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Land use change, soil erosion and alluvial dynamic in the lower Doubs Valley over the 1st millenium AD (Neublans, Jura, France)

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Abstract

Geochemical and particle size analyses, surface scanning magnetic susceptibility, microscopic charcoal counting and pollen analysis, have been carried out on two cores from the lower Doubs valley in order to reconstruct the land use history. The interpretation of anthropogenic pollen indicators and micro-charcoal deposits is discussed in relation to the lithological variation of sedimentary accumulation and evolution of the settlement. The environmental changes which occurred during the 1st and the 6th century AD reflect the impact of human activities on the landscape in the immediate surroundings of the site. Multiproxy indicators indicate that soil erosion as a consequence of agricultural activities including fire practices. A reactivation of hydrologic flow of the river recorded in the sedimentary sequences attests to a larger environmental perturbation between 1st–3rd and 7th–8th century AD.

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Keywords: palaeogeography; erosion; fire; sedimentology; palynology; 1st millenium AD; France

1. Introduction

Soil-forming environments and erosion processes is a much debated question when studying the relationship between human impact and environmental change [1,20]. The impact of human activities (farming, agro-pastoral burning) on mechanical erosion is well established [28,32,46,61,62]. Other parameters, permanent or unvarying (size of watershed, lithology, relief), and variable factors (climate, hydrology, vegetation cover) have an effect on sediment yield and erosion rates [40,42]. Sediment yield also depends on dynamic agents such as gravity on slopes and running water [41]. For each geosystem, it is suitable to study its dynamic according to all parameters inducing erosion processes [1]. It is justified also to consider a joint impact of human and climate in the land use history

[4,6,23,31,49,62]. Natural factors and human history are thus specific to each watershed. They appear as so many determining factors as there are possible reactions to mechanical erosion induced by climate changes and human occupation [58,59].

For a few years now, archaeological survey has been carried out in the lower Doubs valley (Eastern France) to study the evolution of the settlement and to reconstruct the land-use history of the area from Antiquity until the Middle Ages [13]. The spatial extent of the archaeological remains and the chronology of occupation were precisely determined, but several interrogations remained concerning the environment of the settlement and the human impact on landscape. What are the characteristics of land management? Is there some relation between human occupation and river dynamic during the Antiquity? Which are the effects of clearing and cultivation on the sedimentary processes and soil formation?

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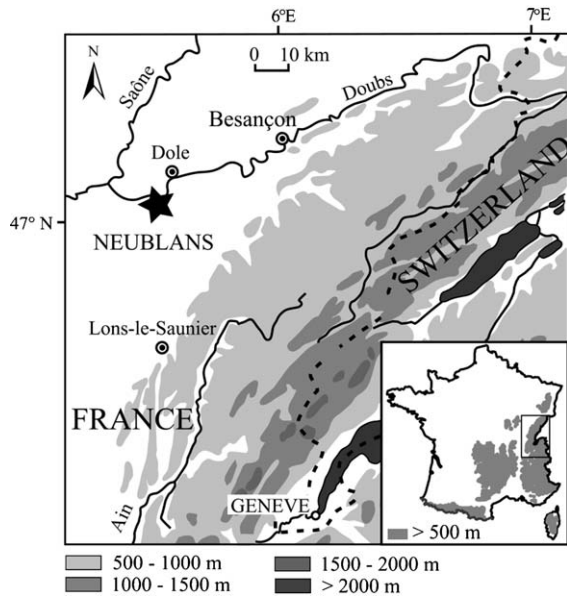


Fig. 1. Geographical situation of the investigation area of Neublans (Jura, France).

A multiproxy approach was adopted to examine a sedimentary sequence of the alluvial plain. The methods included sedimentological analyses (mineralogy, particle size, geochemistry, and surface scanning magnetic susceptibility), charcoal content and high resolution palynological analyses.

Thanks to these multiproxy indicators, it is now possible to propose an interdisciplinary synthesis of the influences of climate and human activities on the type and extent of vegetation and to determine how sedimentary dynamics have been indirectly affected by the environmental changes which occurred during those periods.

2. Geographical and geological settings

The investigation area of Neublans (Jura, France) lies at a mean altitude of 184 m asl and is located in the lower Doubs valley close to the Plateau Bressan, in the upper part of the confluence with the Saône river (Fig. 1). The Plateau Bressan is formed of sandy marl and Saint-Cosme formation (Fig. 2; [22]). Its surface is cut by numerous runnels. Colluviums fill the valley bottoms of the streams draining the surface water of the plateau. These brooks of ephemeral run-off contribute to the floods of the Doubs river. The southern valley side is largely covered by sandy clay colluviums derived from the Sand of Neublans formation underlying sandy marl. In the contact area with the flood plain, these sandy clay colluviums gradually overlap the Holocene alluvial deposits. The Sand of Neublans are dominated by quartz in contrast with the Quaternary alluvial deposits of

Doubs river which are characterised by carbonates [47,48]. The relief of the valley gives evidence of an ancient river course running at the bottom of the Plateau Bressan. At the present time, the Doubs river runs farther to the north in the alluvial plain.

An examination of historical sources allows us to identify the major part of the stream channels formed from the 17th century to the present day (Fig. 2; [53]). The fluvial morphology changes from the upper part to downstream-braided, anastomosing or meandering stream. Since the 18th century, the flow of the river has been successively embanked. Other features such as meander scroll, point bar and natural levee clearly separated from the modern shifting of the river, correspond to ancient drainage patterns of the Holocene period.

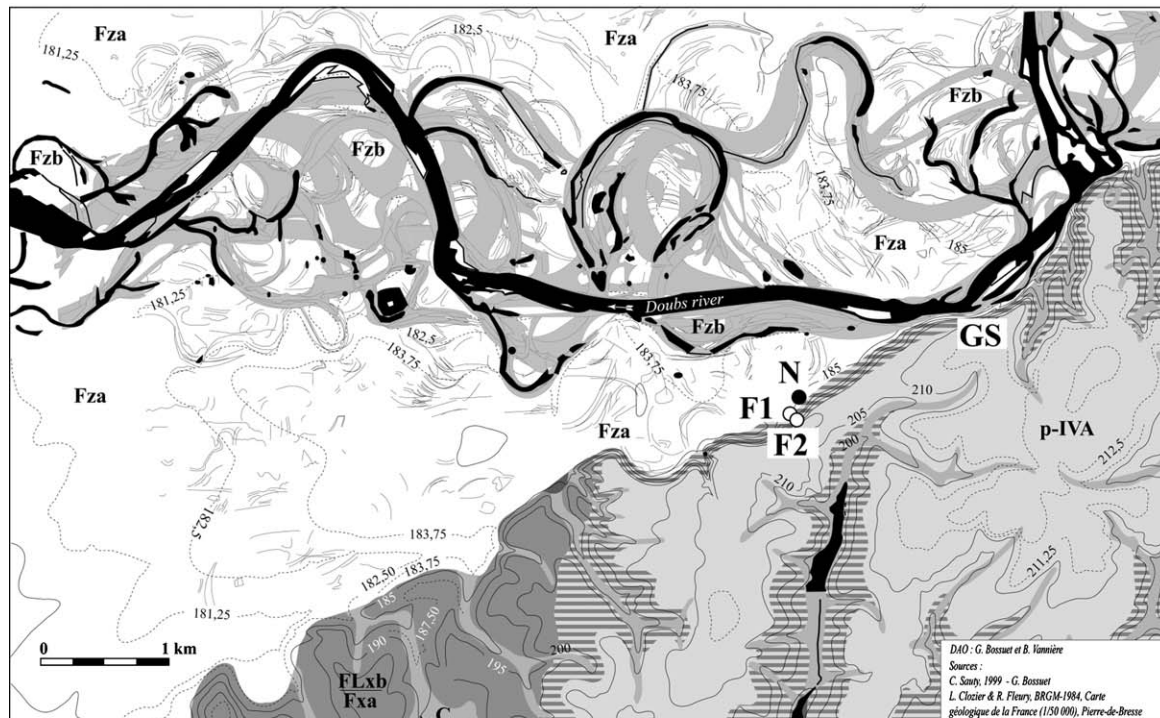
3. Archaeological setting

The Prehistoric period provides significant evidence of settlement spread over the entire window (Fig. 3A). Two fields of burial mounds dating back to the end of the Bronze Age and the beginning of the early Iron Age are both the mark of a lasting, socially structured settlement and of territorial division. From this period, several sites have provided materials corresponding to the late Bronze Age IIIb-Hallstatt C [14].

