremamente più diffusi nella zona del centro storico.

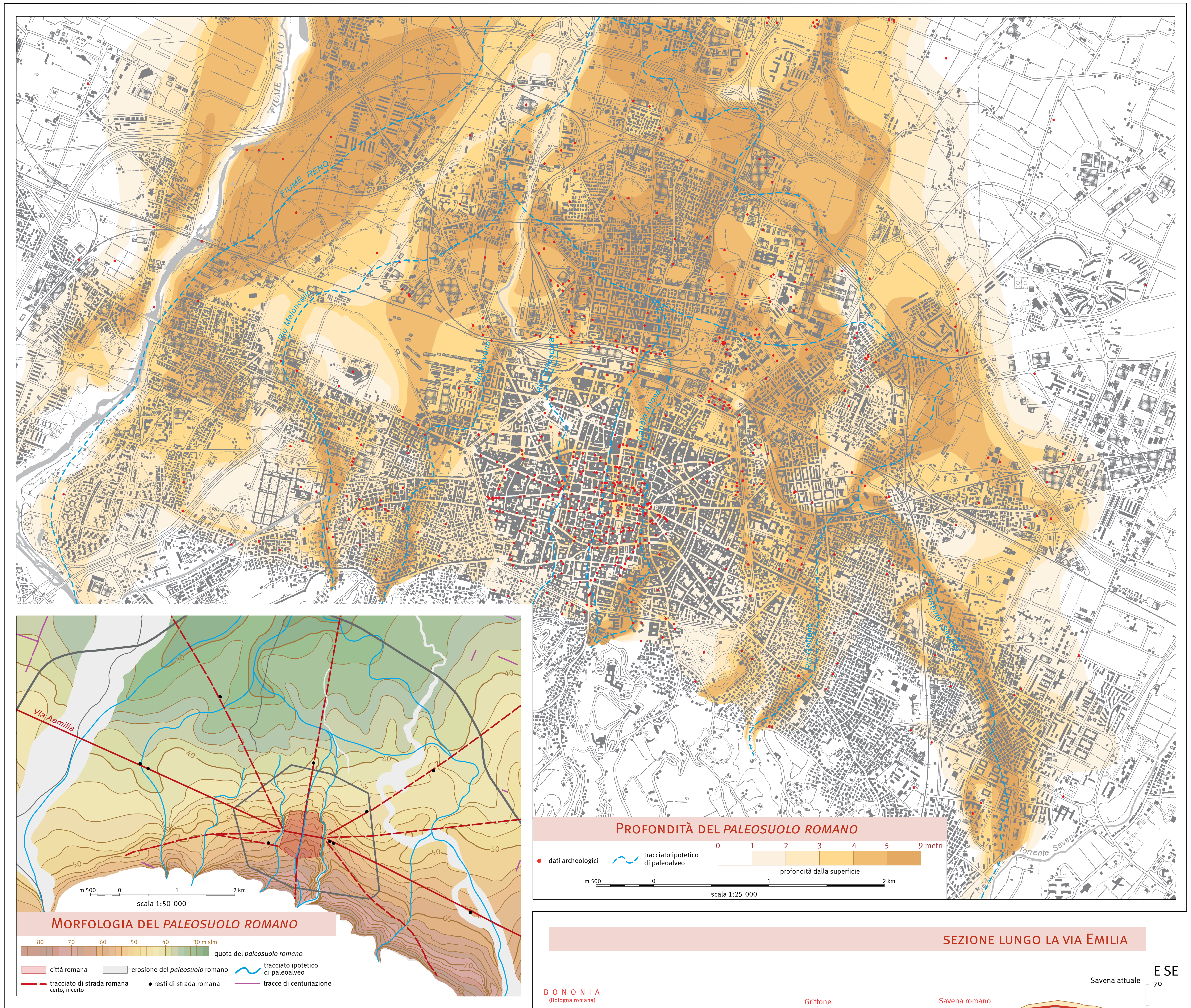
Il tracciato delle antiche vie romane è stato ipotizzato sulla base dei pochi ritrovamenti archeologici disponibili e dell'analisi del rapporto tra alcune vie attuali e l'assetto morfologico del territorio. Il quadro che emerge è quello di un contesto di forte interazione tra le componenti naturali del territorio e l'azione antropica.

