Géomorphologie : relief, processus, environnement, 2012, n° 2, p. 131-154

The last 40 ka evolution of the Central Po Plain between the Adda and Serio rivers

Évolution de la plaine centrale du Pô entre les rivières Adda et Serio au cours des 40 derniers millénaires

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Abstract

We reconstructed the geological evolution and the history of the fluvial network in the central part of the Po Plain in Lombardy, northern Italy, since the Middle Würm. We focused on evidences of dissection and incision of former rivers into the large outwash fans originating from piedmont glaciers of the southern Alps in the Last Glacial Maximum. The studied area is located between the Po River and the Alps north of the Adda/Serio river confluence, around the town of Crema. Morphometric analysis and stratigraphic investigation were carried out, supported by palaeobotany, sand petrography and radiometric dating. The obtained stratigraphic framework is presented by cross sections and by a geological map. During the Middle Würm, an alluvial fan of the Adda River oriented NWN-SSE occupied the area, feeding south and west the Romanengo hill. A substantial reorganisation of the fluvial network occurred during the Last Glacial Maximum. Since 32-30 ka cal. BP, the area was fed by two outwash rivers, originated from the Adda and the Oglio piedmont glaciers, both characterised by a prevalent southward drainage, 160°-170° S in the LGM. After the LGM the fan-head was dissected by trunk channels and, at the downslope fan limit, the southward flow shifted to a southeastern direction. Thereafter, major dissection and downcutting occurred in the Lateglacial, confining the major rivers into large alluvial corridors, further shaped by lateral erosion during the Holocene. The Late Holocene history of the Serio River is marked by fluvial floods during the late Roman Age, and by a capture of the lower reach by the Adda River. The geomorphological evidence supports the historically inferred age assignment of the diversion to 12th-14th c. AD.

Key words: alluvial geomorphology, alluvial plain, fluvial network, event stratigraphy, Last Glacial Maximum, Po Plain.

Résumé

*L'évolution géologique et l'histoire du réseau fluvial dans la partie centrale de la plaine du Pô en Lombardie ont été reconstituées à partir du Würm moyen. Le territoire environnant la ville de Crema entre les rivières Adda et Serio est caractérisé par des paléovallées encaissées dans de grands cônes en lien avec les glaciers du piémont méridional des Alpes pendant la dernière glaciation. L'étude morphométrique et stratigraphique a été supportée par les analyses paléobotaniques, pétrographiques sur sables et galets et par plusieurs déterminations radiométriques. Au Würm moyen, un cône alluvial mis en place par la rivière Adda s'orientait NWN-SSE et occupait la région étudiée, s'appuyant sur la colline de Romanengo au sud et à l'ouest. À partir de 32-30 ka cal. BP [*i.e.*, au début du Dernier Maximum Glaciaire (DMG)], une réorganisation importante du réseau hydrographique (orientation nettement sud) est forcée par le développement de deux sandurs des domaines glaciaires de l'Adda et de l'Oglio. Le sommet des cônes est creusé par les paléochenaux post-DMG, lorsque, à la base des cônes, la direction des paléochenaux, qui était 160-170° pendant la dernière phase d'aggradation, devient sud-ouest. Ce nouveau système de drainage est fossilisé par une phase d'incision importante au Tardiglaciaire, avant que les rivières soient confinées dans des corridors alluviaux et sujets à l'érosion latérale au cours de l'Holocène. L'histoire de la rivière Serio est marquée par des phénomènes d'alluvionnement au cours de l'Antiquité tardive puis par la capture de son cours inférieur par la rivière Adda. Les preuves géomorphologiques concordent avec les sources écrites, suggérant que le changement de tracé se produit entre le XII^e^ s. et le XIV^e^ s. apr. J.-C.*

Mots clés : *géomorphologie fluviale, plaine alluviale, réseau fluvial, stratigraphie événementielle, Dernier Maximum Glaciaire, plaine du Pô.*

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Le dernier cycle sédimentaire enregistré dans la plaine du Pô est caractérisé par l'alternance de phases d'aggradation sur les grands cônes alluviaux connectés aux cirques glaciaires de la marge des Alpes et de phases d'érosion au cours des interglaciaires. La chronologie de ces événements n'est pas bien connue, mais on sait que le taux d'aggradation des sandurs de la plaine du Veneto-Friuli Venezia Giulia a été important pendant le Dernier Maximum Glaciaire jusqu'à 18 ka cal. BP, après une phase de sédimentation plus lente durant le Würm moyen. Dans cet article, nous considérons le développement du réseau fluvial dans la zone centrale de la plaine du Pô (entre les rivières Adda et Oglio ; fig. 1), durant les dernières 40 ka. Les connaissances sur la géomorphologie récente de cette région sont dérivées surtout des données de la carte géologique à l'échelle 1/100000 (Desio et al.*, 1965, 1966), de la carte géomorphologique de la plaine du Pô et de Veneto-Friuli Venezia Giulia (Castiglioni* et al.*, 1997a), des études pédo-stratigraphiques et géoarcheologiques plus récentes (Cremaschi, 1987) et de l'étude des phénomènes* d'underfit streams *qui caractérisent l'hydrographie de la partie distale des sandurs (Marchetti, 1990, 2002).*

D'un point de vue méthodologique, on a préparé un DTM détaillé en se servant des points cotés de la Cartographie Technique de la Région Lombardie (fig. 2). La succession stratigraphique a été décrite sur le terrain à partir de plusieurs affleurements et carottes, dont les plus intéressantes ont été soumises aux analyses radiocarbone, palynologiques et minéralogiques (sables). 14 dates AMS ont été obtenues sur plantes terrestres, calibrées avec CALIB à partir de la courbe de calibration IntCal09 (Reimer et al.*, 2009 ; tab. 2) et indiquées dans le texte « cal. BP ». Certains vestiges archéologiques présents dans les dépôts ont été examinés, étant donné qu'ils peuvent fournir des indices chronologiques utiles. L'analyse palynologique s'est faite sur 400 grains. Les plantes aquatiques et de marais ont été exclues de la somme pollinique. Le diagramme pollinique intègre la séquence de tourbes et de tourbes sableuses déposées dans le marais de Mosi di Crema (fig. 9), quelques données polliniques sur échantillons isolés, prélevés dans les dépôts lacustres de Cresmiero, et la séquence fluvio-palustre de Ripalta Guerina (tab. 5). Pour chacun des 13 échantillons de sables étudiés, 400 points ont été comptés avec la méthode Gazzi-Dickinson (Ingersoll* et al. *1984) sur la fraction totale imprégnée à l'araldite, montée en lame mince standard et colorée avec de l'alizarine. Les spectres polliniques ont été comparés à ceux des sables fluviatiles actuels prélevés au débouché des vallées alpines (tab. 3). L'architecture des unités stratigraphiques est dérivée de l'analyse de trois coupes (fig. 3 à fig. 5) dont une seule fait l'objet d'une présentation détaillée ici (fig. 6). Les unités stratigraphiques ont été identifiées sur la base de la stratigraphie événementielle et fait l'objet d'un relevé par site type et d'un acronyme (fig. 10 à fig. 12).*

Concernant les résultats, les données radiocarbone permettent de dater les 40 derniers millénaires. Les affleurements de tourbe de Casaletto Ceredano ont restitué des âges ^{14}C entre 32-29 ka BP (base) et 27-26 ka BP (sommet). Ces niveaux de tourbe constituent la limite supérieure du Würm moyen (UCC) et la base du cône fluvioglaciaire du domaine de l'Adda (UBC). Un âge de 32-30 ka cal. BP pour le début de la sédimentation fluvioglaciaire est confirmé par la datation d'un tronc à la base du cône fluvioglaciaire du domaine de l'Oglio (URA). L'abandon de la surface d'aggradation contemporaine du DMG n'est pas bien daté mais il est sans doute antérieur à la base du remblaiement de la dépression de Mosi di Crema (^{14}C 12,79±0,135 ka BP, i.e. *14,5-16,2 ka cal. BP), tronquée à partir de cette surface (fig. 3). Le creusement de la vallée post-LGM de l'Adda est antérieur à la date de 11,93±0,16 ka cal. BP obtenue à la base des dépôts de la plaine alluviale à méandres recouvrant la surface d'érosion E2 dans la section de Montodine (fig. 6. La datation de deux troncs séparés de 11 m dans les alluvions graveleuses de la rivière Serio appartenant à la séquence holocène atteste des crues catastrophiques à l'Antiquité tardive. Enfin, la céramique du bas Moyen Age trouvée dans les alluvions les plus anciennes qui encombrent le nouveau chenal du Serio, après la défluviation du 'Serio Morto', concorde avec les sources écrites qui suggère pour cet évenement la date des XII^{e}-XIV^{e} s. apr. J.-C. Concernant l'origine géographique des sédiments, la minéralogie des sables a permis de distinguer deux systèmes fluviaux (Adda-Brembo et Oglio-Serio). L'analyse pétrographique des galets démontre que la rivière Serio a continué à alimenter le cône fluvioglaciaire de l'Oglio dès son confinement (holocène) dans la vallée encaissée. Les données polliniques donnent un âge tardiglaciaire pour les dépôts basaux du marais de Mosi di Crema ou du petit paléolac de Cresmiero, permettant ainsi de dater l'unité UCC qui a barré le bassin de Cresmiero (fig. 3).*

La synthèse de l'évolution du secteur central de la plaine du Pô au cours des derniers 40 ka montre qu'entre >40 ka et 32-30 ka cal. BP (Würm moyen), un cône alluvial mis en place par la rivière Adda s'orientait NWN-SSE et occupait la région étudiée, atteignant la colline de Romanengo au sud et à l'ouest (unité UCC ; fig. 11 et fig. 13A). A partir de 32-30 ka cal. BP, le réseau hydrographique subit une importante modification en s'orientant nettement vers le sud. Ce changement est contemporain de l'aggradation de deux sandurs, appartenant respectivement aux domaines glaciaires de l'Adda (UBC) et de l'Oglio (URA ; fig. 13B). Ainsi, c'est la première fois qu'ont peut dater le début de l'acmé des glaciers de piémont dans le bassin du Pô. Cet événement est synchrone de l'évolution du sandur du Tagliamento et d'autres systèmes glaciaires des Alpes du SE et corresponds au début du Dernier Maximum Glaciaire (Monegato et al.*, 2007 ; Fontana* et al.*, 2008). Le sommet des sandurs est creusé par les paléochenaux post-LGM, puis, à la base des cônes, l'orientation des chenaux, qui était 160-170° pendant la dernière phase d'aggradation, devient SW (fig. 13C). Ce système de drainage est fossilisé lorsque survient l'importante phase d'incision du Tardiglaciaire, à la suite de laquelle les rivières sont confinées à l'intérieur de corridors alluviaux et sujets à l'érosion latérale dans l'Holocène. L'histoire de la rivière Serio est marquée par des phénomènes d'alluvionnement à l'Antiquité tardive puis par la capture de son cours inférieur par la rivière Adda. Les preuves géomorphologiques concordent avec* *les sources écrites, suggérant que le changement de tracé se produit entre le XII^e^ et le XIV^e^ s. apr. J.-C.*

Introduction

The Po plain is the largest alluvial basin in Italy. The recent geological history (*i.e.*, late Quaternary, the last 135 ka BP) of the Central Po Plain is driven by phases of aggradation by large alluvial fans, mostly originating at the Pre-Alpine margin from glacier amphitheatres or from glaciated valley systems. Interglacials and other climate phases of glacier withdrawal from their piedmont culminations are marked by phases of deep entrenchment of major palaeorivers. Although most of the Central Po Plain is formed by sedimentary bodies of late Quaternary age, and despite a number of deep drillings focused on oil exploration and on assessment of nuclear power plants, limited geological information is available about the recent activity of these rivers in the unconfined plain. Also, the timing of aggradation and of intervening erosional phases is poorly constrained.

In this study, we aim to reconstruct the late Quaternary sedimentary cycle along the main river tracks of the northern side of the Central Po Plain. A detailed survey focused on the region north of the confluence of the Adda and Serio rivers, between the domain of Adda River to the west and the one of the Oglio River to the east, around the town of Crema (fig. 1). Here, a complex and intriguing interplay of river evolution, vegetation, climate and tectonics during the