About ten sites of variable significance provide an illustration of the Iron Age, a time of increased economic integration, as observed in the study of artefacts. The transition from an indigenous farm to an actual agglomeration at the so called “Le Tertre” bears witness to the post-conquest dynamism of the second half of the 1st century BC [2].

For the Roman Period, a hundred sites have been identified (Fig. 3B). They all show an even spread of the settlements over the area, notably in the part of the plain liable to flooding [14]. The continuity of the settlement process has been observed in many cases, on different types of site. Various forms of settlement, complementary and socially structured, stand out. Two villages of significant size (30–40 ha) developed partly on the slope and partly in the plain [2]. Two smaller villages were found, along with a few establishments of the size of a hamlet. Many units, limited in size, are located along the Roman roads or in the surroundings of the “grouped” settlements. The impression of a scattered and heterogeneous settlement as well as the coexistence of a densely populated zone in the west and a sparsely populated zone in the centre and south, all stand out.

For this period, two great networks of land division as well as the framework of a third smaller one have



COLLUVIAL-ALLUVIAL COMPLEX

- CF** Undifferentiated Colluvium
- C** Dale bottom Colluvium
- Clayey and argilloarenaceous colluvium from formation p-IVA overlying Sand p-IVs (Sand of Neublans)
- Present river course
- Former river course (1611-1985)
- Prints of ancient drainage pattern

ALLUVIAL AND FLUVIO-LACUSTRINE FORMATIONS OF BRESSE

- Fz a-b** Holocene deposits
- FLxb** Saint-Cosme formation
- Fxa** Flxb - Fluvio-lacustrine complex
- Fxa** Fxa - Basal fluvatile complex
- p-IVA** Clay and sandy clay (Clay of Oussières)
- O** Pedological section
- N** Core drilling
- GS** Geological Section

Fig. 2. Geological map of the investigation area in the lower Doubs Valley. Location of the sequences studied: geological section (GS), pedological section (F1 and F2) and core drilling (N).

been identified. The association of several significant Roman roads, the presence of fords and many access roads, all highlight the important role of crossroads in this area.

Archaeological [14], palynological [25] and sedimentological [62,63] evidence consistently indicate that the farming activity must have reached its peak in the 2nd and 3rd century AD, and then declined during the late Roman Empire (Fig. 3C). As shown by the development of vineyards during the 1st century AD [24], the land was farmed in an innovative and dynamic manner, at the

beginning of the Roman Empire. The late Roman Empire period is best known for the continuity of some of its settlements, economically attractive during Antiquity. The patterns of settlement changed, probably due to the rise of ground water in certain areas [2].

As for the Middle Ages (Fig. 3D), some fifty potential sites have been identified. As early as the Merovingian and Carolingian times, a new way of structuring space developed. Small units of settlement gathered around villages, which thus became poles in the land organisation. Both the concentration of settlements and their

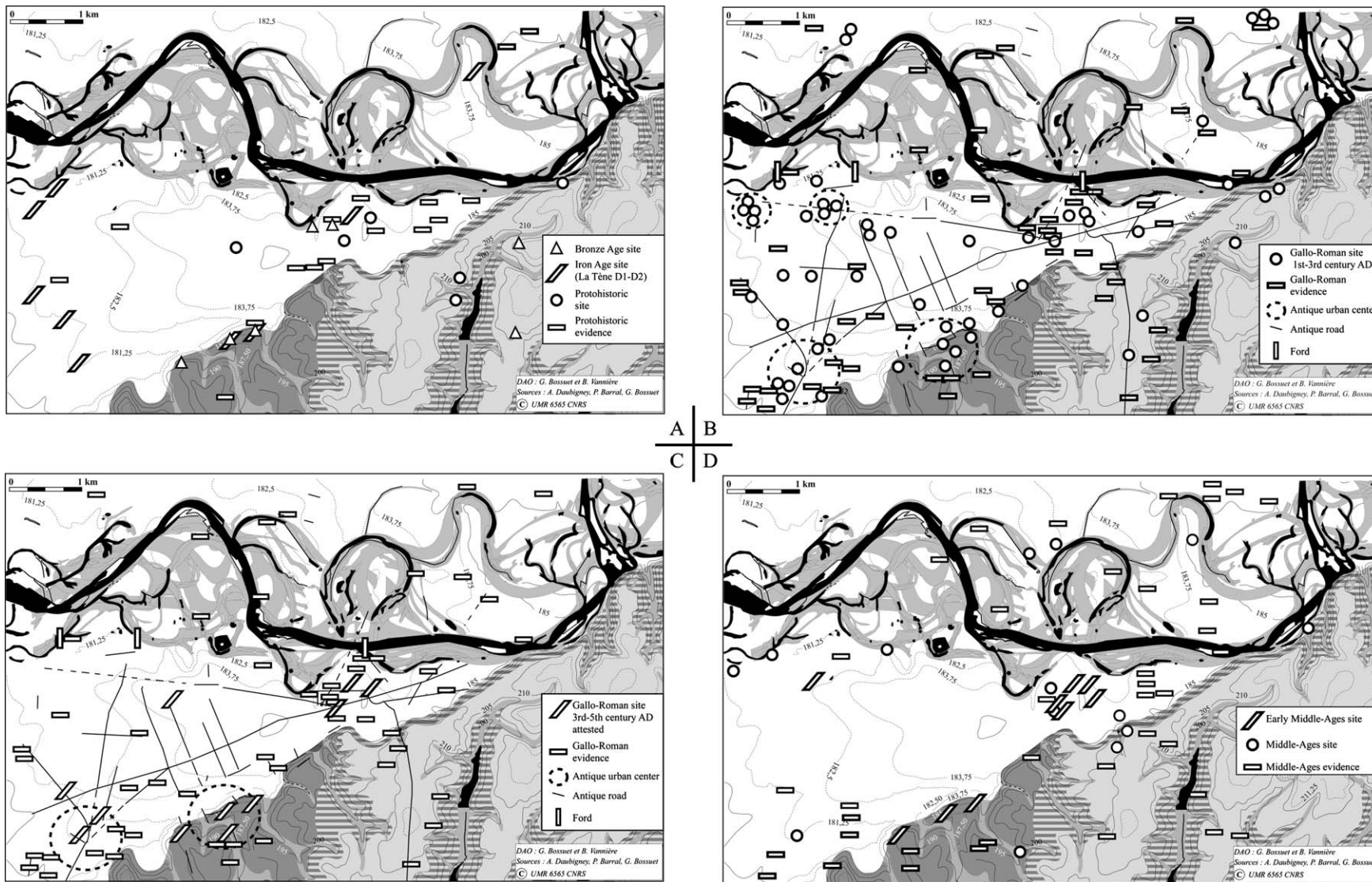


Fig. 3. Successive occupations in the lower Doubs valley as revealed by archaeological prospection. Protohistoric period (A), Early Roman Empire (B), Lower Roman Empire (C) and Middle Ages period (D).