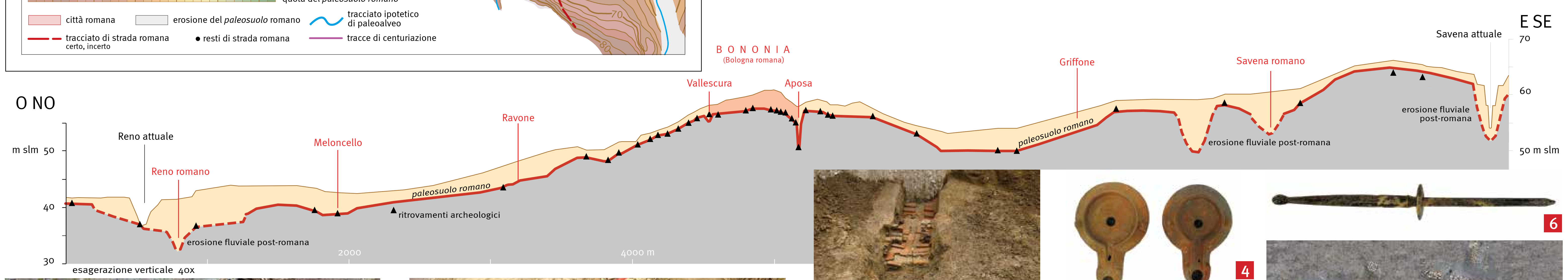
L'intervento dell'uomo sul territorio in epoca romana

In epoca romana, pur essendo maturata una considerevole capacità di trasformare il territorio, si assiste a un sostanziale equilibrio tra la componente umana e quella fisiomorfologica. Le modifiche e le profonde trasformazioni attuate dall'uomo nel paesaggio, in questo periodo storico, hanno sempre infatti tenuto conto della geografia fisica del territorio in cui si veniva ad intervenire, legando strettamente l'intervento umano alle caratteristiche morfologiche del terreno.

Uno degli esempi più evidenti delle trasformazioni che in età romana hanno interessato il territorio, soprattutto il settore di pianura, è senza dubbio fornito dal sistema della centuriazione. La sua realizzazione ha trasformato in modo radicale il paesaggio con l'abbattimento del bosco, la regimazione dei corsi d'acqua, il prosciugamento e la bonifica di ampie zone paludose attraverso un sistema capillare di scolo delle acque adattato alla morfologia del terreno. La centuriazione è ancora percepibile nelle aree in cui il *paleosuolo romano* giace a poca profondità dal piano topografico attuale; in queste aree ancora oggi la viabilità e l'organizzazione del territorio mantengono l'orientamento centuriale.

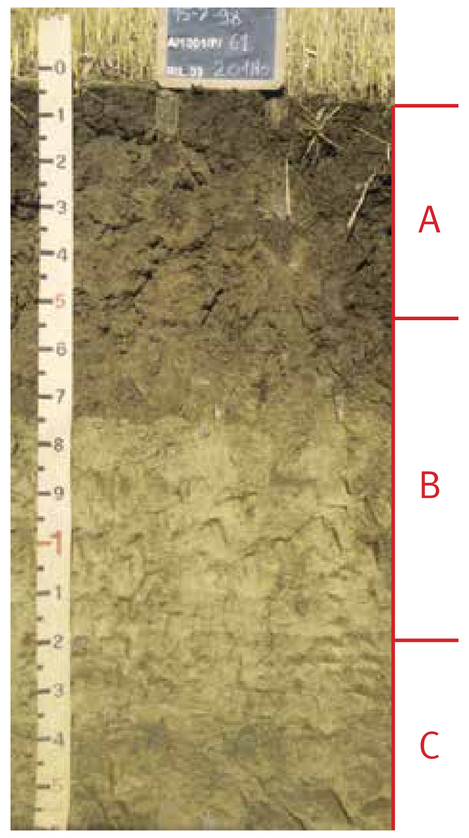
In epoca romana l'insediamento sul territorio è capillare, sia in pianura sia nelle zone pedecollinari; la frequentazione si distribuisce lungo i percorsi vallivi, sede di viabilità di collegamento con i valichi appenninici. Il territorio, scandito dalla presenza di strade di media e di lunga percorrenza, spesso affiancate da piccoli nuclei cimiteriali, vede un alternarsi di impianti produttivi, edifici rurali isolati di varia volumetria e piccoli agglomerati che si distribuiscono in maniera organica sul territorio. Al paesaggio prettamente agricolo e produttivo, dove le zone incolte si riducono sempre più alle fasce golenali e alle aree topograficamente più depresse o di difficile accessibilità, si salda, in uno stretto e imprescindibile binomio, lo spazio urbano e la fondazione delle città può essere considerata uno degli aspetti più importanti e significativi della romanizzazione.