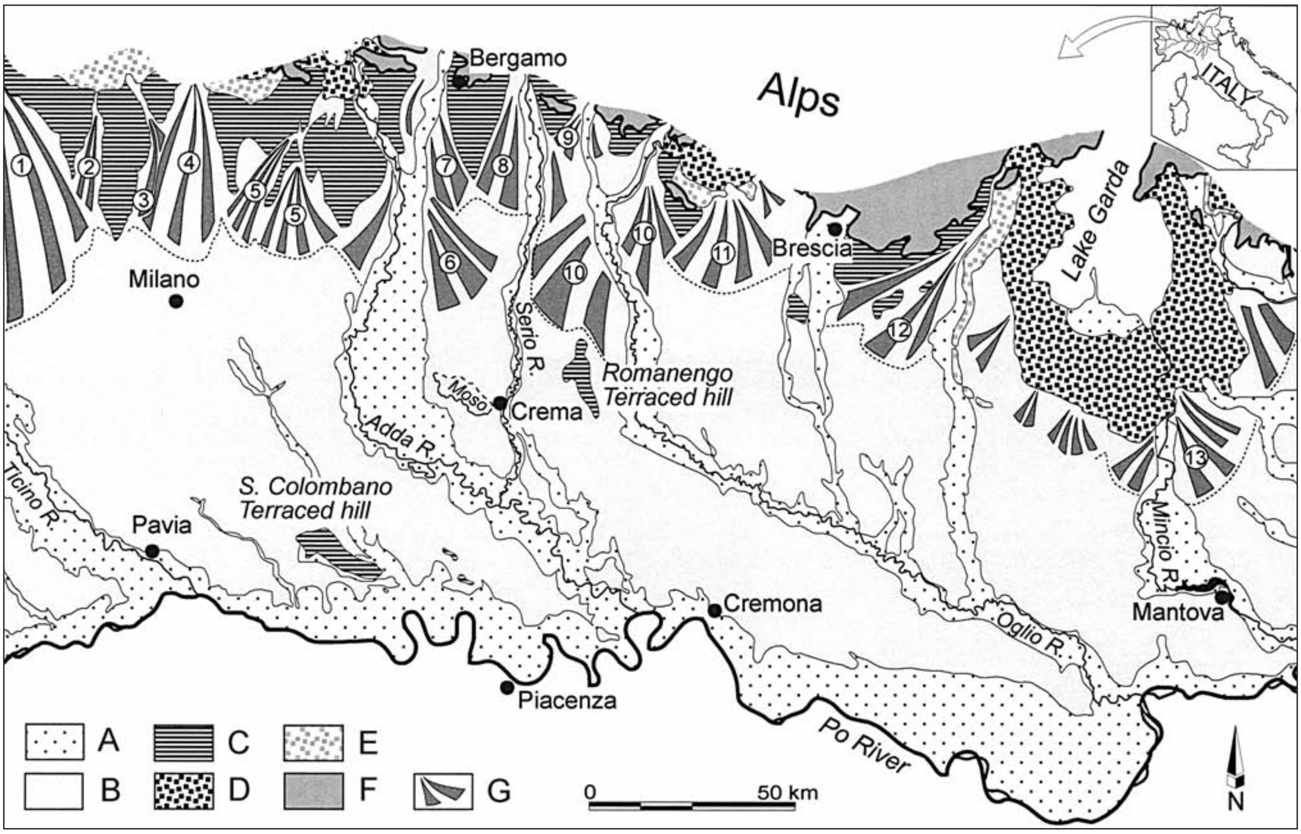


Fig. 1 – **Main geological/geomorphological units in the Central Po Plain north of the Po River**. A: fluvial deposits filling lateglacial valleys, upper surface supporting inceptisols and hydromorphic soils; B: LGM to early Lateglacial fluvial and fluvioglacial deposits, upper surface supporting Holocene alfisols; C: Plio-Pleistocene fluvial deposits, terraced, upper surface supporting vetusols (deep rubified soils); D: Late Pleistocene glacial amphitheatres: mainly glacial, ice-contact, and lacustrine deposits, upper surface at stable places supporting fersiallitic and deeply lisciviated soils; E: Early to Middle Pleistocene glacial deposits supporting vetusols; Unit F: Alpine pre-Quaternary bedrock; G: major LGM alluvial fans. Numbers are referred to the corresponding present river at fan apex (1: Olona; 2: Lura; 3: Seveso; 4: Lambro; 5: Molgora; 6: Adda; 7: Brembo; 8: Serio; 9: Cherio; 10: Oglio; 11: Strone; 12: Chiese; 13: Mincio). A dotted line represents the upper limit of the spring line. Regional references (Geological map sheets, 1:100.000) used are: Sacco, 1891; Desio et al., 1965, 1966; Schiavinato *et al.*, 1967; Boni *et al.*, 1968; Venzo *et al.*, 1969; updated according to recent regional surveys (Jadoul et al., 1990; Bini et al., 2004).

*Fig. 1 – **Principales unités géologiques/géomorphologiques dans le secteur centre-nord de la plaine du Pô, au nord du Pô.** A : dépôts fluviatiles de remblaiement des vallées tardiglaciaires, surface supérieure affectée par des inceptisols et des sols hydromorphes ; B : dépôts fluviatiles et fluvio-glaciaires du LGM/début du Tardiglaciaire, surface affectée par des alfisols holocènes ; C : dépôts fluviatiles plio-pléistocènes en position de terrasse, surface supérieure affectée par des vétusols (sols profonds rubéfiés) ; D : cirques glaciaires du Pléistocène supérieur recouverts de dépôts glaciaires et glacio-lacustres, dans les secteurs stables, présence de sols fersiallitiques et profondément lissivés ; E : dépôts glaciaires du Pléistocène inférieur et moyen affectés en surface de vétusols ; F : roches alpines pré-quaternaires ; G : principaux cônes alluviaux du LGM. Numérotation des rivières à l'apex des cônes : 1 – Olona ; 2 – Lura ; 3 – Seveso ; 4 – Lambro ; 5 – Molgora ; 6 – Adda ; 7 – Brembo ; 8 – Serio ; 9 – Cherio ; 10 – Oglio ; 11 – Strone ; 12 – Chiese ; 13 – Mincio. La ligne en pointillés représente la limite supérieure de la zone de résurgence. Références régionales (feuilles de la Carte géologique de l'Italie, 1/100.000) : Sacco, 1891 ; Desio* et al.*, 1965, 1966 ; Schiavinato* et al.*, 1967 ; Boni* et al.*, 1968 ; Venzo* et al.*, 1969. Les rélévés régionaux plus recentes ont été pris en considération (Jadoul et al., 1990 ; Bini et al., 2004).*

last 40 ka is suggested by many river traces, deeply excavated into large alluvial fans originating from the Pre-Alpine margin, coupled with different sediment provenances and with various palaeobotanical associations spanning the entire range of radiocarbon dating. Our investigations involved several Earth sciences disciplines. A detailed morphometric and geomorphological survey was coupled with a geological survey of Quaternary bodies, supported by stratigraphy and geochronology of key sections and boreholes. Characterisation and definition of sedimentary bodies was obtained by litho-pedostratigraphy, palaeobotany, petrography/minerology, and radiocarbon dating. Differently from the practice followed in several Quaternary mapping projects in Italy, based on the UBSU (Unconformity Bounded Surface Units) procedure, we adopted an integrated stratigraphy based on recognition of major events affecting our geological record. Reasons for this choice are shortly presented in the paper.

A large-scale national project for the Geomorphological Map of Italy (Castiglioni, 1997a) provided the regional framework of landforms and altimetry (Castiglioni, 1997b) for the Po Plain. Other studies were addressed to the relationships between soil development and features of parent material (Cremaschi, 1979, 1987, 1990) and between archaeological remnants and their stratigraphic frame (Baroni and Biagi, 1988; Cremaschi and Marchetti, 1995). Large alluvial fans, radiating from the alpine outlet, were mapped (fig. 1; Guzzetti *et al*., 1997). Overfit channels were recognised in the ancient hydrography. Morphometrical comparison with the present channels allowed estimating the discharge of some palaeochannels active during the last glaciation (Marchetti, 1990, 1991, 1992, 1996). Radiometric datings and palaeobotanical analysis carried out inside the moraine amphitheatres and in their connected fans (Monegato *et al*., 2007) showed that aggradation continued up to 18,000 years ago, with little differences along the Alpine foothills (Marchetti *et al*., 2004). At that time, open vegetation and bare ground characterised the most stable plain surfaces, while tree grooves are documented only in the eastern part of the Po Plain (Ravazzi *et al*., 2004). The uppermost fan surfaces were abandoned during the Lateglacial (Fontana *et al*., 2008), but fluvial sedimentation continued downslope till the beginning of Holocene, at least in some alluvial plains of northeastern Italy (Avigliano *et al*., 2002). Significant steps in the Lateglacial climate warming and afforestation in the plain and along the foothills (Gobet *et al*., 2000; Finsinger *et al*., 2006; Vescovi *et al*., 2007) affected the plain evolution, driving erosion in the upper and medium sectors of river courses (Marchetti, 2002). Nevertheless, before the present study no relevant palaeobotanical evidence was available in the Central Po Plain.

Alluvial fan formation and dissection at the Alpine foothill of Lombardy

An overview of the Quaternary alluvial bodies developed at the foothills of the Central Alps is shown in fig. 1. Remnants of alluvial bodies older than the last glaciation are exposed in the piedmont plain, at the foothills of the Alps. Here, a series of terraced plains (Unit C; fig. 1) are overlain by deep, rubified soils and polygenetic loess cover (Cremaschi, 1987, 1990). They have been interpreted as relicts of sandurs produced during the culminations of Early-Middle Pleistocene Alpine glaciations (Unit E; fig. 1; Cremaschi, 1987; Scardia *et al*., 2010). Isolated emergences of Plio-Pleistocene marine to fluvial successions occur in the plain north of the Po River (isolated terraced hills near San Colombano, Casalpusterlengo, Romanengo and Brescia; Unit C; fig. 1). The latter are related to thrusts faults active in the subsurface of the plain during the Quaternary (Livio *et al*., 2009).

Last glaciation fans and palaeohydrography of the Crema surroundings

The development of piedmont lobes of the Adda, Oglio and Garda glaciers during the last glaciation formed a complex of glacial, ice-contact, and lacustrine deposits (Unit D; fig. 1). Radiocarbon and OSL datings so far available place them in the Last Glacial Maximum, between 30 ka and 19 ka cal. BP (Alessio *et al*., 1981; Cremaschi, 1987; Ferraro, 2009). We correlate these proximal proglacial bodies to fluvial and fluvioglacial deposits (Unit B; fig. 1), whose exposed surface occupies most of the Central Po Plain, and thus called 'Main plain level' by geomorphologists (Petrucci and Tagliavini, 1969). Radiocarbon ages, so far available only in the westernmost plain south of Milano, constrain Unit 2 within the Last Glacial Maximum (Baio *et al*., 2004). The upper belt of Unit B is formed by coalescent fans marked by braided palaeocourses, and by a slope gradient greater than 0.05%. Their lower boundary is reconstructed from digital contour lines obtained from scattered altimetrical points in the Regional Technical Maps of Regione Lombardia. Remarkably, the lower boundary of the fan belt so far defined shows an excellent correlation to a continuous spring line, due to a sudden increase of the water-satured, pelitic component in the sediment (silt and fine sand prevailing; fig. 1). The spring line originates the so-called 'groundwater-fed rivers', a characteristic feature of the minor hydrography south of the spring belt. Groundwater-fed rivers commonly flow over the '*Livello fondamentale della pianura*' (Main plain level), and modified the uppermost surface and its pedogenetic evolution over large areas. However, in the vicinity of major valley rivers, groundwater-fed rivers are also entrenched. Discharge regime of groundwater-fed rivers is known to have changed through the last 15 ka, according to rainfall changes and, during the last 3600 years, after irrigation purposes (De Marinis, 1997) and, more recently, as a consequence of industrialisation. Hereafter we focus on the fans extending in the studied area, *i.e.* related to the following glacial basins from west to east: Adda, Serio and Oglio (tab. 1). The fan bodies belonging to the domain of the Adda glacier extend over a cumulative area of more than 400 km^2; the western fan of the Oglio River over a more than 350 km^2 area, while the fan of Serio River over a more than 100 km^2 area. These sizes are representative for Pleistocene glacially-fed basins and are not comparable to those of modern river catchments. Indeed, during the last glaciation, the main

Basin name	Planimetric area (in km²)	Actual area (in km²)	Mean elevation (in m)	Megafan area (in km²)
Adda	(6) 4617	5051	1569	440
Lura	(2) 82	82	349	91
Seveso	(3) 155	156	325	95
Lambro	(4) 236	240	477	192
Molgora	(5) 94	94	349	320
Brembo	(7) 806	860	1141	60
Oglio	(10) 1963	2121	1467	356
Strone	(11) 83	83	232	310
Cherio	(9) 119	124	549	38
Serio	(8) 574	616	1204	121

Tab. 1 – **Geometrical characteristics of catchments and fan areas.** Modified data from F. Guzzetti *et al.*, 1997. The actual catchment surfaces are computed dividing each pixel of planimetric area by the cosine of the slope in the pixel. Boundaries of fans are estimated on the base of digital contour lines drawn on the basis of scattered altimetrical points in the Regional Technical Maps of Regione Lombardia (bracketed numbers: see fig. 1).

*Tab. 1 – **Caractéristiques géométriques des bassins versants et des cônes alluviaux.** D'après Guzzetti* et al., *1997, modifié. Les surfaces réelles des bassins versants sont calculées en divisant chaque pixel de surface planimétrique par le cosinus de la pente dans le pixel. Les limites des cônes alluviaux sont estimées sur la base des lignes de contour dessinées à partir des points altimétriques sur la Carte Technique Régionale de la Regione Lombardia (numéros entre parenthèses : voir fig. 1).*

catchment of the Central Alps was covered by an ice field from which many tongues radiated down along the main valleys (Florineth and Schlüchter, 2000; Kelly *et al.*, 2004). The Adda glacial basin fed not only the fan nowadays cut by the Adda River (number 6; fig. 1), but westward it formed other fluvioglacial fans, nowadays drained by small rivers [fig. 1; Lura (2), Seveso (3), Lambro (4), Molgora (5)]. The Adda fan (6) was also contributed by the Brembo (7) catchment, a left tributary near the mountain boundary. The Oglio glacial basin fed both the fan (10) and, beside, a second, large eastern fan (11), originating from the amphitheatre of Iseo Lake (Strone, number 11; fig. 1). Recent instances would relate the development of fan (11) to a Middle Pleistocene glaciation (Bini *et al.*, 2007), but new, unpublished geochronometric data support instead a previous attribution to the last glaciation (*cf.* Cremaschi, 1987). The Oglio fan (10) merged with the right fan of Cherio River (9). Finally, the Serio glacial basin included a transfluent branch of the Oglio glacier (Orombelli and Ravazzi, 1995), thus the glacial catchment also extended outside the limit of the modern fluvial basin. However, the glaciation of the Serio catchment remained confined within the Alpine valley, never developing a foreland lobe in front of the plain. Differences in the lithological structure of the late Quaternary Alpine catchments of Adda, Oglio and Serio are reflected in their alluvial petrography, hence provenance analysis allows bounding the fan bodies in the plain. Sediments from the Adda catchment are characterised by quartz, feldspars and metamorphic lithic grains derived from the Austroalpine and Southalpine tectonic units of the Central Alps. Heavy minerals include moderately rich hornblende-garnet-epidote suites with sillimanite and andalusite. The detrital supply from the Serio basin is characterised by carbonate lithic rock fragments yielding a poor amphibole-garnet-epidote suite and containing felsic volcanic grains, chert, and calcareous-sandstone grains derived from Permo-Mesozoic covers of the Orobic Alps. Sediments from the Oglio catchment are characterised by quartz, carbonate lithic grains, volcanic rock fragments and feldspars. Heavy minerals consist of moderately-poor hornblende-dominated suites with minor garnet and epidote from the Mesozoic cover of the Southern Alps and from the Adamello Tertiary pluton.

Fan dissection in the Crema region

The study area is located at the lower boundary of the Adda (6; fig. 1) and Oglio (10) fluvioglacial fans, constraining in the middle, the less wide Serio (8) fan (fig. 1 and fig. 2). The latter fan did not get as far as Crema, as its contribution to the fluvioglacial aggradation of the plain was limited (fig. 1 and fig. 2). On the other hand, the Serio River most probably drove the subsequent erosional phases. The ancient valley entrenched by a putative palaeo-Serio River into fluvioglacial fans was subsequently abandoned after two fluvial capture events that dissected its fluvial track in two fossil reaches: 'Dead Serio' ('B'; fig. 2) and 'Serio di Grumello' ('C'; fig. 2); the low land of Acquanegra Cremonese ('D'; fig. 2) might also be involved in this evolution. The last capture was operated by the entrenchment of the fluvial path called 'Montodine trough' (fig. 2). The captures and fluvial domains so far indicated are hypothetic (Passeri, 1966) and their nature will be examined in the present paper. A large, partially isolated depressed basin, called 'Mosi di Crema', encumbers the drainage so far described ('A'; fig. 2), thus suggesting a complex intriguing evolution close to the town of Crema (fig. 2). The Mosi basin formed close to the area where the Serio River shows a recent drainage evolution possibly related to the surface effects of shallow thrust activity along the area of interaction between the Apennines and the Southern Alps. Recently published data on the subsurface evolution of the Po Plain (Fantoni *et al.*, 2004) suggest that the Apennine thrust fronts were active at least up to the Upper Pleistocene. However, direct stratigraphical information, and bio-geochronological determinations for the development of this depression are not yet available, and new data will be presented here.