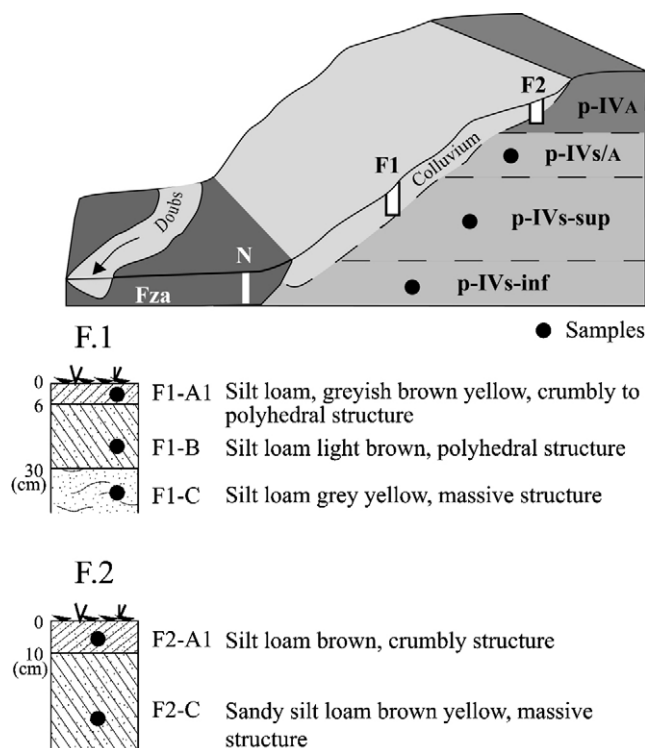


Fig. 4. Schematic 3D geological representation of the valley side. Location of the sampling core from alluvial plain (N), pedological sections from the valley side (F1 and F2) and bedrock (geological formations: p-IVs-inf, p-IVs-sup and p-IVs/A).

spreading go hand in hand with the increasing part played by trade roads and crossroads, all of which can be observed in the emergence of numerous feudal mottes and dynamic demographic poles [14].

4. Material and methods

4.1. Field sampling

A sedimentary sequences (N; from 90 to 520 cm depth), was taken in the flood plain with a Russian sampler, thus avoiding the compaction of sediments. The bore holes were located in a pool, at the bottom of the slope of the Plateau Bressan, probably a cut-off meander, filled up by flood deposits and peaty-clayey sediments (Fig. 4). Pedological sections and geological formations of the Plateau Bressan were also sampled, in order to check the presence of sedimentary components derived from the erosion of the valley side in the previous alluvial-colluvial record (Fig. 4). In Sand of Neublans, three beds can be distinguished: a bottomset bed as a yellow classified sand (p-IVs-inf), an overlying stratum as a grey-iron rust sand (p-IVs-sup), more loamy than the previous bed and an upper bed as a grey-yellow loamy sand (p-IVs-A).

4.2. Radiocarbon dating

The chronology of the deposits is based on the pollen stratigraphy and three AMS radiocarbon dates respectively made for each sample on wood fragment, peat and terrestrial seed (Table 1).

The conversion from radiocarbon ages to calibrated calendar years was made with the program CALIB 4.1.2 [55,56].

4.3. Mineralogy

Calcium carbonate content was determined by measuring the volume of CO_2 evolved when a sub-sample of known weight (1 g) of dry material was reacted with 10% HCl in a calcimeter. Fifty-six sub-samples taken at 10 cm intervals were measured for the whole core.

Routine X-ray diffraction (XRD) analysis were made on bulk powdered samples and on individual fragments using a Philips PW1710 diffractometer. Samples were treated between 3° and $65^\circ 2\theta/40$ kV/20 mA, using Cu $K\alpha$ radiation, a Ni filter, and a scan speed of $1^\circ/\text{min}$. Quantitative XRD analysis is difficult in polyphased heterogeneous mixtures [19], and the relative abundance of minerals was estimated from the height of the main reflection and from comparisons with the reflections of other samples. The estimation of quartz and calcite content is expressed by the ratio $I_{\text{quartz}}/I_{\text{calcite}}$ related to the intensity XRD peaks of these two minerals.

For XRD analysis of the clay fraction, a preparation of oriented aggregates of clays was then collected on a glass slide. The samples were sequentially air dried, glycolated and heated for 4 h at 490°C , for identification of interlayering of clays, i.e., the (001) basal reflection positions after each treatment. The XRD patterns were obtained between 2° to $32^\circ 2\theta$.

4.4. Magnetic susceptibility

Volume susceptibility was measured with portable MS2 magnetic susceptibility meter and a E1 surface scanning sensor (Bartington Instruments Ltd) at 2 cm intervals on the sediment surface of the whole cores. This sensor is designed to measure the susceptibility of split cores with fine resolution [16]. The sensitivity of the magnetic susceptibility meter used was 0.1×10^{-8} SI allowing a high differentiating capacity for sedimentary characterisation [63].

4.5. Particle size analyses

Particle size analysis was achieved by using a coulter laser Micromultisizer LS 230 after sieving at 1 mm. Forty-three sub-samples were taken at 10 cm intervals in the sedimentary core, and eight samples in the pedological sections and geological formations from the valley side (Fig. 4).

Table 1
AMS radiocarbon dating of core N.

Depth	Age ^{14}C BP	Calibrated age 2σ	Laboratory reference	Material
125 cm	1257 ± 40	cal AD [664 (725, 739, 772) 887]	Utc 9398	Terrestrial seed
270 cm	1715 ± 41	cal AD [238 (264, 272, 340) 422]	Utc 6997	Peat
445 cm	1972 ± 34	cal BC [44 (cal AD 28, 41, 49) cal AD 122]	Utc 6999	Wood

In order to obtain detailed information on the grain size distribution sediment samples for granulometric analysis were treated according to the method described by Brun-Cottan [8] and Lesourd [35]. In that way, samples were characterised by the relative area of their particle size populations, and compared between them. The terminology used for description of main particle size class is given as clays: 0–2 μm , silt: 2–20 μm , coarse silt: 20–50 μm , fine sand: 50–200 μm , coarse sand: 200 μm –2 mm.

4.6. Pollen analysis

Pollen analysis was carried out on the core N. Samples were taken at 5 cm intervals between 90–520 cm [24,25,63].

In this study, special attention was paid to the anthropogenic pollen indicators (API). The reliability of pollen evidence to emphasis human influence has been firmly established [5,3,33]. Pollen indicators of human impact are from different taxa and take into account the increase of pollen yielded by cultivated plants (mainly *Cerealia*, *Vitis*), crop-weeds, grass meadows and ruderals (*Plantago lanceolata* and *major/ media*, *Artemisia*, *Rumex*, Chenopodiaceae, Urticaceae, *Polygonum aviculare* type).

4.7. Charcoal content

The analysis of the fire-signal on core N1 was carried out on the basis of a microscopic observation in reflected light (LR) of micro-charcoal (size between 10 and 100 μm) present in the pollen-slides. Reflected light microscopy allows a better characterisation of the dark remains by surface observations and make it possible to separate micro-charcoals from opaque minerals and oxidised vegetal remains [62].

Two types of textures were differentiated in the counting of the charcoal particles: cellulose ligneous structure or rounded massive structure. Cellulose ligneous particles present a cellular porosity and a structure evocative of plant tissues. Their ratio length/width >1.5 is characteristic of charcoal particles [10,11]. The isotropous particles have a ratio length/width ≈ 1 , they are often rounded and characterised by the absence of porosity. Their morphology is a result of a post-depositional fragmentation in soil before their sedimen-

tation in the alluvial sequence record [62]. Thus, any fire signal is inherited from soil erosion. Inversely, elongated cellulose ligneous particles immediately deposited in the alluvial sequence record, appear as signatures of the fire events [62].

Results were expressed in quantity of particles per gram of sediment. However, calculating particle frequencies is more advisable for a valuable interpretation of the significance of peaks in charcoal content [9,62]. In our case, a means of estimating the charcoal particles influx was to calculate the ratio C/P (charcoal/pollen) considering the fluctuations of total pollen concentration as an indicator of variation in sedimentation rate [57].

5. Results

5.1. Mineralogy and magnetic susceptibility

The mineralogy of the sediments is quite similar on the whole core (Table 2). The dominant minerals are quartz and calcite. Semi quantitative results indicate that feldspars and dolomite are present in very low quantities. Samples from geological formations present the same mineral composition. In the sedimentary core N, in geological formations and soils, the dominant clayey minerals are illite, chlorite, kaolinite and smectite with mixed layer clay. The similarity of mineralogy characteristics between sediments from the alluvial plain and sediments from the valley side indicate the genetic origin of the deposits of core N. Only variations in carbonate and siliceous components, in organic matter and structure allow a zonation of phases in the sedimentary sequence (Fig. 5).

Five phases A to E and a sub-phase B'-MS, were identified in reference to the magnetostratigraphy, sedimentological description and mineralogical analysis (Fig. 5).