1 - necropoli lungo un tracciato viario 2 - edificio rustico 3 - conduttura idrica 4 - lucerne 5 - antefissa fittile 6 - conocchia in osso 7 - edificio rustico

Il suolo



[1] tipico aspetto del suolo romano affiorante in pianura.

Il suolo occupa la parte superiore della superficie terrestre e permette la vita dei vegetali, degli animali e dell'uomo. Esso è il risultato della disgregazione e alterazione della roccia ad opera degli eventi climatici, della geomorfologia, del tempo che passa, della vegetazione e degli organismi viventi. Anche l'azione dell'uomo lo condiziona e può modificarlo fortemente.

Attraverso tutti i processi che concorrono alla formazione di un suolo (definiti pedogenesi), il materiale di partenza si trasforma e si riorganizza in strati con caratteristiche peculiari, spessi generalmente da pochi centimetri ad alcuni decimetri, denominati orizzonti [1].

Nella porzione più superficiale del suolo si concentra la materia organica, che conferisce un tipico colore scuro (orizzonte A), e avvengono le principali trasformazioni minerali del materiale d'origine. Se la pedogenesi prosegue per molto tempo (1.000-2.000 anni), uno dei processi che più frequentemente si osservano nei nostri climi è la dissoluzione dei carbonati. I carbonati, tipicamente presenti nel materiale di partenza, vengono lisciviati dall'orizzonte più superficiale e si accumulano sotto forma di concrezioni biancastre nella parte inferiore del sottostante orizzonte B. All'aumentare della profondità i processi pedogenetici diventano via via meno intensi, fino a cessare del tutto (orizzonte C).

Affinché possa avvenire la trasformazione del materiale di partenza è necessario che quest'ultimo rimanga stabilmente esposto sulla superficie terrestre. In un contesto di pianura alluvionale, come quello della pianura bolognese, ciò è possibile se, per un tempo sufficientemente lungo, non si verificano alluvionamenti che porterebbero al seppellimento del materiale d'origine, da parte di acqua e sedimento, e all'interruzione del processo di alterazione. Dalla durata dell'esposizione in superficie del materiale d'origine (decine, centinaia o migliaia di anni), dipende il grado di alterazione del suolo che aumenta progressivamente con il tempo. Analizzando il grado di alterazione di un suolo è possibile pertanto avere una idea approssimativa di quanto tempo esso sia rimasto esposto sulla superficie della pianura.

I suoli, affioranti e sepolti, rinvenuti nella pianura bolognese documentano quindi dei periodi di rallentamento o stasi dell'attività fluviale, a loro volta indicativi di intervalli climatici poco piovosi e sufficientemente lunghi.

La presenza di suoli sepolti (definiti in geologia paleosuoli) nel primo sottosuolo della pianura bolognese testimonia l'alternanza di fasi climatiche più o meno piovose della durata di centinaia o migliaia di anni. Questi paleosuoli sono intercalati da depositi alluvionali che non hanno subito alcuna pedogenesi e che sono indicativi degli alluvionamenti avvenuti nella pianura durante i periodi di maggire piovosità.