Methods

A detailed DTM was prepared to identify the main geomorphic features. Contours lines were obtained from elevation points derived from numerical Cartography (CTRN) of the Region Lombardy (nominal scale, 1:10,000). The evalu-

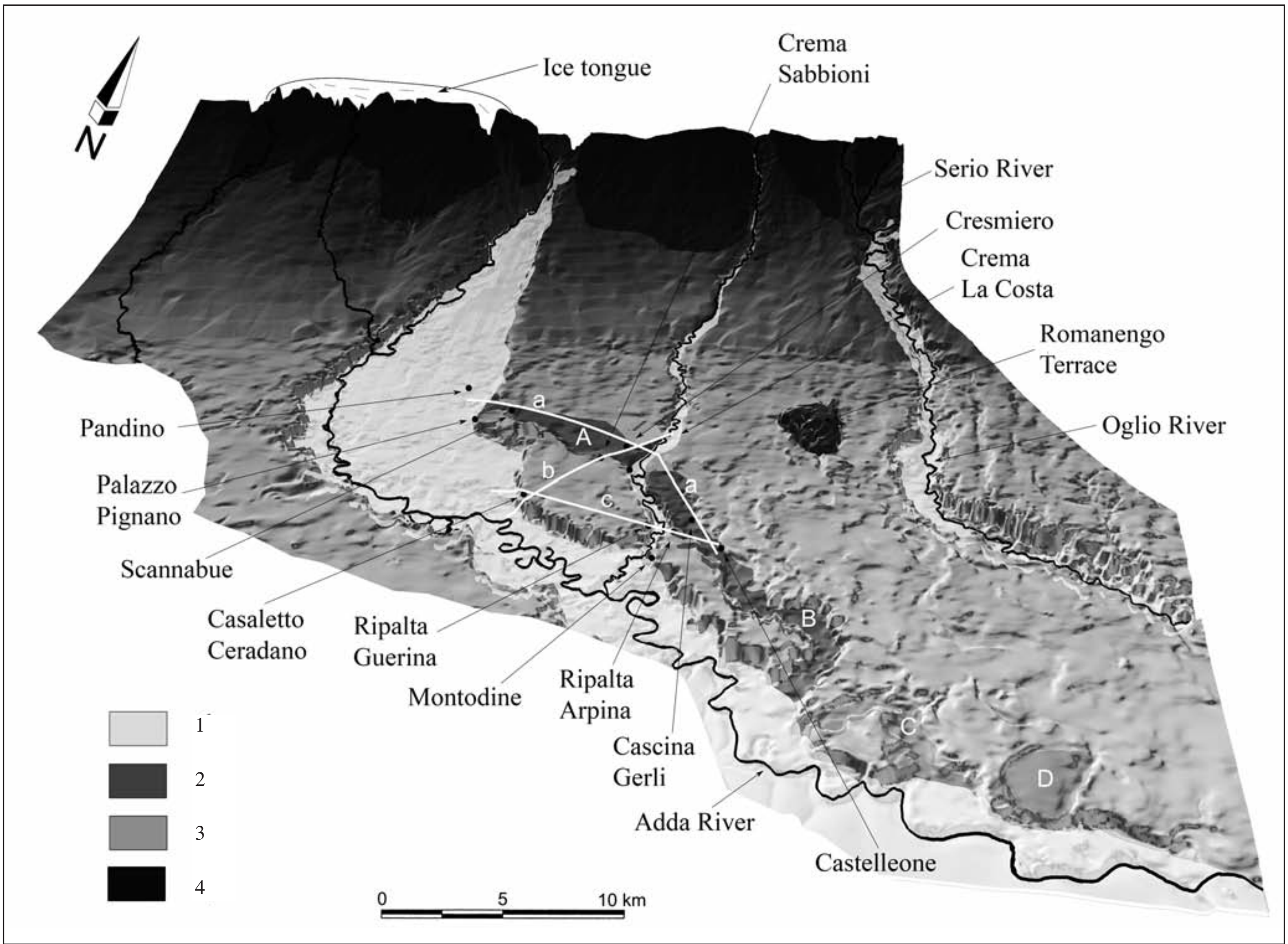


Fig. 2 – **Three dimensional terrain model of the studied area.** 1: Lateglacial to Holocene river valleys; 2: 'Mosi di Crema' (A), 'Serio Morto' (B) and abandoned large meanders (C, D), Lateglacial in age; 3: LGM terraced surface; 4: Pre-Quaternary mountain relief (bedrock) and surfaces terraced before the LGM. White lines show the traces of geological sections: a: Pandino-Castelleone section (fig. 3); b: Crema-Casaletto Ceredano section (fig. 4); c: Casaletto Ceredano-Castelleone section (fig. 5); A: 'Mosi di Crema' sedimentary basin; B: 'Serio Morto' abandoned valley ('Dead Serio'); C: 'Serio di Grumello' abandoned valley; D: low land of Acquanegra Cremonese.

*Fig. 2 – **Modèle numérique de terrain tridimensionnel de la zone étudiée.** 1 : vallées creusées entre le Tardiglaciaire et le début de l'Holocène ; 2 : « Mosi di Crema » (A), « Serio Morto » (B) et grands méandres abandonnés d'âge tardiglaciaire (C, D) ; 3 : surfaces mises en place au cours du LGM ; 4 : relief de montagne (roches pré-quaternaires) et surfaces entaillées avant le LGM. Les lignes blanches indiquent le tracé des coupes géologiques : a : coupe Pandino-Castelleone (fig. 3) ; b : coupe Casaletto Ceredano-Crema (fig. 4) ; c : coupe Casaletto Ceredano-Castelleone (fig. 5). A : dépression de « Mosi di Crema »; B : vallée abandonnée du « Serio Morto » ; C : vallée abandonnée du « Serio di Grumello » ; D : dépression de Acquanegra Cremonese.*

ation of the geomorphic features has been analysed applying tested techniques joined to geomorphological analysis (Dikau, 1989; Miliaresis and Argialas, 1999; Strobl, 2001). The realistic effect was obtained by the hillshade technique lighting the DTM with a point of illumination, usually northwest and tilted 45° from horizontal. The resulting images bear an effective three-dimensional view (fig. 2).

The field survey considered the detailed geomorhological features, the soil characteristics, and first determinations about the petrographical composition of gravels. Stratigraphic sections along the main scarps were manually opened, described and sampled for sand petrography and radiocarbon dating. Finer clastic sediments, organic and biochemical deposits were also sampled for pollen analysis (tab. 5). The outcropping stratigraphic record has been implemented by continuous technical (rotation) drillings and by manual drilling (modified Russian corers and gouge augers in soft and fine sediments).

Sixteen radiocarbon AMS ages were obtained all from terrestrial plants or mammal bones, mainly fruits and seeds, but, in levels poor of terrestrial plant detritus, we accepted wood charcoal and twigs (tab. 2). Overall, we avoided bulk sediment, aquatic plants and shells even in the pre-anthropogenic limnic sediments, due to well-known pitfalls in dating these materials. Calibration has been carried out using CALIB (v. 6.0, Queen's University Belfast) with the IntCal09 calibration curve (Reimer *et al*., 2009). In tab. 2 and along the text the calibration is reported with 1 σ of precision. Throughout the text we'll use either radiocarbon ages, indicated as 'a ^{14}C BP', and calibrated ages, which are indicated as 'a cal. BP' or 'AD'.

Site and section	Sample Acronym	Stratigraphic position	Material	Laboratory code	^{14}C a BP	Calibrated range (in a cal. BP)	^{13}C (in ‰)	Reference
Crema, Cava Alberti	CALBw1	Upper gravel unit	Trunk, external rings	Ua-33641	1735±35	1549-1719	-27.5	this paper
Crema, Cava Alberti	CALBw2	Upper gravel unit	Trunk, inner rings	Ua-33642	1810±35	1689-1825	-25.9	this paper
Sergnano, pipeline SNAM	SER2wood	Cut-and-fill channel, 170 cm depth	Wood	Ua-40320	3405±33	3730-3560	-28.6	this paper
Sergnano, pipeline SNAM	SER2seed	Cut-and-fill channel, 170 cm depth	Cornus mas endocarp	Ua-40319	3482±35	3850-3680	-26.3	this paper
Mosi di Crema	MBAWt1	MBAW 76 cm	Herb peat	Ua-33147	1365±45	1180-1211	-28.6	this paper
Mosi di Crema	MBAWt2	MBAW 224 cm	Small branch (or root)	Ua-33148	4805±45	5463-5612	-30.3	this paper
Mosi di Crema	MBAWt3	MBAW 303 cm	Small branch (or root)	Ua-33149	4775±45	5450-5596	-30	this paper
Mosi di Crema	MBAWt4	MBAW 315-316 cm	Peaty sand	Ua-33640	12790±135	14541-16195	-29.2	this paper
Casaletto Ceredano, section 1	CCERw1	CS CER1 119 cm	Wood	Ua-33261	25975±450	30120-31252		this paper
Casaletto Ceredano, section 1	CCERc1	CS CER1 25-33 cm	Charcoal	Ua-33262	32950±1070	35197-40182		this paper
Casaletto Ceredano, section 2	CCERw2	CS CER2 68 cm	Wood	Ua-34537	26915±510	30472-32391	-27	this paper
Casaletto Ceredano, section 2	CCERc2	CS CER2 46 cm	Charcoal	Ua-34536	29415±690	32008-35153	-25.5	this paper
Ripalta Guerina	RG1	RG1 Layer 1, 0-2 cm	Wood	Ua-34096	> 40000			this paper
Montodine section 1	MONTw1	Topmost fine alluvial seq. between E1 and E2	Wood (pile dwelling)	Ua-37947	3205±30	3369-3472	-28.6	this paper
Montodine 1 'Faglia'	MONTm2	Fine alluvial seq. between E1 and E2	Organic mud streched in fault	Ua-37946	5230±40	5912-6029	-29.3	this paper
Montodine 1 'Corteccia'	MONTb3	Fine alluvial seq. between E1 and E2	Bark	Ua-38948	8731±43	9556-9834	-26.8	this paper
Montodine 1 'Legno 3'	MONTw4	Base fine alluvial seq. between E1 and E2	Wood	Ua-38949	10211±50	11745-12097	-25	this paper
Castelleone - Cascina Gerli S1	CASTw1	14.55 m depth	Wood	Ua-35380	> 40000			this paper
Ripalta Arpina, Cava Franzoni	FRZ	Base quarry	Trunk		26800±150	31033-31405		Friedrich, com. pers.

Tab. 2 – **AMS radiocarbon chronology.** Laboratory code (Ua: Uppsala).

*Tab. 2 – **Chronologie basée sur la datations radiocarbone AMS.** Code du Laboratoire (Ua : Uppsala).*

Tab. 3 – **Mineralogy of fluvial sediments.** Q: quartz; F: feldspars; Lv: volcanic and subvolcanic lithic fragments; Lcc: limestone grains; Lcd: dolostone grains; Ls: sedimentary lithic grains (shale and siltstone lithic fragments); Lm: metamorphic lithic fragments; PA: pyroxenes and amphiboles; HM: others heavy minerals (e.g., epidote).

*Tab. 3 – **Minéralogie des sédiments fluviatiles.** Q : quartz ; F : feldspaths ; Lv : fragments de roches volcaniques et subvolcaniques ; Lcc = grains calcaires ; Lcd = grains de dolomie ; Ls = grains de roches sédimentaires (marnes, siltstones) ; Lm = fragments de roche métamorphique ; PA = pyroxènes et amphiboles ; HM = autres minéraux lourds (e.g., épidote).*

Coordinates	**Samples**	**Q**	**KF**	**P**	**Lvf**	**Lvm**	**Lcc**	**Lcd**	**Lp**	**Lch**	**Lms**	**Lmv**	**Lmf**	**Lmb**	**Lu**	**Mu**	**Bi**	**PA**	**HM**	**Total**
46°18'53.76"N / 9°37'18.76"E	CCERw1	58.7	5.9	10.2	1.6	0	0	0	0	0	2.4	2.0	9.4	1.2	1.2	2.8	4.3	0	0.4	100
45°18'36.18"N / 9°43'05.85"E	RG1	56.5	6.1	14.5	4.4	1.3	0	0	1.5	0	1.1	2.7	6.3	0.6	0.4	1.1	1.1	1.5	0.8	100
45°23'08.64"N / 9°42'40.95"E	CALBw1	35.4	1.6	5.3	10.0	1.0	18.9	4.3	4.5	1.2	3.7	7.7	4.1	0	0.8	0	1.2	0.4	0	100
45°15'45.62"N / 9°49'12.06"E	CTESw1	35.6	4.0	8.3	7.6	1.1	11.4	9.0	2.6	0.4	3.6	1.2	5.5	0.4	0.8	1,0	0.6	2,0	5.1	100
45°18'49.17"N / 9°37'30.48"E	CCERc2	47.6	8.0	13.2	0.4	0	0	0	0	0	0.4	2.8	11.2	0.4	2.4	2.4	4.4	2.8	4.0	100
45°18'49.17"N / 9°37'30.48"E	CCERw2	51.6	7,0	14.0	0.4	0	0	0	0	0	0.4	2,0	10.0	0.4	2.4	2.4	4.4	2.0	3.0	100
45°19'13.31"N / 9°46'57.01"E	CSERw1	35.5	2.8	6.8	8.8	1.1	15.1	6.6	3.5	0.8	3.6	4.5	4.8	0.2	0.8	0.5	0.9	1.2	2.6	100
Depth (in m)	Samples	Q	KF	P	Lvf	Lvm	Lcc	Lcd	Lp	Lch	Lms	Lmv	Lmf	Lmb	Lu	Mu	Bi	PA	HM	Total
3.0	MBAWt3	55.1	5.9	14.4	1.3	1.6	0	0	1.3	1.7	2.1	2.1	7.8	0.6	0.8	0.8	1.3	2.1	0.8	100
3.1	MBAWt4	52.0	7.0	12.0	1.3	1.6	0	0	1.3	1.7	1.0	2.1	11.0	0.6	0.8	0.8	2.5	2.1	2.0	100
1.5	CASTw4	34.7	3.2	6.4	5.1	3.3	27.1	0.4	4.8	1.2	2.4	2,0	5.2	0,0	1.6	0.2	0.6	0.4	1.6	100
5.5	CASTw3	55.2	9.6	13.6	4.1	0.7	0	0	0	0	2.0	3.2	4.8	0.4	0.8	1.2	0	2.0	2.4	100
13.0	CASTw2	53,0	8.0	10.0	4.1	0.7	0	0	0	0	2.0	3.2	9.4	0.4	0.8	2.0	1.0	3.0	2.4	100
14.5	CASTw1	58.0	8.0	12.0	2.0	0.7	0	0	0	0	2.0	2	8.9	0.4	0.8	1.2	1.0	2.0	1.0	100
Samples	Q	KF	P	Lvf	Lvm	Lcc	Lcd	Lp	Lch	Lms	Lmv	Lmf	Lmb	Lu	Mu	Bi	PA	HM	Total	
S3506	51.1	4,0	7.5	0	0	0	0.9	0	0	1.6	0.9	15.9	0.6	0.6	3.7	6.5	2.8	3.7	100	
S3514	13.9	0.6	1.2	4.8	2.1	25.9	15.8	20.3	1.8	5.7	4.8	2.7	0	0	0	0	0	0.3	100	
S3513	31.0	1.8	11.6	9.1	2.5	17.1	3.0	4.0	0.3	3.3	6.0	6.5	0.3	0	0.7	1.3	1.5	0	100	