The basal sedimentary accumulation (phase A) corresponds to silty loam colluviums of massive and compact structure. The grey blue colour attests a reducing and hydromorphic depositional environment involving the formation of a gley. Carbonate content varies between 35 and 45%. The evaluated ratio of quartz/calcite varies from 0.6 to 0.8 with a value of 1.3 at a depth of 430 cm. Sandy and organic layers (radiocarbon dated) were observed. The values of magnetic susceptibility

Table 2

Mineral composition of the sediments for core N (sample numbers refer to depth), for pedological sections F1 and F2 and for geological formations p-IVs-inf and p-IVs-sup.

Samples	Bulk rock				Clay fraction		
	Quartz	Felspars	Calcite	Dolomite	Mica (Illite)	Chlorite+Kaolinite	Smectite (\pm IS)
Pedological sections	F1-A1	***	*		*	*	-
	F1-C	***	*		*	*	-
	F2-A1	***	*		*	*	-
	F2-C	***	*		*	*	-
Geological sections	pIVs-sup	***	*	**	*	*	*
	pIVs-inf	***	*	**	*	*	*
Core drilling N	N 110	***	-	**	-	*	*
	N 150	**	-	***	-	*	*
	N 180	***	-	**	-	*	*
	N 240	**	-	***	-	*	*
	N 260	***	-	***	-	*	*
	N 310	*	-	***	-	*	*
	N 390	*	-	***	-	*	*
	N 410	**	-	***	-	*	*
	N 430	***	-	**	-	*	*
	N 460	**	-	***	-	*	*
	N 500	*	-	*	-	*	*

Semi-quantitative results from XRD analyses are given as: ***: very abundant; **: abundant; *: present; -: detected.

vary from 60 to 250×10^{-5} SI (mean value at 80×10^{-5} SI). Over the general trend of magnetic susceptibility, the curve shows a series of peaks which are strongly marked for the core N2.

A second sedimentary unit (phase B) shows a coarser structure, well differentiated by brown colour and organic components of the matrix. The carbonate content, excluded organic layers at a depth of 270 cm and 350 cm, is higher with a mean value between 55 and 65%. The evaluated ratio of quartz/calcite is <0.3 . Total pollen concentration shows variations of high amplitude correlated both to an organic matter enrichment of sediments and the development of peat facies (at a depth of 270 cm). This phase shows a smooth profile of the magnetic susceptibility curve with low values (10 to 20×10^{-5} SI) that correspond to a change in sedimentation sources (facies more loamy) with an increase of carbonate content involving a dilution of the magnetic signal [28]. In phase B'-MS, a small increase of magnetic susceptibility is recorded (40×10^{-5} SI). Nodules of secondary carbonation and a small decrease of the organic component can be related to this evolution. These nodules result from the secondary precipitation of calcite after a sparing dissolution in soils [21]. A significant increase in the total pollen concentration is related to this evolution. At the end of this phase B, the lower values of magnetic susceptibility (0 to 10×10^{-5} SI) correspond to organic deposits.

The third sedimentary unit of grey yellow colour (phase C) shows a finer texture than the previous unit and an increase of magnetic susceptibility up to 60×10^{-5} SI. The massive structure and the carbonate content between 35 and 40% appear similar to the basal

sedimentary accumulation. The ratio of quartz/calcite is >0.8 and even >1 at a depth of 180 cm. The organic matter is represented by scattered residues of plant cells of millimetre and centimetre sizes. These organic components correspond to the persistence of a hygrophile vegetation growth in the sedimentation area. Magnetic susceptibility and other proxies record a new change in sedimentary sources and erosive process.

The fourth sedimentary unit (phase D) is obviously similar to the third unit characterised by a decrease of carbonate content. The decrease of magnetic susceptibility closely coincides with a passage to organic facies (peat).

Phase E corresponds to a new increase in magnetic susceptibility and to a significant increase in the ratio of quartz/calcite.

5.2. Grain size distribution

Grain size distribution for samples of core N are somehow of plurimodal type (Fig. 6). The relative proportion of particle size class allows to define five sedimentary units (Fig. 7) similar with those displayed by mineralogy and magnetic susceptibility analyses (Fig. 5).

Basal accumulation (A), sedimentary units C and E, are characterised by a clayey fraction and a dominance of silt. The difference observed lies in the slight proportion of coarse sand. The sedimentary units B and D show abrupt increase of grain-size with regard to the other units (Table 3).

Particle size class characteristics of geological and pedological formations are also presented in Figs. 6

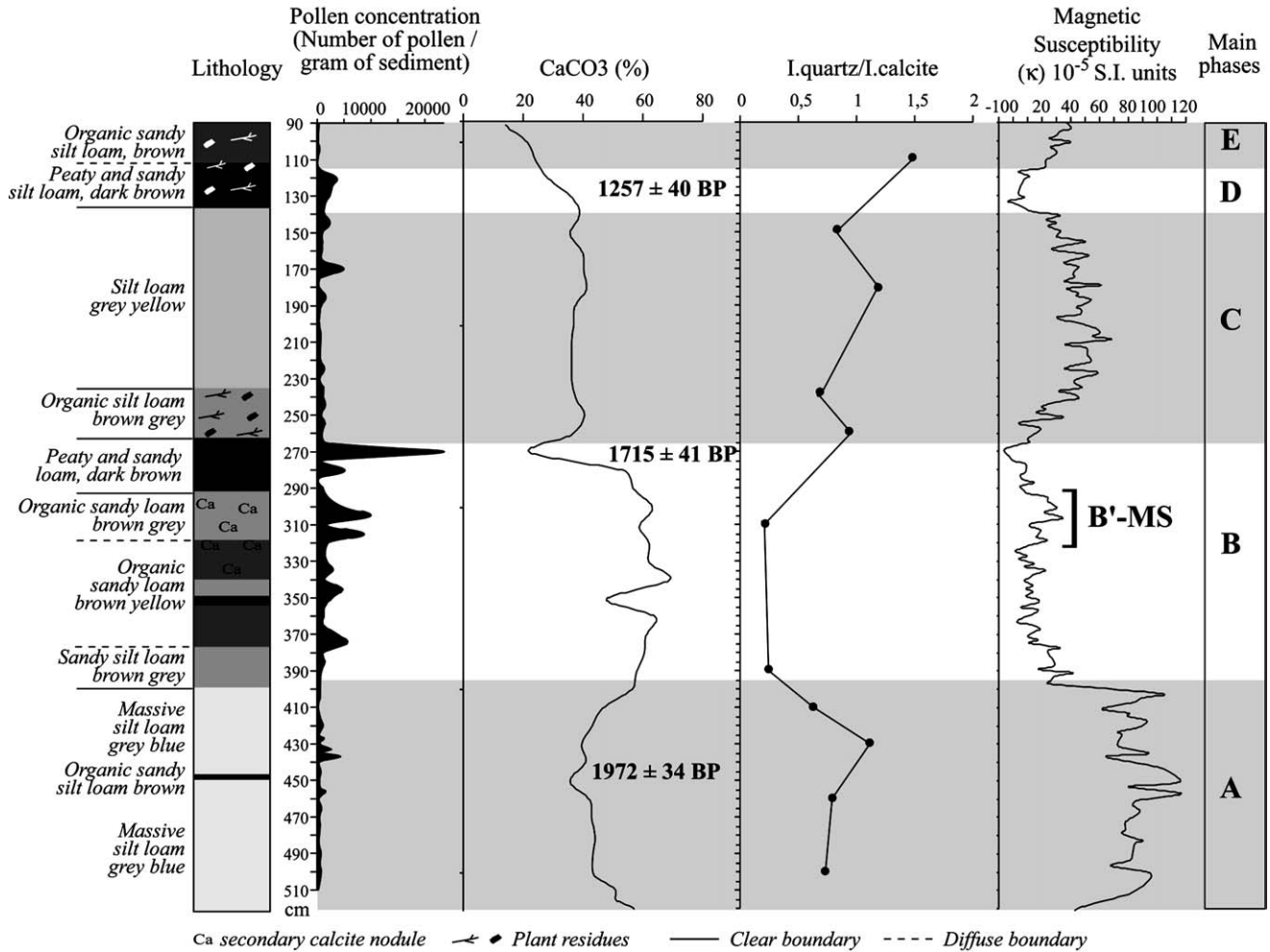


Fig. 5. Core N from Neublans (Jura, France). Lithology, pollen concentration, CaCO₃ (%) content, ratio of Intensity XRD peaks for quartz and calcite, and whole core volume susceptibility. Main phases of the stratigraphic evolution (A to E) and local phase B'-MS.

and 7. The sands (p-IVs-inf) of the bottomset bed are very well sorted (fraction 100–250 μm ≈ 70%). The overlying stratum p-IVs-sup, is more finely textured (fraction <5 μm ≈ 35%). The upper bed (p-IVs-A) appears as a transitional stratum to sandy marl (p-IVA). The fine fraction is well represented, but fine sand assigns these sediments to the geological formation “Sand of Neublans”.