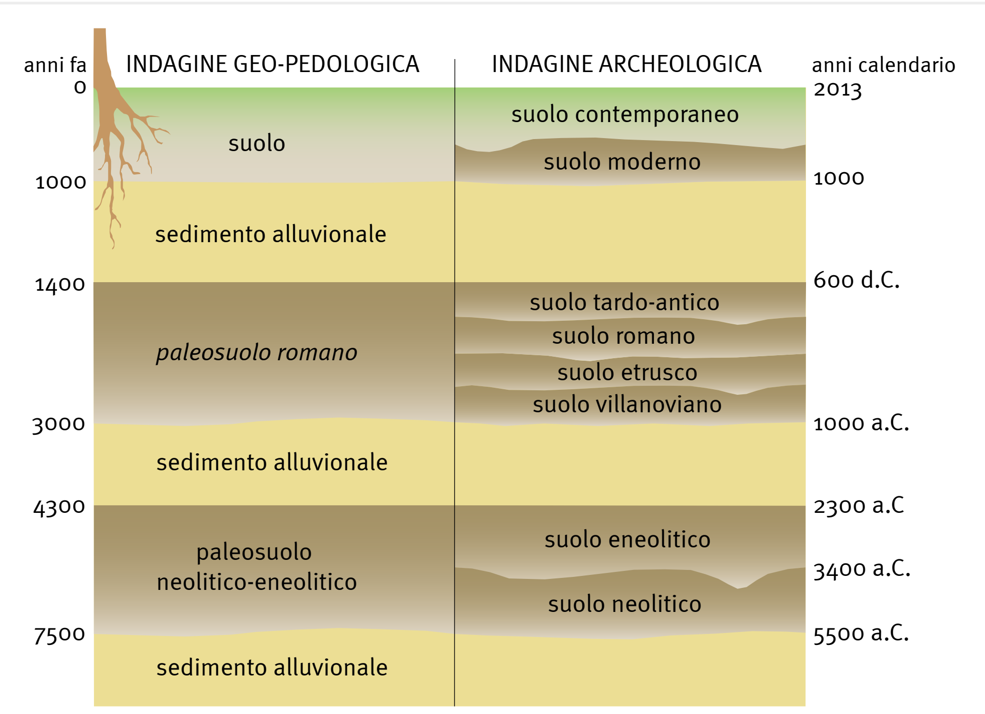
Il *paleosuolo romano*

Nel primo sottosuolo dell'area bolognese sono presenti due suoli sovrapposti la cui età è stata determinata grazie a numerosi ritrovamenti archeologici, a mirate datazioni al Carbonio 14 e all'analisi del loro grado di alterazione.

Il suolo più profondo e antico ha un'età compresa tra il Neolitico (circa 5500-3400 a.C.) e l'Eneolitico (circa 3400-2300 a.C) ed è documentato in un numero limitato di siti. Il suolo più recente ha un età compresa tra l'età del ferro (900-200 a.C., e più raramente dalla tarda età del Bronzo, circa 2300-900 a.C.) fino alla tarda età romana (circa VI sec. d.C), e di esso sono disponibili moltissime testimonianze. Questo suolo si trova in genere a profondità comprese tra 2 e 5 m al di sotto della città odierna e presenta una porzione superiore di colore marrone scuro, spessa generalmente 30 centimetri, caratterizzata dal maggior contenuto di materia organica e dalla lisciviazione dei carbonati (orizzonte A). Al di sotto è presente l'orizzonte B, caratterizzato da un colore complessivamente più chiaro dovuto al minor contenuto di materia organica e, nella sua porzione inferiore, all'accumulo dei carbonati.