The pollen samples were treated according to standard methods (including HF and acetolysis), after adding *Lycopodium* tablets for pollen and charcoal concentration estimations (Stockmarr, 1971). Identification was performed out at x400, x630 and x1000 magnification under Leica light microscopes. Pollen identification followed P.D. Moore *et al*. (1991), W. Punt and S. Blackmore (1976-2004), M. Reille (1992-1995), H.J. Beug (2004) and the palynological collection of CNR-IDPA. Pollen diagrams were drawn using Tilia 1.11, TGView 2.0.2 (Grimm, 2004). The pollen sum used for % calculations includes trees, shrubs, chamaephytes and all upland herbs except aquatic and wetland plants, with a mean pollen count of 600 pollen grains (minimum 600, maximum 1200). No reworked pollen was found. Black and opaque microcharcoal particles longer than 10 μm were counted in pollen slides.

In each sand sample (13 samples, about 200g each), 400 points were counted by the Gazzi-Dickinson method (Ingersoll *et al*. 1984) on the whole sand fraction, impregnated with Araldite, cut into standard thin sections, and stained with alizarine red to distinguish dolomite and calcite. A detailed classification scheme allowed us to collect full quantitative information on coarse-grained rock fragments and to recalculate an extended spectrum of primary proportional parameters (see caption, tab. 3): metamorphic grains were classified according to protolith composition and metamorphic rank (Garzanti and Vezzoli, 2003).

We prepared three geological sections showing the architectural reconstruction of the recognised geological bodies (fig. 3 to fig. 5). Sections and borehole logs were plotted on the transects together with the position of samples radiocarbon examined for radiocarbon dating, palynology, and sand mineralogy.

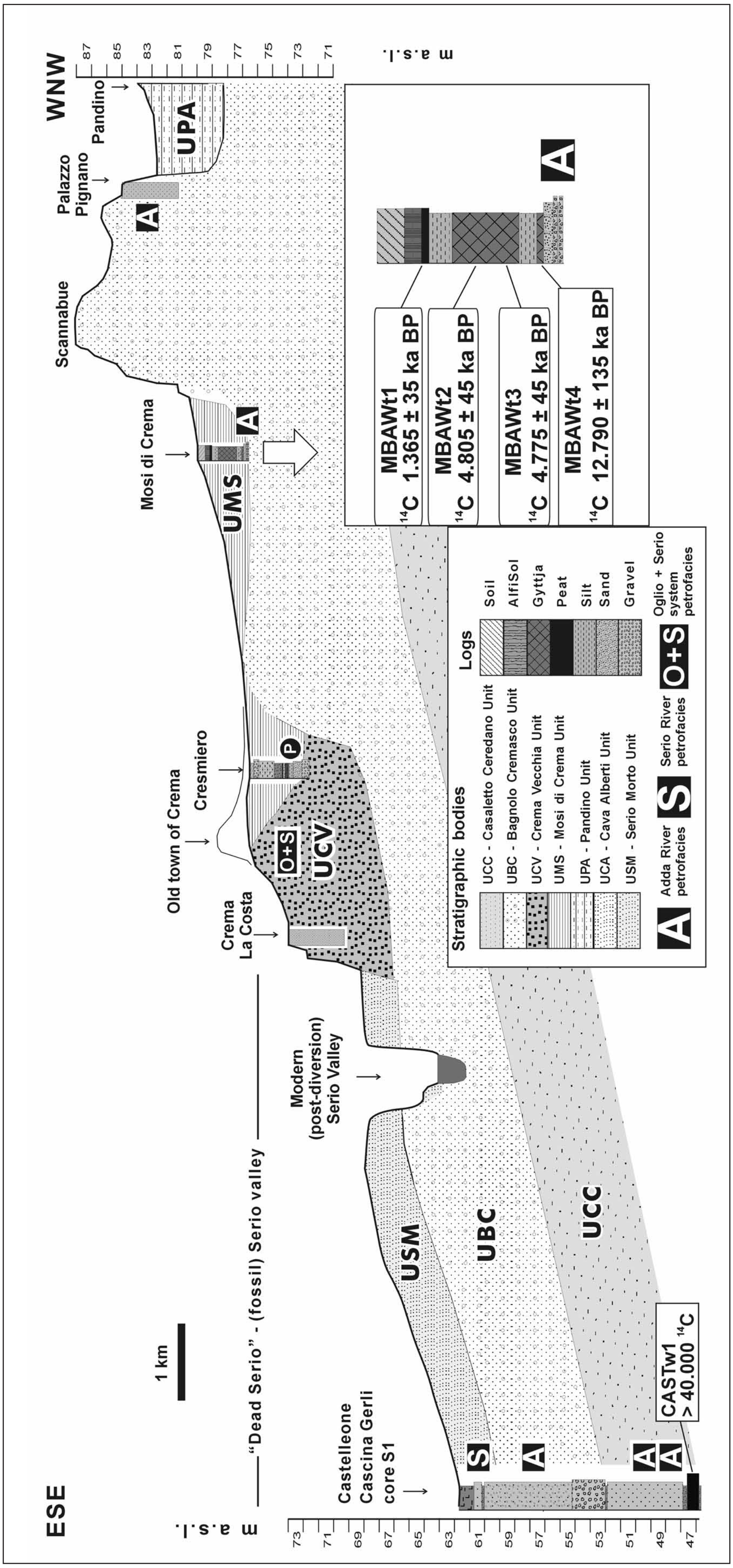


Fig. 3 – **WNW-ESE stratigraphic section from Pandino to Castelleone along the Mosi di Crema basin and the 'Dead' Serio valley (a, fig. 2).**

Fig. 3 – ***Coupe stratigraphique WNW-ESE de Pandino à Castelleone le long du bassin de « Mosi di Crema » et de la vallée du « Serio Morto » (a, fig. 2).***

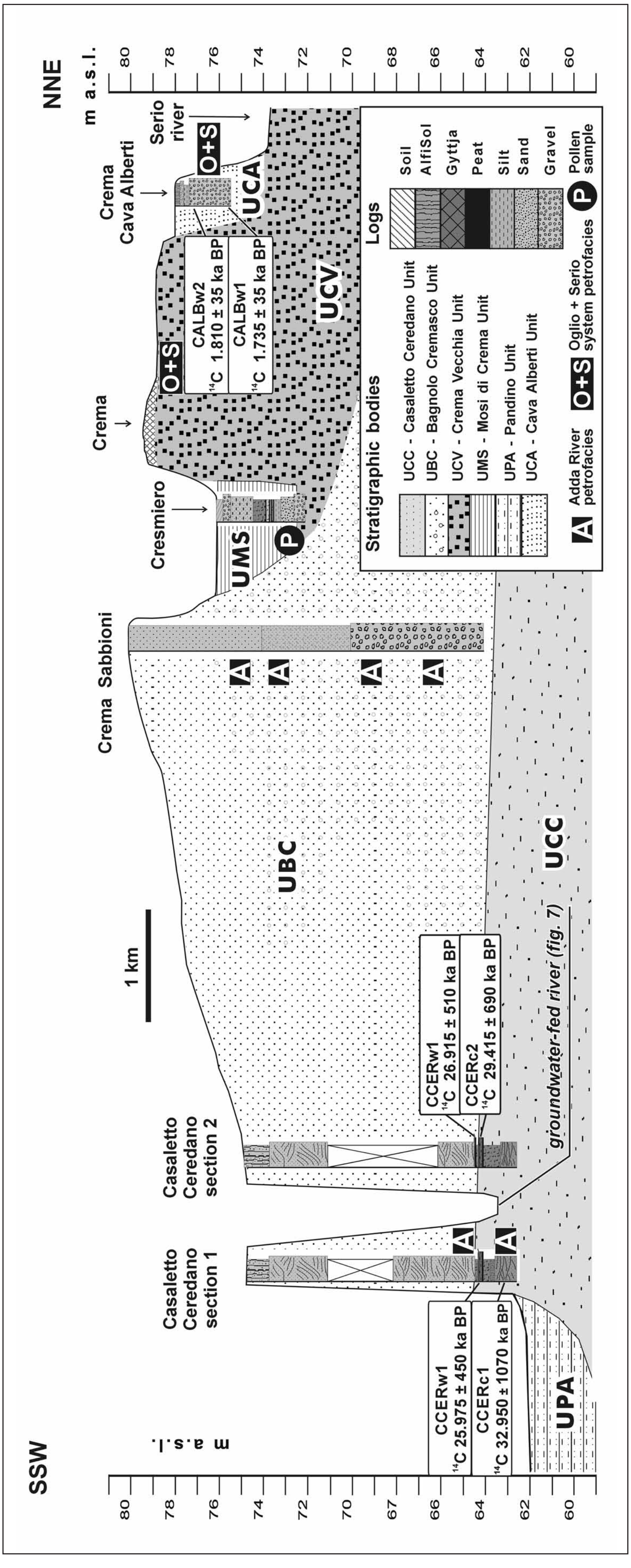


Fig. 4 – **SSW-NNE stratigraphic section from the Adda Valley close to Casaletto Ceredano to the Serio River north of Crema (b, fig. 2).**

*Fig. 4 – **Coupe stratigraphique SSW-NNE de la vallée de l'Adda près de Casaletto Ceredano à la Rivière Serio, nord de Crema (b, fig. 2).***

Two roughly perpendicular transects, ESE-WNW (fig. 2, section a; fig. 3) and NNE-SSW (fig. 2, section b; fig. 4) were traced across the town of Crema and the nearby 'Mosi di Crema' depression. An additional W-E transect in the lowermost portion of the studied area helps reconstructing the geometric relationships between the two main fans of the Adda and Oglio rivers (fig. 5). An additional stratigraphic section will be examined (Montodine, fig. 6), because it represents a key documentation for the erosional Lateglacial events and for the capture age of the Serio River.

Results

Hereafter, we first present the results of the analysis, hence we integrate the information in the stratigraphic framework (*cf. supra*).

Radiocarbon chronology

As shown in tab. 2, the AMS ages span the entire ^{14}C life, and two samples turned out to be radioactivity exhausted (*i.e.*, >40 ka according to the Lab background). Both dates older than 40 ka come from compressed peat occurring in the deeper, finer levels of the Quaternary succession of the area (Unit of Casaletto Ceredano, UCC; fig. 3, 4, 5, *cf. infra*), either buried or exposed at the bottom of the Serio River entrenchment. Upward in the same sandy-silt to organic succession we obtained four consistent ages between 32-29 and 27-26 ^{14}C ka BP, respectively from base and top of a single seam of compressed peat discovered at Casaletto Ceredano (fig. 4, 5, 7). Although ages close to ^{14}C 30 ka are frequently affected by natural contamination causing a high dispersion of ages (Chappell *et al.*, 1996; Higham *et al.*, 2009), and despite difficulties in calibration, they suggest a middle Würm age for the Casaletto Ceredano compressed peat and establish a maximum age of about 30-31 ka cal. BP for the boundary between the Casaletto Ceredano Unit and the subsequent Bagnolo Cremasco Unit (UBC, fig. 4 and fig. 5 and fig. 10 and fig. 11). Furthermore these ages are consistent with a ^{14}C age of 26,800±150 a BP reported (Kromer *et al.*, 2008) for a trunk found at the base of the gravelly deposits quarried at Cava Franzoni (fig. 5), 9 km east of Casaletto Ceredano. The latter age refers to the onset of the Ripalta Arpina Unit (URP, fig. 5, fig. 10 and fig. 12). A set of four datings was obtained from

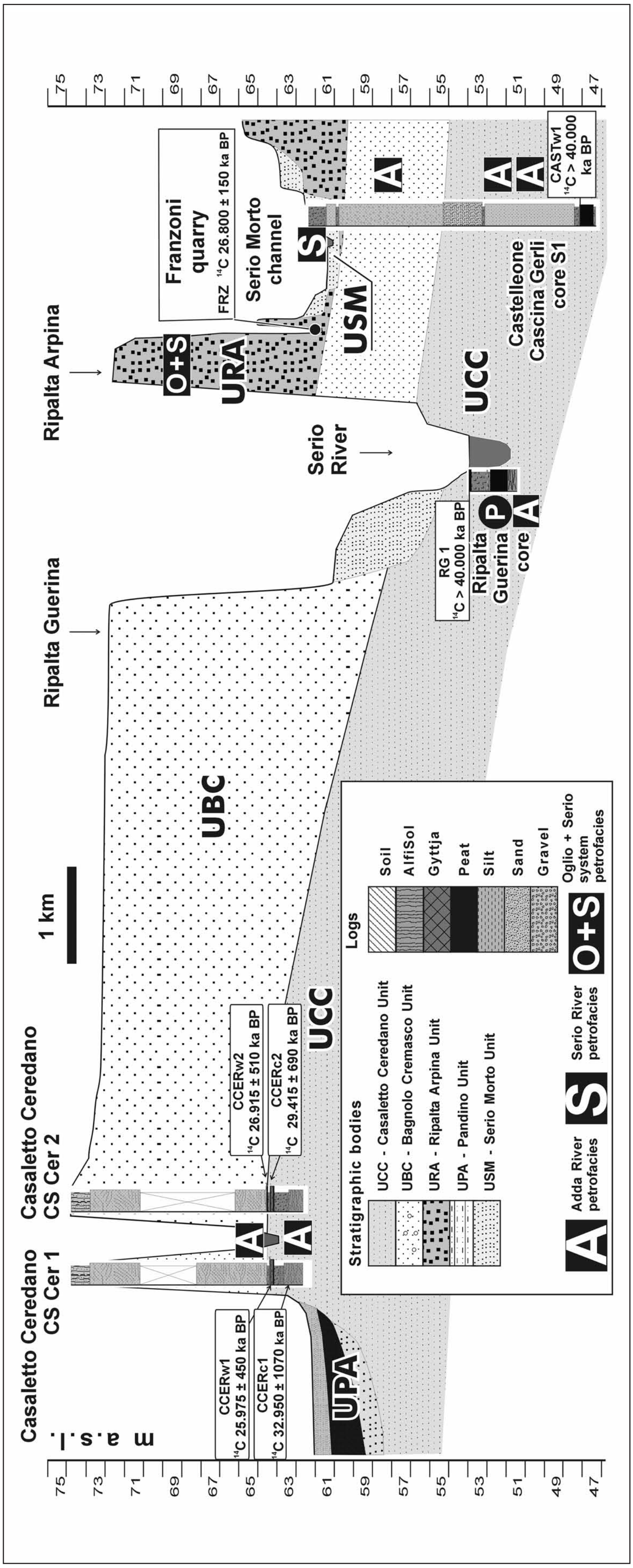


Fig. 5 – **NWN-ESE stratigraphic section from Casaletto Ceredano to Castelleone (c, fig. 2).** Compare the deeply entreched valley hosting the Serio River with the abandoned channel of the Serio Morto ('Dead Serio'), after a late Middle Age capture by the Adda River (fig. 13C).