Grain size distribution of soil samples are plurimodal; the dominant particle size classes are <50 μm. For soil F1, there is no particle up to 100 μm in size. Only deep F1-C horizon shows a grain size class up to 200 μm. For pit F2, sands are represented in the fraction up to 200 μm. The F2-A1 horizon is a more finely textured, with a smaller content of sand.

The particle size class up to 1000 μm appears as typical from peat layers and organic matter enrichment of sediments. The significant proportion of the 100–150, 150–200 and 200–250 μm particle size classes in sedimentary phases B and D of the filling reveals an erosion of

the formation p-IVs-inf. However, this fraction is of no great significance in the size grading of sediments. The occurrence of the grain size class 600–700 μm in the sediments filling attests to an erosion of the deep layers of soils on the Plateau (represented by horizon F2-C in soil section F2). This erosion process is again recorded by the particle size class 250–400 μm which is typical of the p-IVs/A facies.

5.3. Vegetation and fire history

Five main phases (A, B, C, D and E) can be clearly identified in charcoal curves and in the evolution of the API (Fig. 8 & Fig. 9). They are similar to these defined in the previous sedimentological analyses.

Phase A, corresponds to a period of intense agricultural development centred over the first two centuries AD. High rates of *Poaceae* and pollen indicators of pasture would indicate an open landscape. Pollen of arable land (e.g. *Cerealia*, *Secale*, *Cannabis*) show high

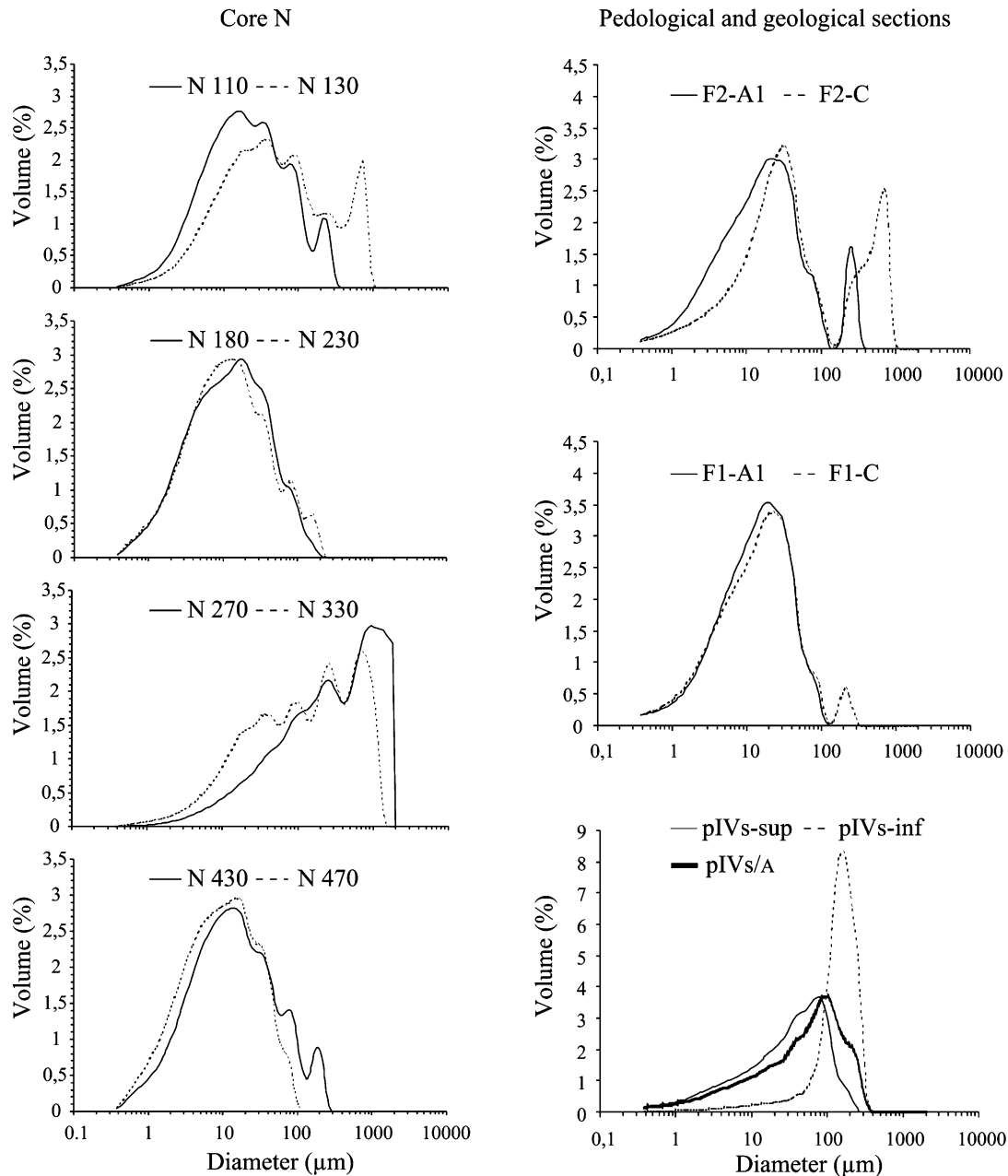


Fig. 6. Typical curves of particle size analysis in volume (%) for several samples from the core N (sample number refer to depth), pedological sections F1 and F2 and geological formations p-IVs-inf, p-IVs-sup and p-IVs/A.

values reflecting the cultivation of cereals and hemp in the surroundings of the site. *Vitis* pollen accounts for 1 to 4% indicate a probable cultivation of vine on the valley side as far back as the 1st century AD ([cal BC 44, cal AD 122]; Table 1; [24]). Study of the modern pollen rain of *Vitis* shows clearly its low pollination [30]. The sheet erosion of the valley side and the runoff of the fine sediments could explain the transport and the deposition of *Vitis* pollen in the sedimentary accumulation of the flood plain. The fluctuations of human impact indicators and charcoal content appear synchronous, suggesting a use of fire for cultivation. The forest cover is represented

by *Quercus*, *Carpinus* and *Fagus pollen*. *Alnus* pollen probably represents the riparian woodland. A low decrease of API is recorded at the end of the phase A. The high rates of *T. angustifolia*, might be considered a local pollen rain.

Evidence of a decrease in agricultural activity is gathered in phase B. It begins approximately around the second half of the 2nd century AD ([238 (264, 272, 340) 422] cal AD; Table 1). The pollen spectra show a sharp decrease in API and lower frequencies of microscopic charcoal particles, except sub-phase B'-PCh where an occurrence of massive particles is closely connected to an