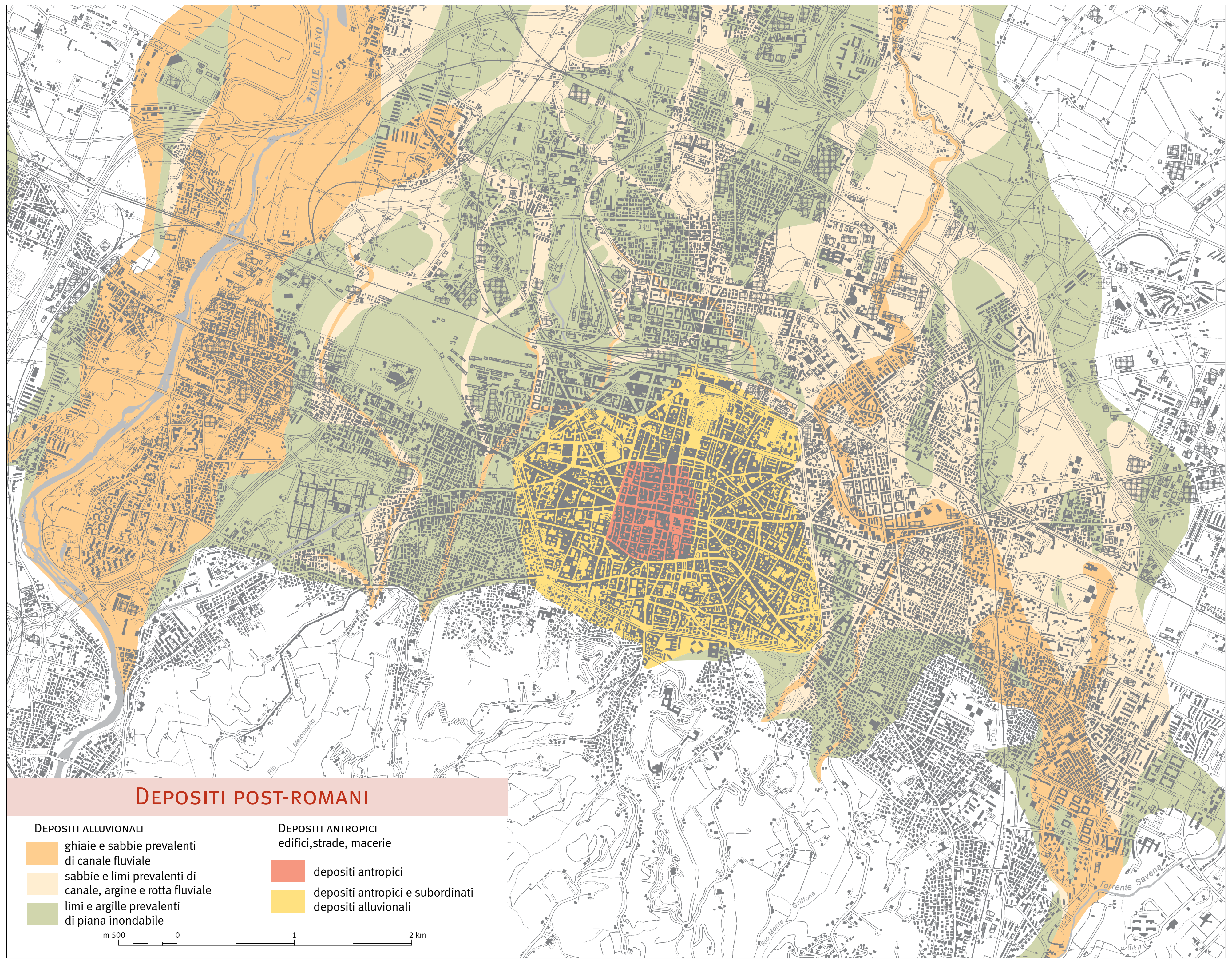
All'interno dell'orizzonte A di questo suolo si rinvengono di frequente manufatti e resti archeologici che testimoniano le varie fasi di occupazione del territorio, che si sono succedute nell'arco di tempo in cui questo suolo è stato esposto alla superficie prima del suo seppellimento (dall'età del ferro fino alla caduta dell'Impero romano). Dato che la gran parte di questi rinvenimenti è relativa al periodo romano, questo suolo sepolto viene qui indicato come *paleosuolo romano* [2].

Nel momento della formazione del *paleosuolo romano* si verificarono condizioni ambientali favorevoli allo sviluppo degli insediamenti. Il clima mite insieme all'opera di regimazione delle acque fecero sì che per un lungo periodo non si verificassero alluvionamenti importanti nella pianura bolognese. Furono questi gli elementi predisponenti la formazione del suolo romano, il cui seppellimento è invece il risultato della complessa interazione tra variazioni climatiche ed eventi storici.



[2] schema di correlazione tra i paleosuoli individuati secondo l'approccio geologico-pedologico e i suoli riconosciuti su base archeologica. I suoli sono intervallati da sedimento alluvionale all'interno del quale non ci sono significative evidenze archeologiche.