*Fig. 5 – **Coupe stratigraphique NWN-ESE de Casaletto Ceredano à Castelleone (c, fig. 2).** Observer la vallée profondément incisée de la rivière Serio et le paléochenal du Serio Morto abandoné à la fin du Moyen Age à la suite d'un capture par la rivière Adda (fig. 13C).*

the key-section of Montodine at the confluence area of Adda and Serio rivers (fig. 6). Here, the age MONTw4 (11,770-12,090 a cal. BP) of a wood from meandering deposits establishes that by this time the main erosional phase of the Adda valley was completed (fig. 6), thus this event predates the end of the Pleistocene. The subsequent ages span the early to late Holocene fine fluvial and palustrine deposition within the Adda valley, before the capture of the Serio River. Besides, these ages document local, but important events in the middle Holocene neotectonic evolution and Middle Bronze Age pre-historic settlement of the region (*cf. infra*), deserving further work. Indeed, peat deposits exposed at Montodine section between surfaces E1 and E2, and radiocarbon dated to the first half of the Holocene (fig. 6) are deformed by a low angle reverse fault, possibly representing a surface expression of thrust activity. The ages obtained from the course of the Serio River and from surrounding fluvial deposits north of Crema highlight the main steps of alluvial deposition of the Serio River. Two ages (SER2 seeds 3680-3850 a cal. BP, and SER2 wood 3720-3560 a cal. BP) from a channel fill of the Serio

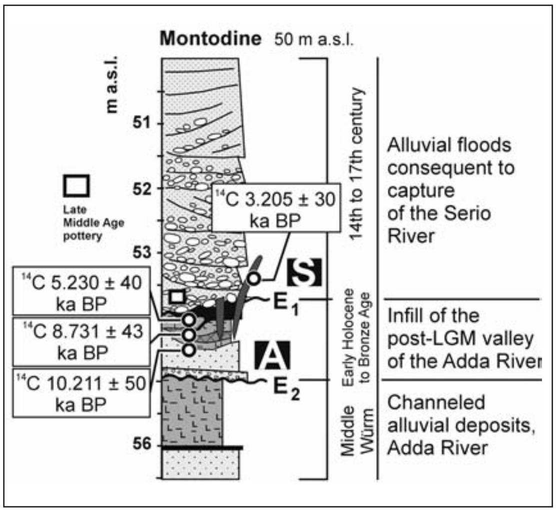


Fig. 6 – **Montodine section. Lithostratigraphical log and radiocarbon dating.**

*Fig. 6 – **Coupe de Montodine. Log lithostratigraphique et datations radiocarbone.***

Fig. 7 – **The Middle Würm peat layer outcropping at Casaletto Ceredano, along the base of the scarp bounding the LGM fluvioglacial fan of the Adda River.** In the foreground, the groundwater-fed spring emerging at the peat layer contact.

*Fig. 7 – **La couche de tourbe du Würm moyen affleurant à Casaletto Ceredano, le long de la base de l'escarpement délimitant le cône de l'Adda du DMG.** Au premier plan, résurgence au contact de la couche de tourbe.*

River near Sergnano (see position in appendix 1) point to a cut-and-fill phase which affected the plain left to the modern Serio River bed in the early Bronze Age (UBC (g-r) in fig. 10 and fig. 11). The centre of two trunks imbedded in a thick sequence of coarse gravels (site of Cava Alberti; fig. 4), at 11 m stratigraphic distance each other (CALBw1 and CALbw2; fig. 4), provided the same statistical age at 95% confidence level, with a pooled ^{14}C age of 1772±25 a BP, calibrated AD 209-341. This points to a catastrophic alluvial flood event of late Roman Age. Concerning the radiocarbon chronology and history of the Mosi di Crema, the filling of the Mosi di Crema basin (fig. 3) provided four datings. A Lateglacial age from the base filling (12,790±135 a ^{14}C BP, *i.e.* 14.5-16.2 ka cal. BP) is consistent with the pollen composition from the same level, suggesting that the sediment infill started early in the Lateglacial, before the Bølling-Allerød interstadial complex. This also provides a minimum age for the abandonment of the fluvioglacial fan surface (6) due to Adda River. Two ages obtained from wood in the overlying decomposed peat would place the thickest interval of the organic accumulation in the Middle Holocene, whereas the pollen record suggests still a Lateglacial-Early Holocene age (fig. 9). Wood parts submitted to dating were identified as *Alnus* branches, or possibly roots. Thus, the discrepancy between ages and pollen biochronology may be explained considering roots penetrating the deep peat from an alder swamp surface settled *in situ* during the Middle Holocene. Contamination by alder roots is a well-known process in alluvial mires (Brown and Keough, 1992). The uppermost ^{14}C age, obtained on terrestrial peat, suggests that organic accumulation at Mosi di Crema continued until the Middle Ages, in agreement with written documents (Fino, 1566). Defini-

Sites	Coordinates	Elevation (in m a.s.l.)	Types of section	Analyses
Sergnano, Centr. Metano SNAM	45°25'39.27''N / 9°40'59.50''E	86 m	Trench	P/S/R
Crema, Cava Alberti	45°23'08.64''N / 9°42'40.95''E	78 m	Section exposed	S/R
Mosi di Crema Petro 3	45°22'30.50''N / 9°39'15.36''E	75 m	Core	S
Mosi di Crema Petro 2	45°22'06.05''N / 9°39'45.77''E	74 m	Core	S
Mosi di Crema, MBAW	45°22'39.81''N / 9°36'18.20''E	80 m	Core	P/S/R
Crema, Loc. Cresmiero	45°21'45.16''N / 9°40'17.73''E	76 m	Core	P
Crema, Loc. Sabbioni	45°21'15.76''N / 9°39'58.84''E	79 m	Core	S
Crema, Loc. La Costa	45°21'00.58''N / 9°41'09.13''E	75 m	Section exposed	S
Castelleone, Cascina Serafina	45°19'13.31''N / 9°46'57.01''E	70 m	Section exposed	S
Casaletto Ceredano, section 1	46°18'53.76''N / 9°37'18.76''E	64 m	Section exposed	P/S/R
Casaletto Ceredano, section 2	45°18'49.17''N / 9°37'30.48''E	64 m	Section exposed	P/S/R
Casaletto Ceredano, section 3	45°18'49.58''N / 9°37'54.77'E	73 m	Section exposed	S
Ripalta Guerina	45°18'36.18''N / 9°43'05.85''E	55 m	Core	S/R
Ripalta Arpina, Cava Franzoni	45°18'31.45''N / 9°43'18.34''E	64 m	Section exposed	S
Castelleone, Cascina Gerli S1	45°18'29.00''N / 9°44'22.51''E	59 m	Core	S/R
Montodine, Section 1	45°16'55.59''N / 9°42'19.08'E	51 m	Section exposed	S/R
Cappella Cantone, Cava Testa	45°15'45.62''N / 9°49'12.06''E	59 m	Section exposed	S

Appendix 1 – **Location of studied sites. Coordinates obtained from Google Earth.** P: pollen analysis; S: sand petrography; R: pebble petrography.

*Appendice 1 – **Localisation des sites étudiés. Les coordonnées ont été obtenues avec Google Earth**. P : analyse pollinique ; S : pétrographie des sables ; R : pétrographie des galets.*

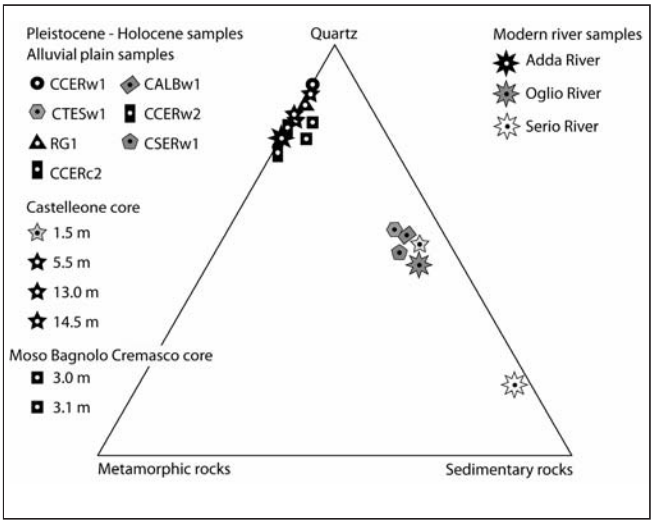


Fig. 8 – **Ternary diagram of sand fraction composition.** See tab. 3 for sample acronyms.

*Fig. 8 – **Diagramme ternaire de la composition de la fraction sableuse.** Voir le tab. 3 pour les acronymes de l'échantillon.*

tively land reclamation coincided with the realisation of Vacchelli channel (1887-1892).

Archaeological and documentary evidence of geological evolution

The region of Crema is rich in archaeological finds, beginning with Mesolithic artefacts associated to the alfisols on the upper surface of the URA unit (Baioni, 2009). However, we will consider here only artefacts holding stratigraphic relationships with relevant geological events. Several piles have been found in the Montodine section, standing on the upper surface E1, truncating Middle to Late Holocene, fine alluvial and palustrine deposits of the Adda River (fig. 6). After their radiocarbon age, these piles are to be related to a Middle Bronze Age perifluvial structure, not yet known, settling along the Adda River, with no petrographic contribute from the Serio River. Piles have been exposed on the erosional surface E1, and covered by coarse gravel, this latter petrographycally pertinent to the Serio River (tab. 4 and fig. 6). Late Middle Age pottery, identified as 'graffita padana', and dated to 14th c. AD, was recovered from the lowermost gravels (fig. 6). This find allows dating the alluvial floods of the Serio River, pertinent to the fluvial trough excavated by the Serio River at Montodine. Given that the Montodine trough is embanked within the 'Dead Serio' valley (compare fig. 2, fig. 3 and fig. 10), we argue that this pottery provides an evidence of early alluvial events of the Serio River after its capture. The diversion caused the

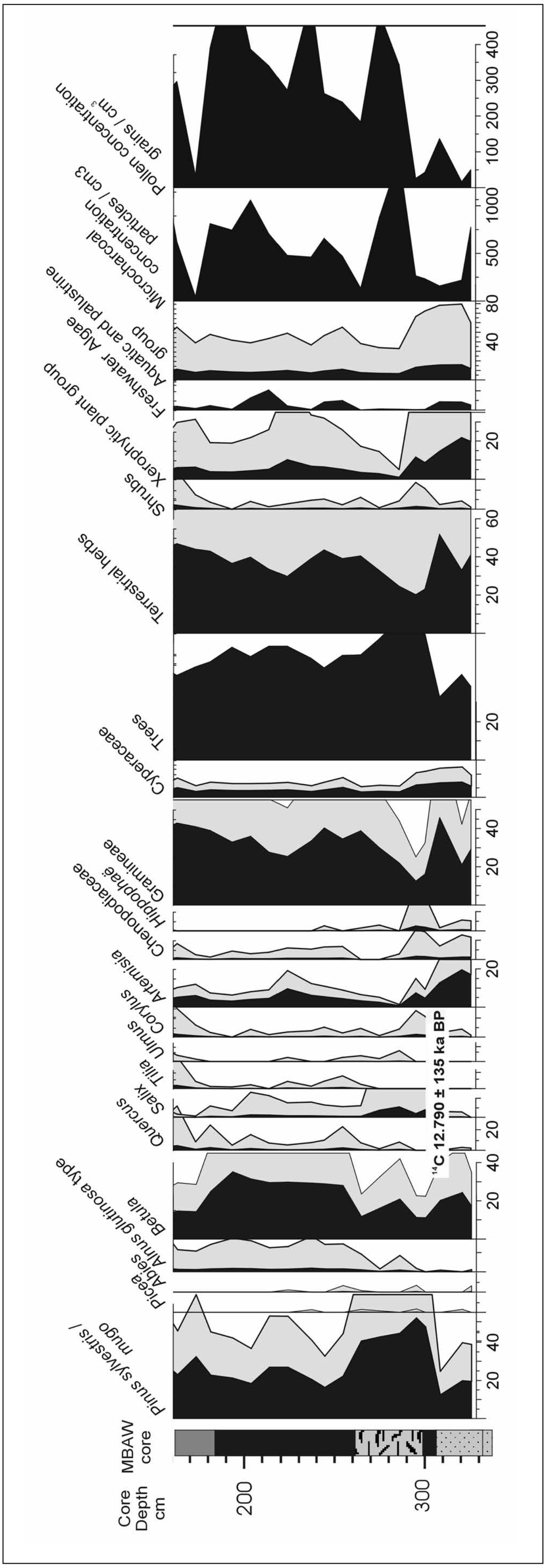


Fig. 9 – **'Mosi di Crema' pollen record from core MBAW, lower section.** Many curves have been exaggerated x2 (grey filling). Analyst: Massimiliano Deaddis.