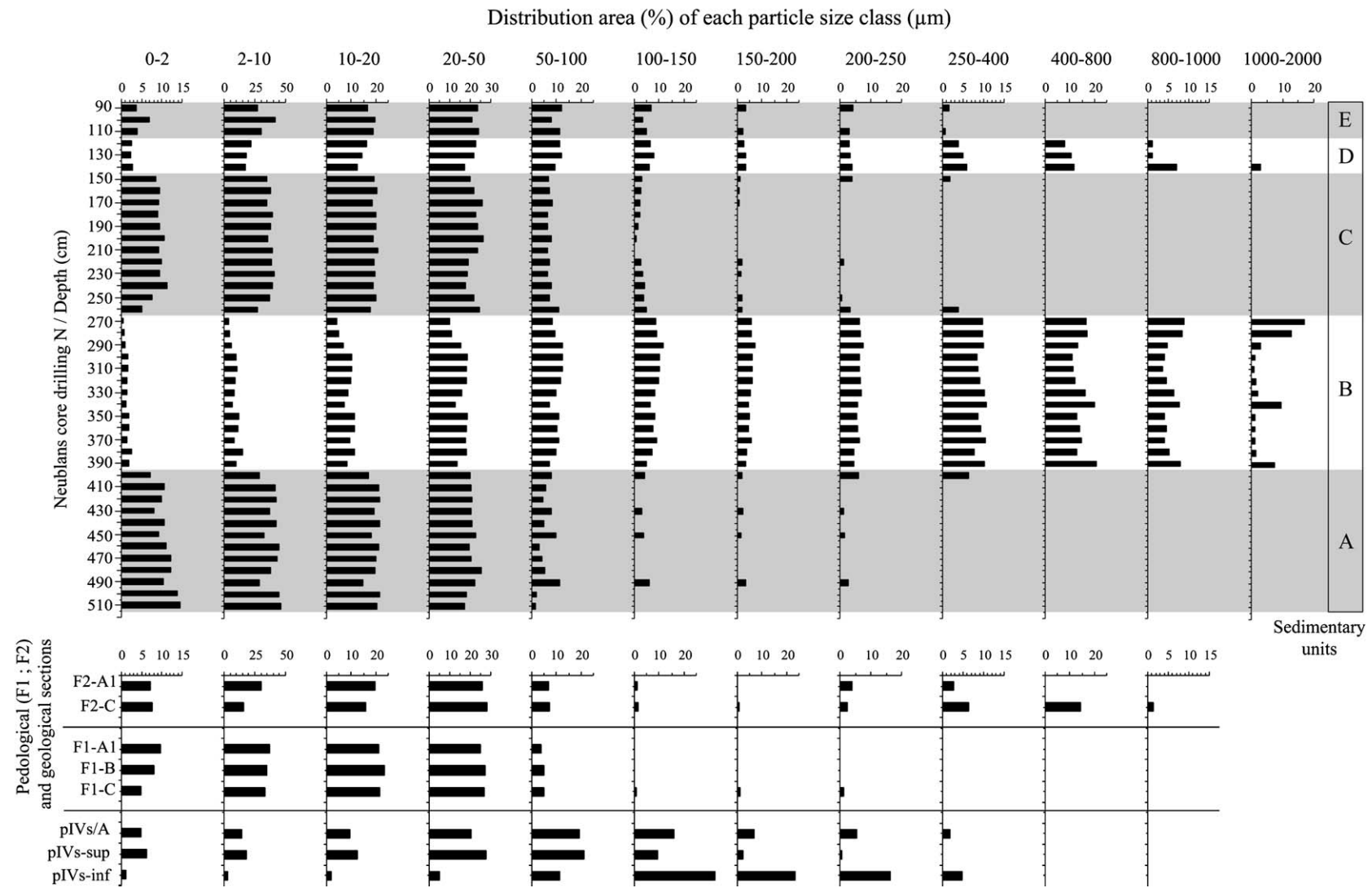


Fig. 7. Size grading for the whole core N, for pedological sections F1 and F2 and for geological formations p-IVs-inf, p-IVs-sup and p-IVs/A.

Table 3
Description of the sedimentary units from the whole core N

Sedimentary unit	General characteristics	Punctual observations
A	Clay: 7–14% Silt: 60–70%	Some layers 5 to 10% of fine sand are interbedded at 430, 450 and 490 cm deep
B	Clay <3% Sand >50% This facies is characterised by two classes adjusted on 150–200 µm and 400–800 µm (for example samples N 270 and N 330; Fig. 6).	Three levels with 1000–2000 µm fraction up to 8% correspond to organic matter and peat facies.
C	Clay: 7–14% Silt: 60–70%	The 100–150 µm class marks the transition between the previous and following facies.
D	Clay <3% Sand >50% This facies is characterised by two classes adjusted on 150–200 µm and 400–800 µm.	An organic layer at a depth of 140 cm well differentiated by a particle size up to 800 µm.
E	Clay: 7–14% Silt: 60–70% Sand >100 µm: 3–8%	

increase of *Vitis* pollen. A riparian woodland (*Alnus*, *Betula*, *Salix*, *Fraxinus* and *Carpinus*) colonised the surroundings of the site [25,63]. The evidence of reforestation is marked by an increase of total pollen number/grams of sediment. The higher variations of the ratio are tied to the peaty deposits which mark a temporary break in the sedimentation. The development of *Equisetum* at the end of the phase B appears as a local phenomena in relation with the environmental hydromorphy.

A renewal of agricultural activities is recorded in phase C. It occurred between the end of the 3rd century and the beginning of the 5th century AD (Table 1). This development seems to be continuous throughout the phase, until the early Middle Ages. Pollen of plants reflecting these agricultural activities (e.g. *Cerealia*, *Secale*, *Cannabis*) show higher rates. However the pollen association is slightly different from that of phase A, the absence of *Vitis* pollen marks the disappearance of the vineyard on the valley side. High rates of *Alnus* and *T. angustifolia* pollen indicate a wetter environment and they can partially mask the representation of other taxa. The analysis of charcoal content reveals a succession of several fire-events (C1-PCh, C2-PCh and C3-PCh) associated to an increase in API. The diagram of charcoal influx clearly shows 3 peaks of cellulose–ligneous particles which are systematically followed by an abrupt decrease in tree pollen in the ratio AP/NAP (Arboreal Pollen content/Non Arboreal Pollen content). The three fire events appear also synchronous to the development of apophytes and to the higher values of *Poaceae*. They reflect the impact of burning and clearing in the surroundings of the site.

At the top of the sequence (phase D), *Alnus* pollen is dominant in the spectrum. The small decrease of API and charcoal curves in phase D could represent a slowing down of agricultural activities during the Early Middle Ages ([664 (725, 739, 772) 887] cal AD; Table 1). The phase E shows a light increase of API correlated with a new peak in charcoal content.

6. Discussion

6.1. Sediment sources and erosive process

During phases B and D (Fig. 7), particle size allows the recognition of the common origin of the sandy fraction. This is supplied from deep layers of soils and substratum of the hill as displayed equally by the high carbonate content of sediments. The upper part of the valley side (F2) and the edge of the plateau (p-IVs/A) seem to be specially affected. The medium and lower parts of hill could have been protected by the forested vegetation cover. The increase in organic component and the development of peaty facies reveal a humidification of the environment with depositional phases alternating with phases of soil stabilisation. High variations of the pollen concentration agree with the model of successive alluviation, colluvial and soil forming processes. Well sorted sediments together with carbonate component give evidence that alluviation of the Doubs river is predominant in phases B–D. The carbonate fraction proceeds either directly from erosion processes of geological formations unaffected by pedogenesis or alluviation of the Doubs river with high content of silt and calcareous sand. Sediments were deposited during hydrologic events; floods are representative of a strong hydrodynamic system generating incisive erosion. The Plateau and the valley side are affected by gully erosion (Fig. 10).

During phases A and C, the fine fraction is dominant; particle size reflects a transport of low energy favourable to loamy and clayey sediments. The regular sedimentation was interrupted by some more sandy deposits which proceeded from the bottom layer of the hill (p-IVs).