Sotto Bologna



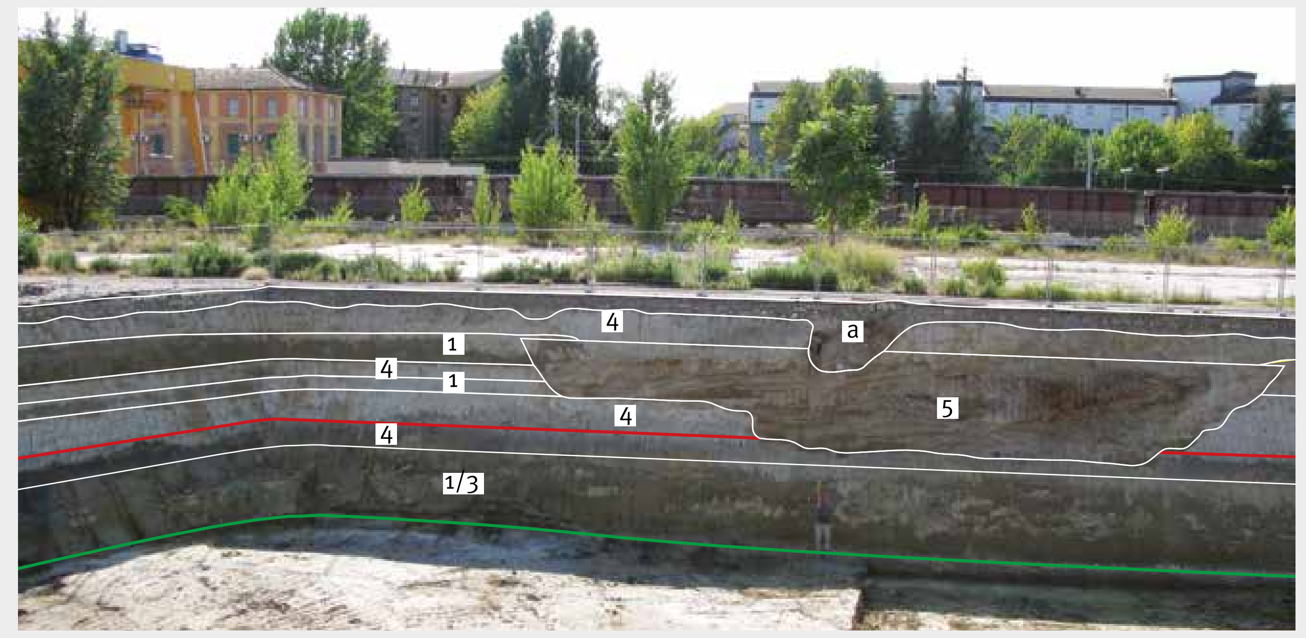
La carta mostra la tipologia e la distribuzione dei sedimenti che hanno seppellito il *paleosuolo romano* e che sono, a loro volta, ricoperti dagli edifici e dalle strade della città odierna. Questa carta è stata realizzata interpretando e correlando tra loro le numerose informazioni geologiche presenti nell'area urbana bolognese, quali soprattutto sondaggi e scavi eseguiti per le fondazioni degli edifici e delle infrastrutture cittadine. In ciascuno dei punti analizzati è stata individuata la profondità del *paleosuolo romano*, e si è poi valutato lo spessore e il tipo dei sedimenti presenti al di sopra di esso.

Si tratta di ghiaie, sabbie alternate a limi e limi alternati ad argille, la cui distribuzione nel sottosuolo non è casuale. I depositi ghiaiosi identificano le zone in cui scorrevano i corsi d'acqua principali. Le ghiaie del Reno, a ovest, interessano quasi tutta l'estensione della carta, mentre nella parte orientale i depositi ghiaiosi del Savena si assottigliano verso nord, lasciando spazio ad ampie porzioni occupate da depositi sabbioso-limosi che testimoniano le divagazioni del torrente nella pianura. Tra il Reno e il Savena, il primo sottosuolo cittadino è invece occupato prevalentemente da limi e argille che rappresentano i depositi di piana inondabile dei rii che scendono dall'Appennino. In questa zona sono presenti anche sottili corpi ghiaiosi e sabbioso-limosi, che indicano i possibili percorsi del Rio Meloncello e dei torrenti Ravone, Griffone e Aposa (quest'ultimo individuato unicamente nel settore a nord del centro storico). Limi e argille di piana inondabile sono anche presenti lateralmente al percorso del Reno e del Savena e testimoniano le zone topograficamente più depresse, dove decantavano i sedimenti più fini.

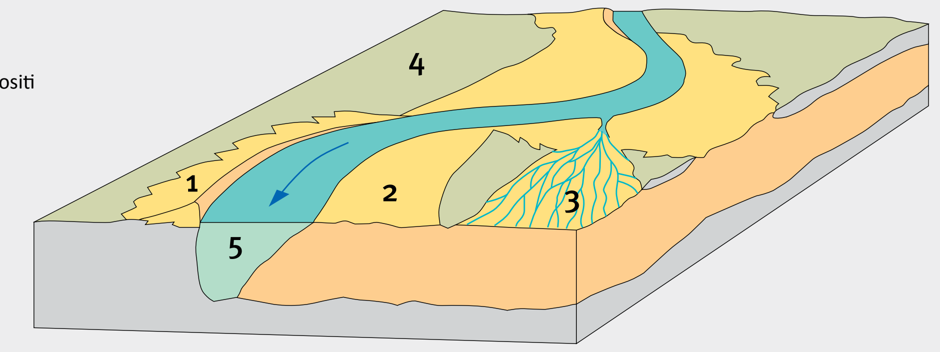
Nell'area occupata dalla città romana, dove la presenza antropica è stata pressocché costante fino ad oggi, i depositi alluvionali sono assenti e sul *paleosuolo romano* poggiano esclusivamente depositi antropici che testimoniano l'evoluzione nel tempo del tessuto urbano bolognese. Nella restante parte del centro storico, ad esclusione della zona nord-occidentale, coesistono nel sottosuolo prevalentemente depositi antropici e sporadiche testimonianze di alluvionamenti.