*Fig. 9 – **« Mosi di Crema », données polliniques provenant du carottage Mbaw, section inférieure.** Plusieurs courbes (en gris) ont été exagérées x2. Analyste : Massimiliano Deaddis.*

Fig. 10 – **Stratigraphic framework of the recognised geomorphological units and legend of the geomorphological map.**

*Fig. 10 – **Cadre stratigraphique des unités géomorphologiques reconnues et légende de la carte géomorphologique.***

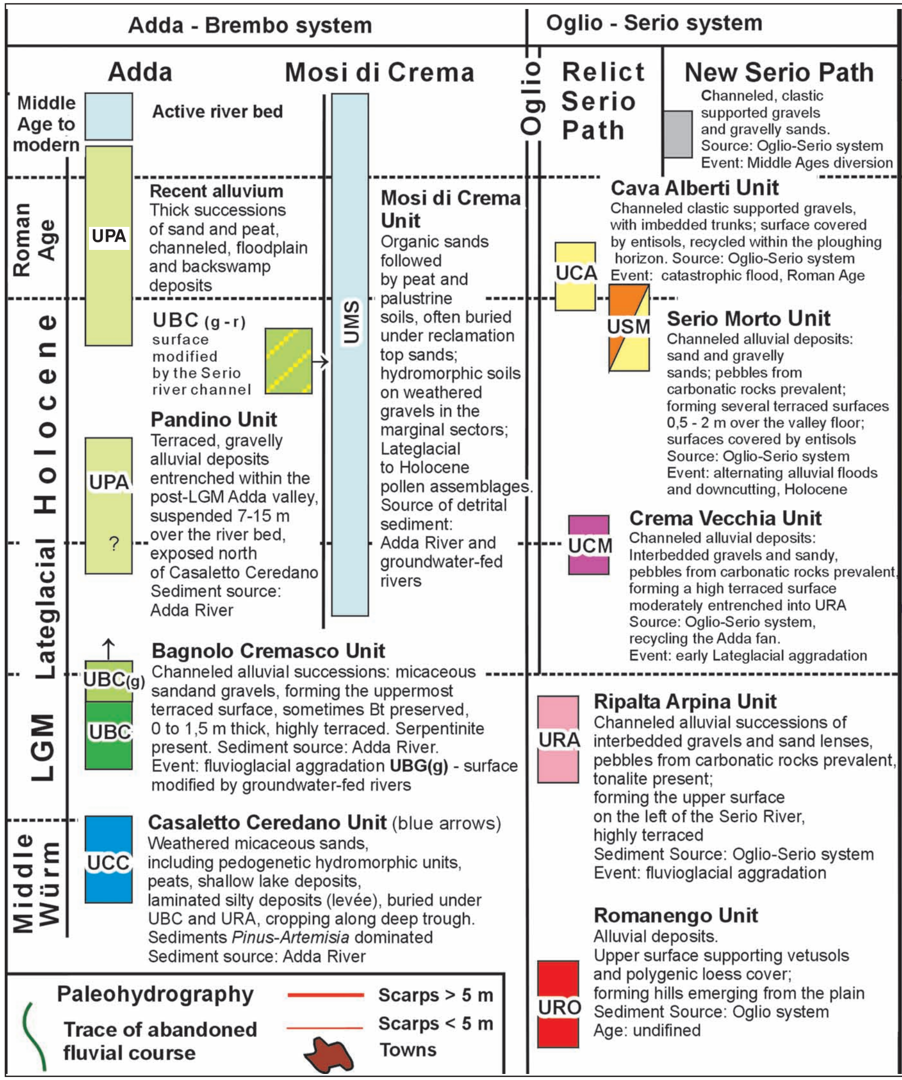
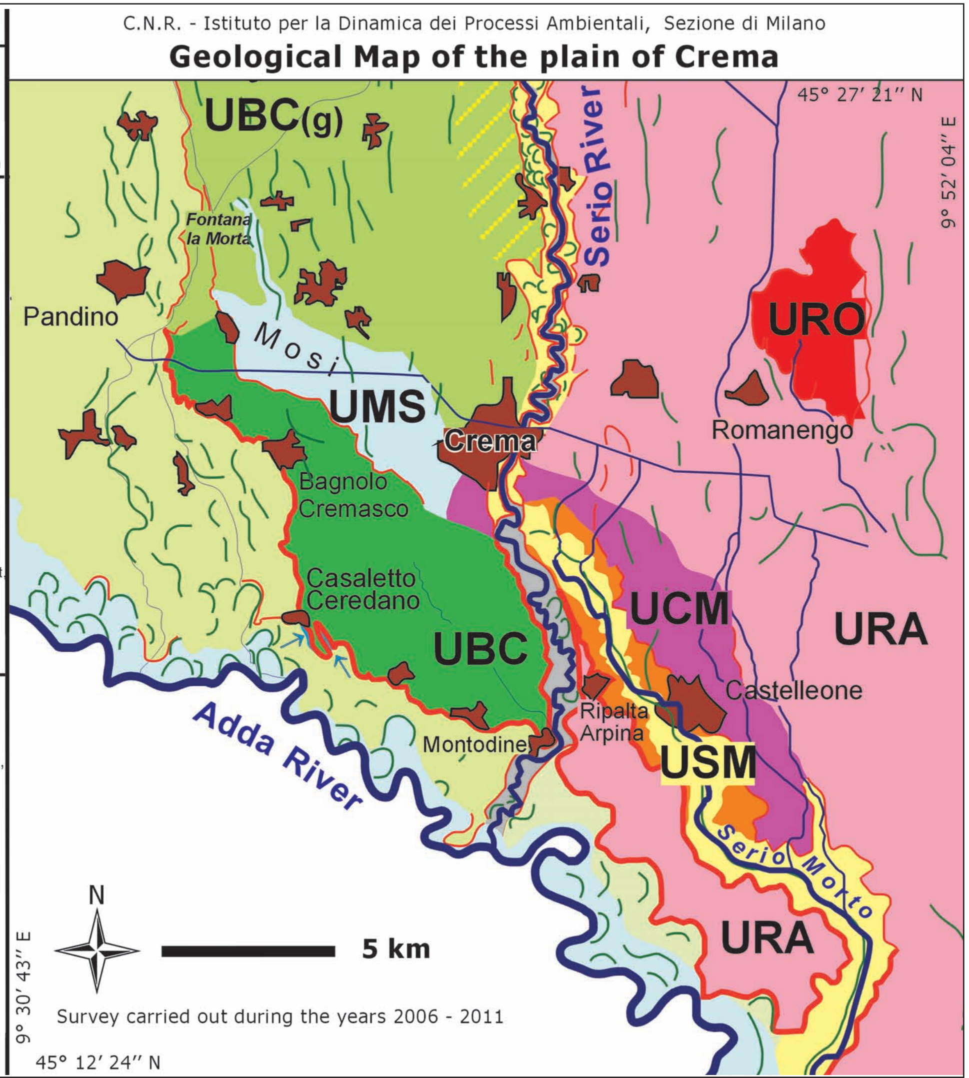


Fig. 11 – **Event stratigraphic-based geomorphological map of events in the Central Po Plain of Lombardy between the Adda and Serio rivers.**

*Fig. 11 – **Carte géomorphologique basée sur les événements stratigraphiques dans la plaine centrale du Pô en Lombardie entre les rivières Adda et Serio.***



Localities	Depth (in cm)	Volcanic rocks	Gneiss	Micaschist	Serpentinite	Quartzite	Sandstone	Limestone	Dolostone	Tot
Ripalta Arpina, Cava Franzoni		7	24	31	0	17	1	12	8	100
Mosi di Crema, Petro 2	100	9	5	0	0	20	1	50	15	100
Mosi di Crema, Petro 3	90	5	38	10	5	30	1	10	1	100
Montodine, Section 1	500	10	5	1	0	28	11	37	8	100
Castelleone, Cascina Gerli S1	1070	5	48	14	1	28	3	1	0	100
Castelleone, Cascina Gerli S1	1350	8	43	16	2	29	2	0	0	100
Crema, loc. La Costa	330	7	51	10	3	25	4	0	0	100

Tab. 4 – **Bulk petrography of pebbles.**

*Tab. 4 – **Pétrographie des galets.***

abandonment of the 'Dead Serio' path, and cutting the Montodine trough. Accordingly, historical documents suggest that the 'Dead Serio' path was still active in the 10th c. AD (Ferrari, 1992), while the river name *Serius novus* occurs first in a document dated to AD 1361, and the first citation about an abandoned fluvial path '*flumen Serii mortui*' date back to the end of 14th c. AD (Ferrari, 1992). Finally, a complete Roman pot was found close to Formigara, embedded in sands forming a terraced body 1 m above the floor of 'Dead Serio' (see fig. 11). The pot is dated to 1st-2nd c. AD. This suggests that the 'Dead Serio' channel was active during the Roman Age and also afterwards. However, since the Roman Age it experienced only moderate downcutting, while along the modern Serio River path a terraced unit of Roman Age (USM; fig. 3 and fig. 5) is suspended 7 m above the modern riverbed. Again, this is in agreement with written sources, suggesting that the 'Dead Serio' was active throughout most of the Middle Ages, but was abandoned before a strong downcutting phase related to the last phase of the Montodine trough entrenchment. As already discussed, the latter was caused by the capture event occurred between the 12th c. and the 14th c. AD.

Tab. 5 – **Percentage pollen spectra from Cresmiero and Ripalta Guerina cores.**

*Tab. 5 – **Spectres polliniques (%) obtenus sur les carottes Cresmiero et Ripalta Guerina.***

Sites and depth	Cresmiero 270-274 cm	Cresmiero 249-255 cm	Ripalta Guerina 188-192 cm	Ripalta Guerina 60-66 cm
Trees				
Abies alba			0.5	0.6
Picea abies			0.2	0.3
Pinus sylvestris /mugo	28.5	40.5	15.9	60.7
Alnus glutinosa type			0.5	
Betula sp.	15.3	17.7	23.4	6.0
Quercus sp.	0.3	0.2	2.2	0.3
Salix sp.	0.7	0.8	1.0	8.4
Trees tot.	**44.8**	**59.2**	**43.7**	**82**
Shrubs				
Buxus sempervirens			1.7	0.6
Corylus avellana	0.5	1.2	2.4	0.3
Cornus type			0.2	
Ephedra sp.	0.1	0.2		0.6
Hippophae rhamnoides	1.1	0.2	0.5	0.9
Rosaceae			0.2	
Juniperus sp.	2.3	0.5	3.6	1.2
Shrubs tot.	**4.0**	**2.1**	**8.6**	**3.6**
				…/…

Sites and depth	Cresmiero 270-274 cm	Cresmiero 249-255 cm	Ripalta Guerina 188-192 cm	Ripalta Guerina 60-66 cm
Herbs				
Anthemis type	0.7		2.4	0.3
Aster type	1.6	0.2	0.7	
Brassicaceae				2.1
Campanula sp.			0.5	
Caryophyllaceae	0.3	0.3		
Centaurea nigra sp.	0.1			
Chicorioideae	0.4		1.0	0.3
Euphorbia sp.		0.2		
Filipendula sp.	0.3	0.2		
Graminae	15.9	14.2	26.7	9.3
Umbelliferae	1.2	1.4		0.3
Herbs tot.	**20.5**	**16.4**	**31.3**	**12.3**
Putative Antropogenic taxa				
Plantago lanceolata		0.2		
Rumex sp.	0.4	0.3		
Putative Antropogenic taxa tot.	**0.4**	**0.5**		
Xerophytes				
Artemisia sp.	26.4	19.8	13.5	0.9
Chenopodiaceae	2.3	1.0	2.2	
Helianthemum sp.	0.4			0.3
Rubiaceae	1.2	1.0	0.7	0.9
Xerophytes tot.	**30.3**	**21.8**	**16.4**	**2.1**
Aquatics/palustrine herbs				
Cyperaceae	10.0	7.0	37.4	13.3
Myriophyllum sp.	0.1			
Ranunculaceae	0.1			
Sparganium sp.	0.4	1.5	0.9	14.4
Thalictrum sp.	1.4	0.2		
Typha sp.			1.5	1.7
Freshwather algae concentration grains/g				
Pediastrum sp.	14307	84000	112.6	76.5
Extrafossils				
Botriococcus	251	14467		76.5
Equisetum	251	419	112.6	229.4
Ceratophyllum spines	150	419		
Glomus type				76.5
Monolete spores				76.5
Type 353	250	419	225.3	152.9
Fungii	1950	2516	54848	133292
Extrafossil indeterminatae	166			1529

Sediment provenance analysis

Terrigenous fluvial sediments are complex mixtures of monocrystalline and polycrystalline grains eroded from diverse geological units, and supplied in various proportions by numerous streams to successive segments of a trunk river. If end-member compositional signatures of detritus derived from each main tributary is known, relative contributions from each of these sources to total sediment load can be quantified mathematically with a regression mixing model (Weltje, 1997; Draper and Smith 1998). This statistical model is used here to compare detrital modes from modern sand and ancient sandstone, and to objectively identify the best modern analogue for any sample of ancient sedimentary deposit (Vezzoli and Garzanti, 2009). In the Castelleone S1 core (samples from

14 m to 5.5 m depth; fig. 3 and fig. 8), a typical Adda petrofacies was found (tab. 3). It is characterised by quartz, limestone grains, feldspars and volcanic rock fragments with minor metamorphic, terrigenous and serpentine-schist lithic grains. Heavy minerals include garnet and epidote. This petrographic composition indicates dominant sediment provenance from the Mesozoic sedimentary cover of the Southern Alps, and well compares to the detrital signature of the modern Serio River with local contribution from the Central Alps (Adda River; *R*=95%). In the Mosi di Crema core (samples at -3.3 m and -3.1 m; fig. 3 and fig. 8), fluvial detritus is characterised by quartz, feldspars (mainly plagioclase), abundant metamorphic rock fragments with minor felsitic volcanic grains and serpentine-schist lithic grains. Heavy minerals include amphiboles. This petrographic composition indicating mainly sediment provenance from the metamorphic basement of the Central Alps, and well compares to the detrital signature of the modern Adda River (*R*=97%). Sediments from the Casaletto Ceredano section (samples CRA, CERB and CERT, tab. 3; fig. 4 and fig. 8) and Ripalta Guerina (sample RG1) include abundant quartz, feldspars (mainly plagioclase), metamorphic rock fragments with minor serpentine-schist lithic grains. Heavy minerals are characterised by amphiboles and garnet. Again, this petrographic composition indicates sediment provenance from the metamorphic basement of the Central Alps mainly, and well compares to the detrital signature of the modern Adda River (*R*=95%). Detritus from Cava Alberti, Cava Testa and Cascina Serafina (samples CA1, fig. 3A; CT1 and CSER) is characterised by quartz, limestone and dolostone lithic grains, felsitic volcanic rock fragments, feldspars and minor metamorphic lithic grains. Heavy minerals consist of amphiboles (hornblende) with minor garnet and epidote. This petrographic composition indicating mainly sediment provenance from the Mesozoic cover of the Southern Alps and from the Adamello Tertiary pluton, and well compares to the detrital signature of the modern Oglio (*R*=98%) and Serio rivers.