Magnetic susceptibility allows the interpretation of these results more accurately (Fig. 5). In the sedimentary accumulation, the increase in magnetic concentrations can be related to the sediment sources and erosive processes of soils [15,17,54]. Magnetic susceptibility

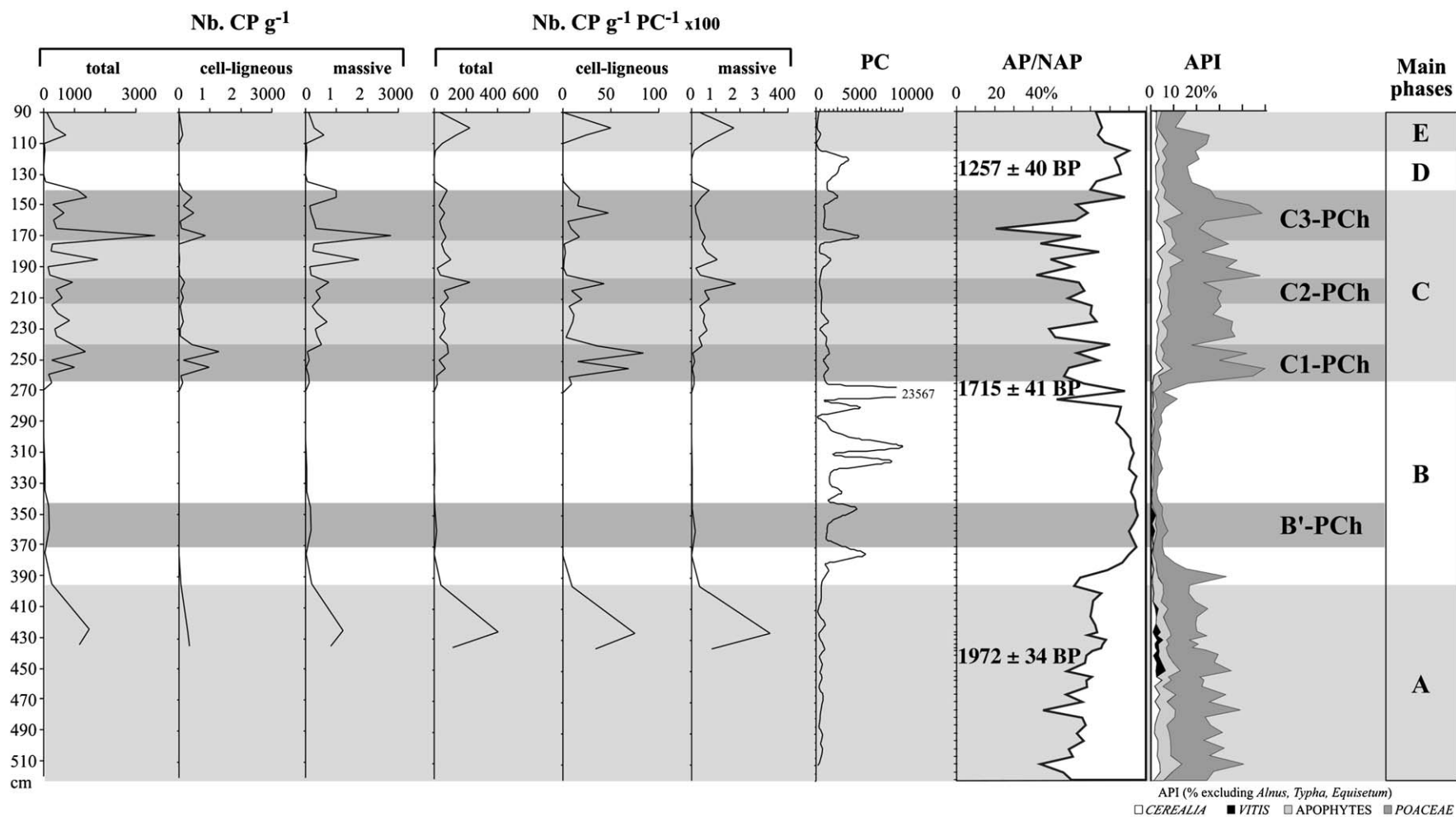


Fig. 8. Charcoal content diagram and simplified pollen diagram from the core N of Neublans. Nb. CPg⁻¹: Number of Charcoal Particles per gram of sediment; Nb. CP g⁻¹ PC⁻¹: Number of Charcoal Particles per gram of sediment expressed relative to Pollen Concentration; PC: Pollen Concentration (number of pollen per gram of sediment); AP/NAP: Arboreal Pollen/Non Arboreal Pollen. Main phases of the stratigraphic evolution (A to E) and local phases B'-Pch, C1-PCh, C2-PCh and C3-PCh.

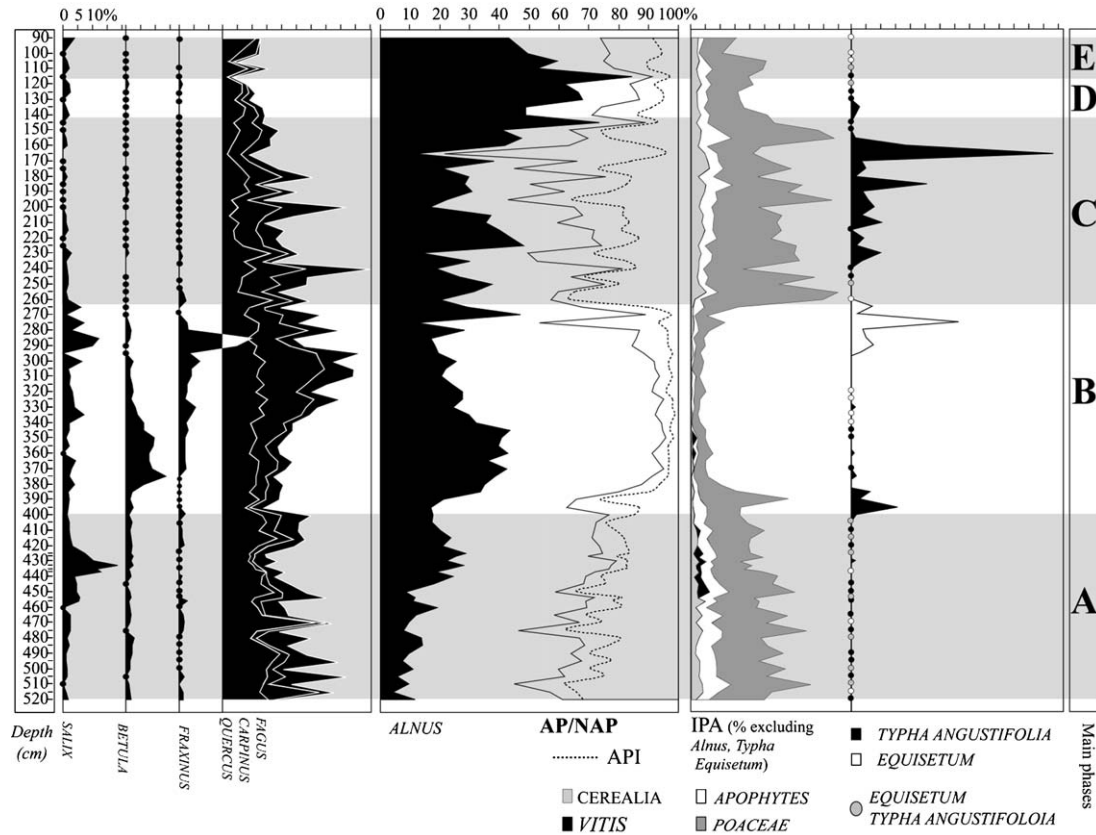
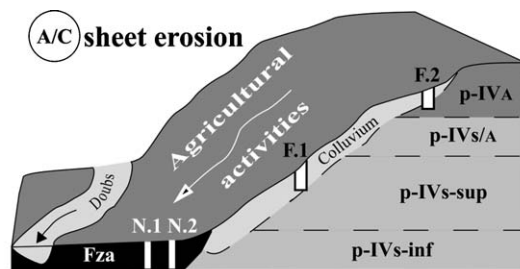
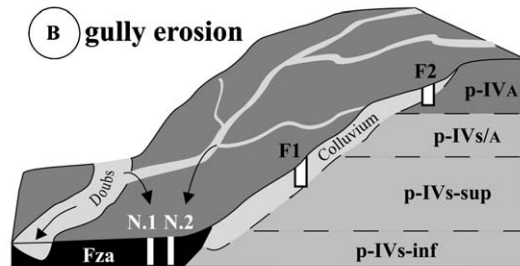


Fig. 9. Simplified pollen diagram from the core N of Neublans, 184 m asl (Jura, France)/

depends mainly on magnetite concentration in sediments. Nevertheless, in the case of low concentration of ferrimagnetic minerals (magnetite and maghaemite), the value of magnetic susceptibility can be largely influenced by diamagnetic minerals (quartz, carbonates) [60]. A dilution of magnetic signal can also be observed in organic sediments [66]. For core N of Neublans, the lower values of magnetic susceptibility correspond to peaty facies, organic loams and to a large extent, to carbonate silt (phases B and D). At the opposite, clayey facies are marked by high values of magnetic susceptibility (phases A and C). This observation is in accordance with the conclusions of Mullins [44] and Maher [39] about magnetic minerals of pedological origin which are preferentially linked to the clayey fraction. The increase of magnetic susceptibility in sediment records is often due to fire action on soil [26,34,45,51,52]. In the case of Neublans, the relation between soil erosive processes and increase in magnetic susceptibility is well established. However, simultaneous occurrence of charcoal influx, indicator of fires, and high values of magnetic susceptibility is not yet explained. For instance, in deposits of sub-phase B'-MS, the increase in magnetic susceptibility corresponds with any variation in charcoal particle influx. Dearing et al. [17] consider that the secondary formation of ferrimagnetic minerals (magnet-



Erosion of the top layer of cultivated soils on the valley side. Silty loam deposits resulting from unconcentrated runoff.