Il seppellimento del *paleosuolo romano* è avvenuto, all'incirca tra il V e il IX secolo dopo Cristo, in un contesto di significativo deterioramento climatico. Dopo un lungo periodo di clima favorevole, che consentì la formazione del *paleosuolo romano*, si registra un incremento delle precipitazioni nell'intera area mediterranea e nel nord Europa che si traduce, nella Pianura Padana, in una maggiore propensione dei corsi d'acqua all'esondazione. In questo periodo, una complessa successione di eventi storici porta ad un aumento generalizzato della vulnerabilità del territorio. L'assenza di manutenzione della rete idrografica, dovuta alla mancanza di un quadro organico di governo del territorio per la crisi economica e sociale dell'Impero romano, e la concomitante situazione climatica sfavorevole si tradussero in disastrose esondazioni. Il succedersi di queste esondazioni determinò il forte accumulo di sedimento al di sopra del *paleosuolo romano* che risulta oggi sepolto da ingenti spessori (fino a 9 metri) di materiale di origine alluvionale.

Gli ambienti deposizionali fluviali



[1] ricostruzione stratigrafica dei depositi di un ambiente fluviale del passato in uno scavo nel quartiere Navile. I numeri indicano i depositi relativi agli ambienti deposizionali descritti dallo schema [2]. Linea rossa: *paleosuolo romano*; linea verde: paleosuolo neolitico-eneolitico; **a**: depositi antropici.



[2] schema degli ambienti e dei depositi di un sistema fluviale attuale

1 - argine
2 - barra di meandro
3 - ventaglio di rotta
4 - piana inondabile
5 - canale

[6] fiume pensile tipico dell'attuale pianura alluvionale emiliano-romagnola

I sedimenti presenti nel sottosuolo di Bologna sono stati deposti in ambienti simili a quelli che attualmente compongono la pianura bolognese e che, nel loro insieme, definiscono un ambiente fluviale. All'interno di questo ambiente possiamo distinguere: il canale fluviale, il sistema degli argini e delle rotte fluviali e la piana inondabile [2].

La sedimentazione al di fuori del canale fluviale ha luogo quando, a seguito di un evento di piena, le acque di un fiume superano gli argini e allagano la pianura circostante rilasciando il sedimento che trasportano. La parte più grossolana (sabbie fini e limi sabbiosi) viene depositata vicino al canale fluviale e contribuisce allo sviluppo verticale dell'argine, mentre la parte più fine (limi e argille) decanta nella piana inondabile. In un successivo evento di piena le acque, oltre che tracimare dagli argini, possono romperli in un punto e formare un ventaglio di canali effimeri (ventaglio di rotta). La deposizione di sedimento avviene anche all'interno del canale fluviale, dove i depositi più grossolani presenti nel sistema fluviale (ghiaie e sabbie) si accumulano sotto forma di barre.

Le ricostruzioni geologiche del sottosuolo nelle zone di pianura alluvionale si basano sull'osservazione degli ambienti fluviali attuali e vengono condotte attraverso lo studio di scavi e carotaggi. La distribuzione dei sedimenti e la geometria degli strati permettono di ricostruire nel sottosuolo gli ambienti fluviali del passato, mostrandoci come questi si sono modificati nello spazio e nel tempo. Ghiaie e sabbie medio-grossolane organizzate in corpi sedimentari lentiformi, di spessore plurimetrico e con base tipicamente concava, vengono interpretati come depositi di canale [1]. Caratteristica di questi depositi è l'organizzazione interna secondo una stratificazione, denominata dai geologi, orizzontale o incrociata ad alto angolo, che è il risultato dell'azione delle correnti all'interno del canale fluviale [3 e 4]. Sottili alternanze ritmiche di sabbia fine e limo rappresentano i depositi di argine, mentre i depositi di piana inondabile sono formati da limo e argille, spesso ricchi di sostanza organica [5].