Pollen record and biostratigraphy from Mosi di Crema and other sites

Several recent palynological investigations on the vegetation history in northern Italy provide the base for a late Quaternary biostratigraphic assessment of the Po basin bioprovince (Wick, 1996a; Wick and Tinner 1997; Vescovi *et al*., 2007; Pini *et al*., 2009; Pini *et al*., 2010). We analysed the palynostratigraphy of the Mosi di Crema basin filling with the aim to obtain biostratigraphic and palaeoenvironmental information. Furthermore, isolated samples were analysed in order to obtain further biostratigraphic data for single layers. The pollen diagram from Mosi di Crema, lowermost interval (fig. 9), shows a typical Lateglacial assemblage, dominated by cold temperate trees (*Pinus sylvestris/mugo*, tree *Betula*), xerophytic chamaephytes and herbs (*Artemisia*, Chenopods), and other herbs (Gramineae). The base record (320-295 cm depth) lacks any broad-leaved warm temperate tree pollen; furthermore herbs and xerophytes prevail (Non Arboreal Pollen >50%). This composition recalls the early Lateglacial asemblages known at the Alpine foothills (Wick, 1996b; Gobet *et al*., 2000; Finsinger *et al*., 2006; Vescovi *et al*., 2007) and points to a vegetation dominated by a forest-steppe. A ^{14}C age of 12,790±135 a BP, *i.e*. 14.6-15.6 ka cal. BP (level 298 cm depth), is consistent with this figure. A massive afforestation observed in northern Italy at the onset of the Interstadial Complex, about 14.7 ka cal. BP (Ravazzi *et al*., 2007), is shown here by a sharp pine rise at 295 cm depth, soon followed by appearance of warm-temperate broad-leaved woody plants (*Quercus, Tilia, Corylus*) with low abundances (295-170 cm depth). Indeed a pine-birch dominance, accompanied by continuous occurrences of warm temperate trees with low percentages, is characteristic for the Bølling-Allerød interstadial complex in the westernmost part of the Po basin (Ravazzi *et al*., 2007). The onset of the Holocene in northern Italy is marked by a sudden rise of warm temperate tree pollen abundances (Wick, 1996a; Finsinger *et al*., 2006). Expanding warm temperate pollen can be traced in the Mosi di Crema succession at about 170-130 cm depth. However, since level 180 cm depth, the organic deposit is characterised by strong bioturbation, heavy decomposition and poor pollen preservation, thus a detailed Holocene pollen record could not be retrieved.

Integrated stratigraphy

Event stratigraphy-based geological map of the region of Crema

Distinctive lithologic, sedimentological, petrographical and palynostratigraphic properties, combined to stratigraphic relationships and supported by geochronometric determinations, allowed recognition of a number of event-stratigraphic units. Event diachronic stratigraphy (Whittaker *et al*., 1991; Lowe and Walker, 1997) is a category of composite interpretational stratigraphy that refers to short-term phenomena that left some trace in the geological records. In the case of alluvial filling in foredeep and foreland basins, climate changes and man activities represent the main driving events for hydrodynamical changes of rivers. Sediment bodies so far distinguished are not strictly corresponding to Unconformity-bounded Stratigraphic Units (ISSC, 1987), in the fact that we did not use unconformities as the basic concept for differentiating alluvial units, although this approach has been adopted elsewhere (Autin, 1992). It is primary the events, and not the boundaries that are specifically designated (*e.g*., Walker *et al*., 1999). As underlined by S.A. Schumm (1993) and A.D. Miall (1997), the importance of base-level controls in fluvial systems, such as eustasy, decreases upstream, hence the concepts of sequence stratigraphy are hardly applicable at the Alpine foothills. Instead, basin subsidence, source area uplift, vegetation cover, climate change and human processes prevail. In the practice of stratigraphic reconstruction of alluvial plains, the accessibility to the subsurface must also be considered. While reconstructing recent alluvial plains, mostly based on core evidence and on indirect seismic data, the apparent boundaries may be uninformative, while the signifi-

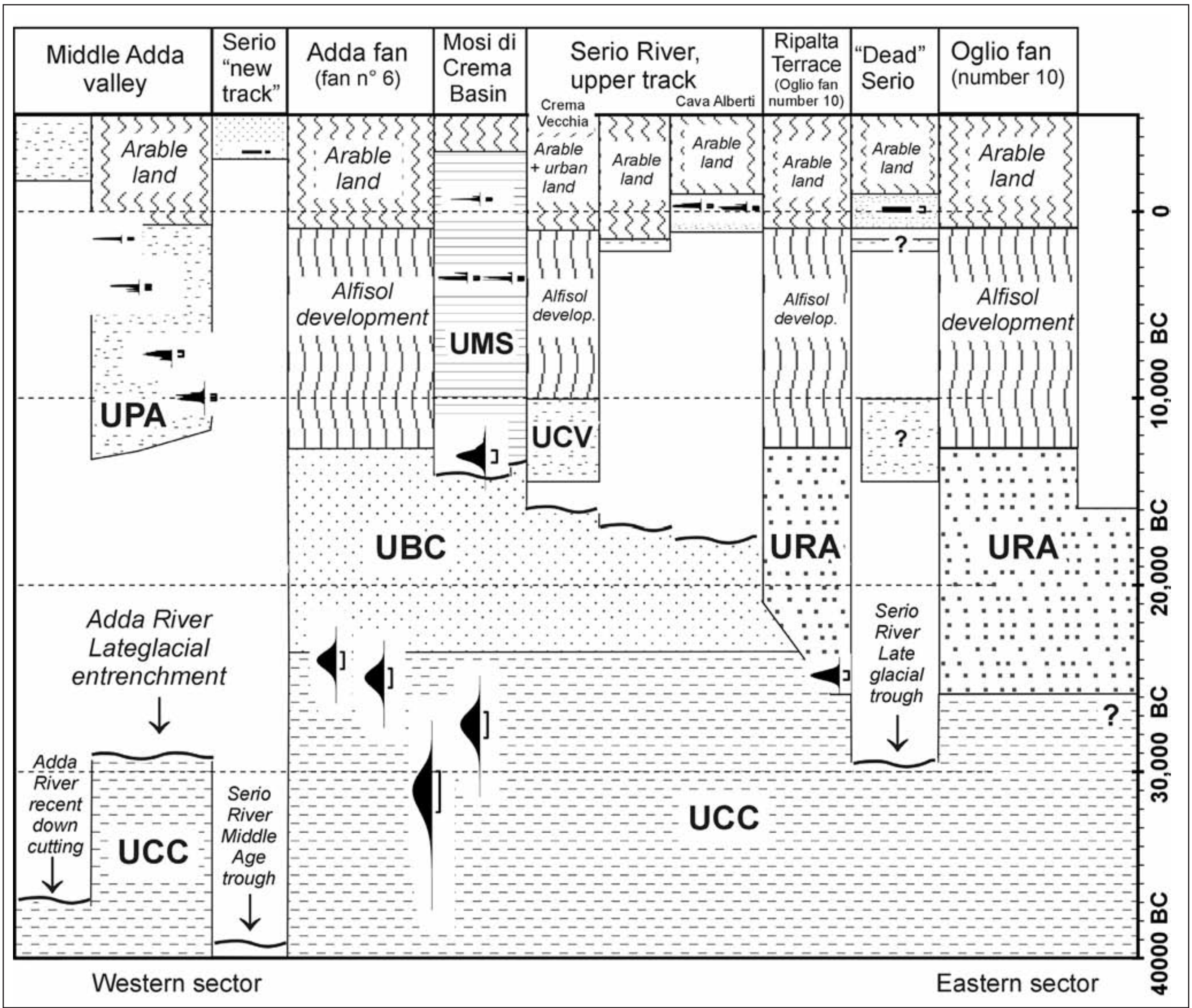


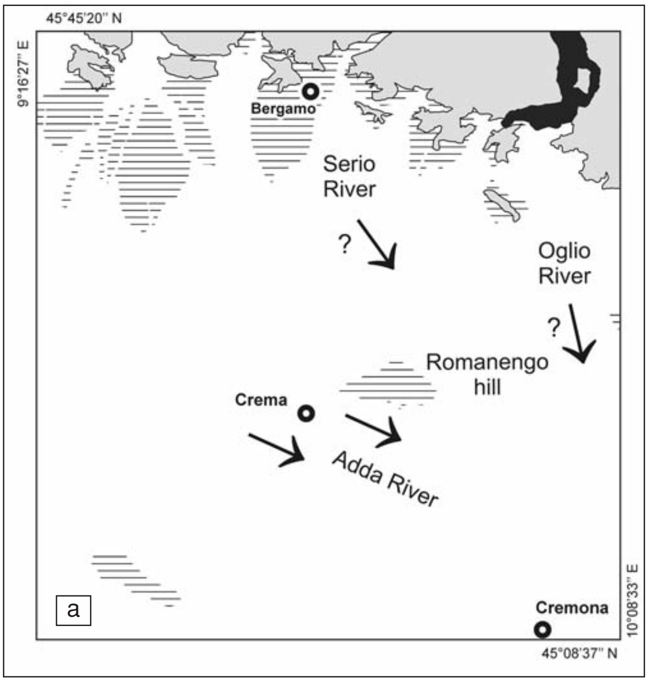
Fig. 12 – **Chronostratigraphic frame showing the time spanned by sedimentary units, by intervening gaps and by pedogenetic processes recognised in the middle Lombardy plain between the Adda and Serio rivers.** The supporting datings are represented both by their probability distribution curve, and by 1 range.

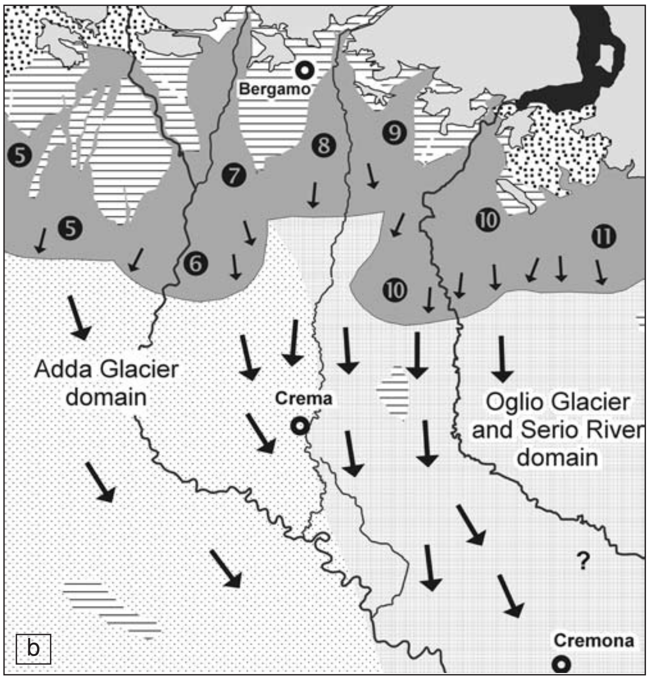
*Fig. 12 – **Cadre chronostratigraphique précisant la période de mise en place des unités sédimentaires, les lacunes stratigraphiques et les processus pédogénétiques reconnus dans la plaine lombarde entre les rivières Adda et Serio.** Les datations tiennent compte à la fois de la courbe de distribution de probabilité et de la marge d'erreur à 1 .*

cant unconformities may not bear a physical evidence, but they are only to be inferred from the properties of the delimiting bodies, such as palaeontological, petrographical, and magnetic data (Monegato *et al*., 2011). In the adopted stratigraphic procedure, the overall consideration of sediment properties, is helpful to characterise the major event(s) responsible for its formation, and represents the factual evidence for unit definition, while the development of bounding unconformities may be useful for the geometrical assessment, regardless to their lateral extent. We avoided any attempt to rank the distinguished sedimentary bodies in a hierarchical system; this would be misleading. We abstained from naming sedimentary bodies subject to active building, such as active riverbeds (fig. 10 and 11).

Stratigraphic framework between the valleys of Adda and Serio rivers

Two main fluvial domains (Adda-Brembo rivers and Oglio-Serio rivers) have been recognised and ordered according to their stratigraphic relationships, plus additional units that belongs to local basins (*e.g*., unit of Mosi di Crema, UMS) or to specific events (*e.g*., unit of Serio Nuovo, USN, is formed after the Serio River capture; fig. 10 and fig. 11). The unit description in stratigraphic order is given in fig. 10, while stratigraphic relationships are provided in fig. 12, and locations in appendix 1 (type section or log). The reference chronostratigraphy is based on F. Preusser (2004) and C. Ravazzi *et al*. (2007) for the regional subdivision of Alpine Pleistocene, to





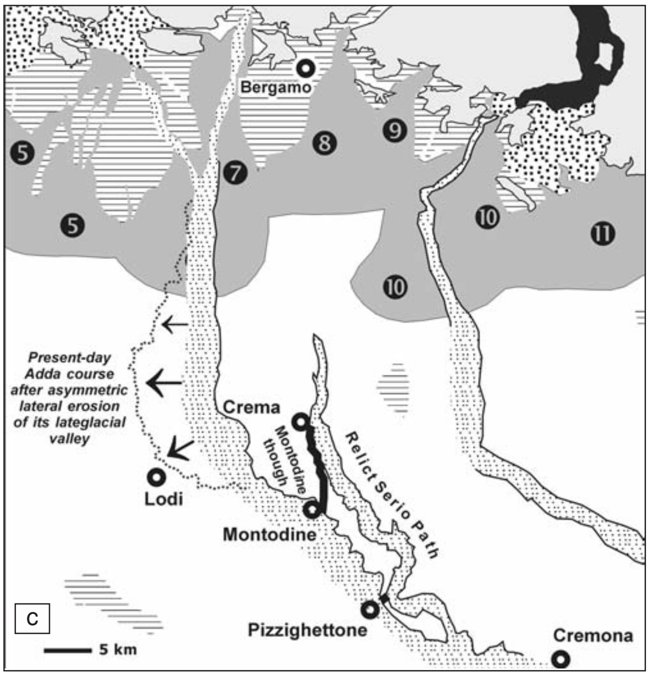


Fig. 13 – **Scheme of the main steps of the fluvial network evolution** (a: Middle Würm; b: Last Glacial Maximum; c: Lateglacial and Holocene). In 'a' and 'b', the arrows show the fluvial drainage directions. In 'b', the solid lines correspond to the present-day drainage and the different dotted pattern of the alluvial plain highlight reflects the different sand petrographic domains. In 'c', the solid line shows the Lateglacial scarps of the main valleys and the arrows indicate the lateral erosion within the Adda Valley; solid thick lines show the paths of the Serio River after the capture events at Pizzighettone and at Montodine. See fig. 1 for explanation of the other patterns and numbers of alluvial fans.