Erosion of the lower layers of soils and bedrock on the valley side. Sandy loam deposits resulting from flooding of Doubs river and reactivation of dry brooks occurred during the 3rd century hydrological crisis.

Fig. 10. 3D modelling representation of erosion and depositional processes during the main phases (A, B, C; see also Figs. 5, 6 and 8) of the land-use history of Neublans site.

ite and maghemite) resulting from a rise in temperature during fire appears as a minor mechanism or as a local phenomenon in comparison to oxidation-reduction and biochemical processes due to microbial activity in soils. Generally, susceptibility magnetic measurements are not closely linked to fire signals [26,36,43]. Therefore, the increase in magnetic susceptibility appears as a result of soil erosion arising from clearing and cultivation activities on the valley side [15,29,32].

Soils were generally submitted to two types of degradation: the first one, which was slow and progressive, occurred under a permanent vegetation cover which modified pedogenesis, the second one, more rapid, which affected cultivated soils. Beginning with a degradation of soil structure, it emerges in most cases during erosion processes [18]. Deforestation not only changed the vegetation but also exposed the soils to the erosion forces of wind and water. Unprotected by a permanent vegetation cover, they were more exposed to sheet erosion [18,58]. Finer elements of phases A and C would proceed from soils uncovered after clearing of the valley side. In that way, the cultivation of vine on the valley side most certainly accelerated erosive processes of soils. The entrainment phases A and C results both from running off of fine elements of the upper layers of soils linked to agricultural activities (Fig. 10).

6.2. Reconstruction of land-use history and hydrological changes

The land-use history of the studied area can be summarised in five main phases: A, B, C, D, E (Figs. 5 and 8 & Fig. 9).

During period A, the landscape opened by clearing and burning, is assigned to pastures and cultivation, especially vineyard. Sheet erosion of soils due to agricultural activities on the valley side is recorded. The scheme of land management of the valley side can probably be generalised to the whole area. Archaeological maps of the valley and plateau (Fig. 3A and B) show numerous traces of human occupation since the Iron Age. On the plateau, the pollen diagram from the pool “l'étang Daufin”, near Authumes site, proves that changes of vegetation cover resulting from human impact are recorded as far back as the first Iron Age, [844,546] cal BC [50]. The human impacts increased progressively to reach a maximum during the 1st and 2nd centuries AD [14].

The decrease of agricultural activities occurring during phase B, begins after the second half of the 2nd century AD. Pollen spectra record a high decrease of API and forest recolonisation (Fig. 9; [25]). Changes in drainage pattern and river flow are synchronous with successive flooding events recorded between AD 50/250 in neighbouring rivers such as the Saône and Rhône and in some other fluvial basins of Western Europe [7,4,65].

This renewal of hydrological activity reflects a major climatic deterioration of the Holocene period. It may coincide with a short but durable rise in lake levels occurring at 100/200 cal AD in the Jura Mountains, phase of “Petit Maclu 1” [37,38]. From an archaeological point of view, it is not possible to assert that the decrease in agricultural activities observed locally has a regional equivalent. The human occupation remains dense throughout the period despite chronological dubiousness about the antiquity of settlement. It is only in and after the 3rd century AD that the first signs of a human occupation controlled by climate and hydrologic constraint become discernible [2]. However, no significant evidence of a decrease in expansion was really recorded in the lower Doubs valley by archaeological documentation [14] and pollen analysis [25]. The riparian woodland, by filtering the pollen spectra, caused a dilution of anthropogenic signal in the core surroundings. Sedimentological analysis reveals preferentially some environmental changes induced by climate and its components such as hydrology and vegetation cover. However, the decrease of agricultural activities on the valley side seems to be effective. The absence of charcoal particles in the sediments and deforestation occurring in B phase agree with this interpretation. The historical abandonment of vine cultivation [14] and pedologic specificity of the valley side appear as a plausible explanation for the modification of agricultural development in the region during the 2nd and 3rd centuries AD, but it is necessary to study the history of farming on a large scale by including the whole geomorphological entity of the valley side.

Phase B'-MS (Fig. 5) attests a temporary break in sedimentation process, probably in inundation, and pedogenesis induced a rise in evapotranspiration rate synchronous with a drying phase of the environment [12]. The development of pedogenesis under forest cover may have favoured a mineral magnetic increase in soils [15]. This phase is characterised by the absence of API along with the expansion of deciduous woodland (Fig. 9). There is no impact of human activities on the landscape in the immediate surroundings of the site. The sequence of organic and peat layers interbedded with calcareous sandy loam reflects changes in the environmental conditions.

In phase C, magnetic susceptibility values and pollen spectra, different from those of phase A, reflect a regional human impact on the environment. High values of *Poaceae* (20 to 30%) and species found in pastures (e.g. *P. major/media*, *P. lanceolata*, *Rumex*) are dominant in the pollen spectra, evocative of an open-landscape. The high rates of *Alnus* and *T. angustifolia* partially mask the representation of the others species (Fig. 9). This pollen association and organic sediments reveal a wetter local environment. Evidence of deforestation, marked by the decline of arboreal pollen

and high charcoal particle concentration, could be related to the expansion of agropastoral activities and to a new agricultural expansion beginning during the 3rd and 4th centuries AD. The valley side was regularly cultivated and farmed until the 8th century AD. During this period, peaks of charcoal suggest a recurrent use of fire for clearing or maintenance of the agricultural landscape. The fire signals give evidence of three phases of human impacts (sub-phases C1-PCh, C2-PCh and C3-PCh; Fig. 8). The various peaks of API curves indicate successive clearing and an extension of points farming. The timing of these particular events is actually unknown. New chronological reference, such as radiocarbon dates or archaeological data, would permit precision in the dynamics of land management. The continuous occurrence of large particles of charcoal during this phase is the result of plough soil erosion related to agricultural practices [62].

Phase D, similar to the sedimentary phase B, is dated to [664,887] cal AD (Table 1). It marks a new climatic deterioration, contemporaneous with the transgressive phase of Petit Maclu 2, recorded at 650/750 AD in lake-level fluctuations in the Jura [37,38]. Evidence for of this climate deterioration is noted by Berger [4] in the Rh ne valley is the 7th and 8th centuries AD. During phase D, a recrudescence of *Alnus* gives clear evidence of a humidification of the environment but no significant decrease in agricultural activities is recorded by palynology.

7. Conclusion

The study of physical and biological characteristics of the sequences of Neublans allows us to define respectively the role of climate control and of human impacts in sedimentation. In the investigated area, the process of sedimentary accumulation was influenced by a strong local human impact on the environment; it expresses a more regional influence when the intensity and frequency of rainfall became the predominant factor. Then, the natural dynamics of the environmental evolutions appear as a constraining factor of human occupation.

Agricultural activities unquestionably represent a factor of soil erosion, but it is a specific type of erosion which affects fine elements. The clearing seems to favour surface run off and sheet erosion. Climatic deterioration may generate, by changing the water balance, erosion which can entrain more coarse materials. It is very likely that land management has amplified these phenomena, but only the joint impact of the two main factors affecting sedimentation, human activities and climate, could explain the occurrence of the more violent sedimentary crisis. Same climatic hypothesis is proposed by Groove [27] to explain fluvial deposits in Mediterranean context during the early Holocene. Micro-charcoal analysis and specially morphological particles differen-

tiation appear as a relevant mean for the identification of specific stage in the land management during historic and prehistoric periods [64]. In the multi-proxy approach, fire signals provide original information's about temporality of human impact and type of practices.

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