La geologia del sottosuolo della pianura bolognese evidenzia come, nelle ultime migliaia di anni, la distribuzione degli ambienti fluviali abbia subito diverse modificazioni. Queste avvenivano soprattutto durante periodi particolarmente piovosi, quando il reticolo idrografico diventava instabile e i fiumi potevano variare il loro percorso in un contesto che, in epoca preistorica, era completamente naturale.

Il primo sistematico progetto di governo delle acque iniziò in epoca romana, con la regimazioni dei corsi d'acqua e la bonifica delle aree paludose. A seguito della crisi economica e demografica che accompagnò la caduta dell'Impero romano, si verificò una prolungata assenza di interventi ed opere idrauliche, che divennero invece via via sempre più importanti a partire dall'XIII - XIV secolo. Da questo momento in poi l'uomo, per proteggersi dalle esondazioni dei fiumi, li ha confinati e ristretti in arginature artificiali, alte fino ad una decina di metri rispetto alla pianura circostante [6]. Oggi questi argini artificiali si innalzano sul panorama piatto della pianura emiliano–romagnola, a testimonianza di quanto sia rilevante il nostro controllo sulla dinamica naturale dei corsi d'acqua.

[3] dettaglio di un deposito di canale fluviale caratterizzato da ghiaie prevalenti organizzate secondo una stratificazione incrociata ad alto angolo [4] dettaglio di un deposito di canale fluviale in cui si osservano sabbie organizzate secondo una stratificazione incrociata ad alto angolo [5] dettaglio di un deposito di piana inondabile, osservato in un carotaggio, costituito da argille e limi con accumuli di sostanza organica.

La sezione geologica lungo la via Emilia

Il sottosuolo della città di Bologna è costituto da ingenti spessori di depositi alluvionali, risultato dell'attività dei corsi d'acqua provenienti dalla vicina catena appenninica. Ghiaie, sabbie, limi e argille sono presenti nel sottosuolo di Bologna per centinaia di metri di profondità.

La sezione geologica, tracciata grosso modo lungo la via Emilia, si spinge sino a circa 35 metri di profondità. La forte esagerazione della scala verticale (40 volte maggiore di quella orizzontale) permette di apprezzare la differenza di quota topografica tra la parte orientale (più elevata) e la parte occidentale della città, nonché la posizione rilevata occupata dal centro storico.

La sezione mostra chiaramente come le ghiaie e le sabbie si concentrino alla periferia della città, qui depositate dal Fiume Reno e dal torrente Savena. Il sottosuolo del centro storico, al contrario, è costituito unicamente da argille, limi, e da rari e isolati corpi sabbiosi o ghiaiosi depositati dai rii minori. La distribuzione delle ghiaie nel sottosuolo, che registra la posizione dei corsi d'acqua nel passato geologico, mostra come il Reno e il Savena si siano avvicinati più volte al centro storico della città senza però mai attraversarlo. È proprio in quest'area, maggiormente protetta dalle alluvioni, in virtù di una posizione topograficamente rilevata, che venne fondata la colonia romana di Bononia.

Nel dettaglio, la sezione mostra, dall'alto, un sottile spessore di depositi antropici, corrispondenti principalmente ai sottofondi stradali e alle fondazioni nonché a macerie, manufatti e resti di edifici. La linea rossa sottostante, che attraversa tutta la sezione, indica il *paleosuolo romano* , la cui osservazione diretta (nei sondaggi o scavi) è segnalata dai triangoli neri. I depositi immediatamente al di sopra di questa superficie sono quelli descritti dalla Carta dei depositi post-romani. La linea verde rappresenta il suolo neolitico–eneolitico che è individuato solo in un piccolo settore del sottosuolo del centro storico e nell'area compresa tra il Savena attuale e quello di età romana. La linea gialla indica il paleosuolo che segna il passaggio tra l'Olocene e il Pleistocene (circa 10.000 anni fa). Questo paleosuolo è stato individuato nella parte centrale del sottosuolo cittadino, all'interno dei depositi argilloso-limosi di piana inondabile; lateralmente si interrompe, a ovest e a est, contro le ghiaie fluviali del Reno e del Savena.