*Fig. 13 – **Schéma des principales étapes de l'évolution du réseau fluvial** (a : Würm moyen ; b : Dernier Maximum Glaciaire ; c : Tardiglaciaire et Holocène. En « a » et « b », les flèches indiquent les directions du drainage fluvial. En « b », les lignes pleines correspondent aux cours d'eau actuels et les différents figurés dans la plaine alluviale précisent les domaines minéralogiques homogènes des sables. En « c », les lignes continues correspondent aux versants tardiglaciaires des vallées principales et les flèches indiquent l'érosion latérale dans la Vallée de l'Adda ; les traits continus indiquent le parcours de la rivière Serio après les captures à Pizzighettone et à Montodine. Voir fig. 1 pour l'explication des autres figurés et la numérotation des cônes alluviaux.*

K. Lambeck and J. Chappell (2001) and G. Orombelli *et al.* (2005) for the Last Glacial Maximum (LGM) time span. Hereafter a short account of unit characterisation and stratigraphic relationships is given.

The architecture of recent stratigraphic units in the Central Po Plain is characterised by the alluvial gravelly to sandy bodies related to fluvioglacial fan development, *i.e.* the Bagnolo Cremasco Unit (UBC) in the Adda domain and the Ripalta Arpina Unit (URA) in the Oglio domain. The radiocarbon chronology restricts their development to the latest Middle Würm-LGM, eventually extending to the very beginning of the Lateglacial, *i.e.* 32-30 ka cal. BP to about 17 (15) ka cal. BP. In the field, they can be easy recognised because they form the maximum aggradation surface, supporting alfisols with distinct B_t illuvial horizons, and sharp decarbonatation front at 2 m to 5 m depth (ERSAL, 1987).

Older fluviatile deposits (Romanengo Unit; fig. 10) emerge as hills over the main LGM aggradation surface, their limits being marked by a distinct terrace, their upper surface supporting vetusols and a polygenic loess cover, while a decarbonatation front cannot be detected in the field, unless marking the contact to a petrocalcic horizon underneath (locally called 'Ceppo'). This high terraced unit partially dammed the Oglio fluvioglacial fan (URA) and probably controlled the development of its southwestern distal part.

The UBC overlies a succession of fine clastic and organic bodies belonging to channelled alluvial deposits, called Casaletto Ceredano Unit (UCC), after the site where the most significant cropping section is located (fig. 4 and fig. 7). Radiocarbon and pollen evidence sets the UCC deposits in the Middle Würm; despite, their base was not reached. Neither unconformities nor changes in petrography separate UBC from UCC unit. Actually they are differentiated by a change in sedimentary environment occurred after an increase of detrital supply and of sediment load, dated to 32-30 ka cal. BP (25-26 ka ^{14}C BP) independently in the Adda and in the Oglio domain (fig. 4 and fig. 5). The UBC/UCC boundary slopes about 0.1% toward SE (fig. 3), suggesting that, before the LGM, the palaeodrainage in the Adda River system was oriented NW-SE, feeding south the Romanengo hill (fig. 13). Support to this figure is also provided by analysis of the peat layer, dated 30-40 ka at Casaletto Ceredano, outcropping extensively along the front of the terraced scarp bounding south the UBC unit (fig. 12). The geometry of the peat mire body could be reconstructed from the field survey. We therefore concluded that the mire developed as a filling of an abandoned channel of the Adda River, oriented ENE-SSW. This channel direction and gradient also accounts for the geometric relationships between the Middle Würm Adda fan (UCC) and the overlapping Oglio fan (URA) East of the town Crema (fig. 5). We suggest that the development of the Oglio fan was first confined by the Romanengo hill, being addressed eastward, and that only after ^{14}C 26 ka BP it partially overflowed the Romanengo threshold, along its northern sector that seems drowned in the URA sediments, and reached the Middle Würm palaeo-Adda valley (fig. 13).

The units younger than the fluvioglacial fans so far described are entrenched at lower altitude, thus erosional surfaces are expected to bound them (fig. 3 and 12). In the Adda River domain, the terraced sequence includes, from the highest, the Pandino Unit (UPA). In turn, UPA is deeply entrenched in the modern Adda Valley, which contains a vertical sequence of terraced units, not detailed here. In the Oglio-Serio rivers domain, the highest terraced deposit (Crema Vecchia Unit; UCV) was still supplied by the Oglio fluvioglacial fan, as testified by the pebble abundance of basic, horneblende-rich intrusive rocks, originating from the Adamello pluton (tab. 4). This composition may rely to the Oglio River, or to its left tributary palaeo-Serio River, recycling the fluvioglacial fan (fig. 13). Instead, the lower terraced units (Cava Alberti Unit, UCA; Serio Morto Unit, USM) petrographycally do belong to the Serio River catchment, although still contaminated by detritus recycled from the bounding fluvioglacial units. UCA and USM form the terraced system developed along the upper tail of the Serio valley as well as in the 'Dead Serio' valley, while they are absent along the new Serio path, *i.e.* the Montodine through. Here, only the USN unit occurs (fig. 3, fig. 5, fig. 9 and fig. 10).

Finally, the Mosi di Crema Unit (UMS) consists in palustrine filling of the 'Mosi di Crema' basin. This basin originated early in the Lateglacial, after a moderate incision of the Adda fluvioglacial fan which affected part of the fan north of the Mosi di Crema basin [UBC(g)]. This downcutting phase occurred after the abandonment of the fluvioglacial fan by the main glacier-fed river, and was probably operated by local groundwater-fed rivers. One important groundwater-fed river discharging into the Mosi di Crema basin originates today at Fontana La Morta (fig. 11). Although this area of springs is not shown by the regional spring line (dotted line, fig. 1), its location at the lower boundary of fan (6) is still related to a sudden increase of the water-satured, pelitic component in the sediment, occurring at the fan lower edge. An increased artesian water pressure at the early deglaciation times may have drown the downcutting of the Mosi di Crema depression. Subsequently this depression was dammed by UCV (see Cresmiero log, fig. 3, fig. 4 and fig. 13). A Lateglacial damming age is argued both by the radiocarbon age of the base infill at MBAw core (fig. 9), and by the pollen record from the dammed lake deposits (tab. 5). Palustrine deposits and hydromorphic soils formed during most of the Holocene until reclamation in modern age.

Synthesis: the evolution of the fluvial network during the last 40 ka

The Crema region is a well-documented example for fluvial network evolution along the northern side of the Central Po Plain between the last glaciation and the Holocene.

Middle Würm SE-oriented drainage of the Adda fan

The first step of the reconstructed geological setting can be placed at an intermediate stage of the Middle Würm, beyond the radiocarbon limit, but after the end of temperate phases characterising the MIS 5, *i.e.* in a time window between 45 ka cal. BP and 70 ka cal. BP. The region of Crema was fed by an alluvial fan formed by the Adda River (UCC unit), developing south and west of the Romanengo relief; the channel direction was oriented ENE-SSW 110-120° (fig. 13A). Middle Würm deposits have not been studied yet north of the Romanengo hill; however, only deposits of the Oglio River are reported there (Cremaschi, 1987). The Serio River did not contributed to the fluvial detritus of the Adda fan, most probably it was tributary of the Oglio River north of the Romanengo hill (fig. 13A).

Last Glacial Maximum development of fluvioglacial fans

A substantial reorganisation of the fluvial network occurred during the Last Glacial Maximum. Since 32-30 ka, the area was fed by two alluvial fans, the Adda fan (6, fig. 1) and the Oglio fan (10, fig. 1). Their upper surfaces are exposed, thus the fluvial drainage at the final stages of aggradation can be precisely reconstructed by the analysis of contour lines and the orientation of fluvial ridges. The course directions of the Adda fan were NNE-SSW 140-150° at the downslope fan limit located north of the Mosi di Crema, while they turned south (160°) in the alluvial plain extending south of Crema.

The Oglio fan (10) partially overflowed the Romanengo hill and reached the Middle Würm palaeo-Adda valley. The course direction at the downslope limit of the Oglio fan was SSW 210° (fig. 13B). In agreement with these directions, and with sand petrography, the two LGM fans merged along the area at Crema, leaving there an interfan depression.

Early phases of fan dissection and the tracing of modern fluvial network

Fan-head trenching started between the end of LGM and early Lateglacial, before 14.5-16.2 ka cal. BP. Unfortunately, we miss strict age constrains for the initial trenching of the fluvioglacial fans in Lombardy. It is documented that apex trenching of Venetian megafans was closely related to collapse of glacier piedmont lobes at 18-19 ka cal. BP (Monegato *et al.*, 2007; Fontana *et al.*, 2008). We therefore assume that by this time the dissection of the upper part of the fan by the post-LGM trunk channel had already started (fig. 13C). The abandonment of fluvioglacial fans left the Serio channel which became hosted along the Crema interfan depression. The phase of fan-head dissection by the post-LGM trunk channels also involved a change in channel direction at the downslope fan limit, *i.e.* from the southward flow 160-170° documented for the LGM to a southeastern orientation. The latter track is partially preserved in the modern network of entrenched valleys (fig. 1). This characteristic tail of the Central Po Plain river setting has been regarded as a river anomaly, related, in some instances, to tectonic activity (Burrato *et al.*, 2003). A specific focus to this issue remains beyond the scope of the present paper. However, the following facts emerged from the present study:

(i) The Mosi di Crema depression, oriented SE 120°, originated after moderate incision of the Adda fan between the end of LGM and early Lateglacial, before 14.5-16.2 ka cal. BP. Sand petrography excludes both the Adda and the Serio rivers from being responsible for downcutting, while the groundwater-fed rivers emerging at the lower limit of the Adda fan (6, fig. 1) may have been involved;

(ii) Since the Serio River becomes hosted along the Crema concavity, its lower track turned left tracing the 'Dead Serio' channel, oriented SE 150°. This occurred between the end of LGM and early Lateglacial, before 14.5-16.2 ka cal. BP.

(iii) The post-LGM trunk channel of the Adda River had almost completed excavation of the modern valley by the end of Pleistocene (*cf. supra*). Given that drainage was essentially meridian during the LGM, a change in channel direction at Lodi occurred between the end of LGM and the end of Pleistocene. It is argued that leftward displacements of channel direction that affected the lower tracts of rivers in Lombardy are a consequence of fluvial network reorganisation at the end of the last fluvioglacial phase.

Lateglacial main downcutting phase and Holocene lateral erosion

The Lateglacial erosional phase formed large alluvial corridors confining the major streams. Today, in the studied area, the Adda and Serio valleys are bounded by vertical scarps 4 m to 21 m high. According to the age of sediments covering the erosional surface E1 in the section of Montodine, most of the observed vertical erosion should be restricted to the Lateglacial, while the development of younger asymmetric terraced units (UPA) within the entrenched valley of the Adda River points to the contribution of lateral erosion since then (fig. 13C). By this time, it may be assumed that the minor hydrography connected to main rivers undertook regressive erosion from the scarp margins.

The Holocene history of the Serio fluvial track: floods and Late Middle Age capture

North of Crema, the moderate entrenchment of the Serio River is mostly due to downcutting of post-Roman age. Indeed this reach suffered important Holocene aggradational phases, notably a Bronze-Ages phase [UBC (g-r) in fig. 10 and fig. 11] and a flood phase in the 3rd-4th c. AD (UCA) (late Roman Age) that almost filled the Lateglacial through. The most recent downcutting phase was promoted by the capture of the Serio River at Montodine (fig. 13C). Although the present work did provide geological evidence supporting the documentary age of the capture between the 13th and 14th c. AD, no indication emerged as for its triggering mechanism. The terraced scarp bounding south the UBC unit hosts a spring line supported by impermeable peat layers (fig. 5). There, the major groundwater-fed streams undertook regressive erosion from the scarp margins into the sand-gravel bodies, removing finer grains. It may be supposed that headwall erosion in the upper part of one of these short courses reached back to the Serio valley, partially filled up by late Roman age floods. Eventually an artificially excavated canal may also have contributed to the capture event. The mechanism of river capture here discussed may be responsible for dissecting the relict Serio path further South, at Pizzighettone (fig. 13C).

Conclusions

The multidisciplinary survey of a sector of the Central Po Plain in Lombardy allowed reconstructing the evolution of the fluvial network in the last 40 ka. Chronological determinations placed the onset of fluvioglacial fan aggradation at the beginning of the Last Glacial Maximum, a circumstance not yet established. An overall fluvial network reorganisation occurred at the end of the last fluvioglacial phase, which also affected a leftward displacement of channel direction of the main rivers from a LGM meridian drainage. As far as the region between the Adda and Serio rivers is concerned, this hydrographic pattern originates from the LGM-Lateglacial transition and was maintained after the Lateglacial excavation of the modern valleys. It appears that this reorganisation had not been triggered by the seismic and the tectonic activity recorded in the region during the Holocene. The present study also highlighted the effects of headwall erosion by groundwater-fed rivers, eventually combined with major floods, triggering river captures. This mechanism of river evolution finds a convenient scenario within the Alpine side of the Central Po Plain, characterised by an entrenched fluvial network within unconsolidated alluvial deposits, and fed by high groundwater levels, evolving under a humid-temperate climate.

Acknowledgements

The present work was prompted by the enthusiastic spur of one of us (MD), who also found the key outcrops at Casaletto Ceredano and Montodine. The facilities and historical expertise provided by Valerio Ferrari (Provincia di Cremona) are gratefully acknowledged. This work benefited of a financial support of Banca Popolare di Crema. Thanks are due to the archeologists Marco Baioni (Museum of Castelleone), Claudia Fredella, Federica Matteoni, Marta Rapi (university of Milano) and Thea Ravasi (Museum of Crema) for their support to artefacts identification during the survey. The advices by the reviewers Giovanni Monegato (CNR – IGG, Torino), Gabriella Forno (University of Torino), Kim Cohen (University of Utrecht) and by the editors Gilles Arnaud-Fassetta and Alessandro Fontana helped to improve the quality of an early version of the manuscript. This paper is a contribution to the Palaeoclimatology Research Line TA.P02.005 'Geological evolution, Quaternary climate and environmental changes and relationships with human civilizations', *CNR-IDPA*.

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Article soumis le 3 avril 2011, accepté le 2 septembre 2011.