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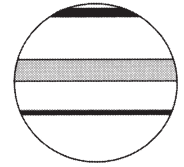
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# Quantitative analysis of climate versus human impact on sediment yield since the Lateglacial: The Sarliève palaeolake catchment (France)

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## Abstract

Minimum rates of solid (SSY) and dissolved (DSY) sediment yield (SY) were evaluated in t/km<sup>2</sup> per yr from sediments stored in the Sarliève palaeolake (French Massif Central) for seven phases of the Lateglacial and Holocene up to the seventeenth century. The catchment (29 km<sup>2</sup>), mainly formed of limestones and marls, is located in an area rich in archaeological sites in the Massif Central. The respective impacts of human activities and climate on SY were compared by quantification of human settlements through archaeological survey and palynological data. During the Lateglacial and early Holocene up to about 7500 yr cal. BP, variations in SSY and DSY rates were mainly related to climate change with higher rates during colder periods (Younger Dryas and Preboreal) and lower rates during warmer periods (Bölling-Alleröd and Boreal). However, CF1 tephra fallout induced a sharp increase in SY during the Alleröd. During the middle and late Holocene after 7500 yr cal. BP, SSY and DSY greatly increased (by factors of 6.5 and 2.8, respectively), particularly during the Final Neolithic at about 5300 yr cal. BP when the climate became cooler and more humid. After this date, at least 75% of the SSY increase and more than 90% of the DSY increase resulted from human activities, but SSY rates showed little variation during Protohistoric and Historic Times up to the seventeenth century. SSY and DSY rates and DSY/SSY ratio indicate that catchment soils began to form during the Lateglacial and Preboreal, thickened considerably during the Boreal and Atlantic, finally thinning (rejuvenation) mainly as the result of human-induced erosion during the sub-Boreal and sub-Atlantic. Increased mechanical erosion during the late Holocene also induced an increase in chemical erosion.

## Keywords

archaeological survey, climate-change impact, French Massif Central, Holocene, land-use impact, Lateglacial, palaeolake, soil erosion, solid and dissolved sediment yield

## Introduction

Current earth surface sediment yield, mainly assessed from solid and dissolved fluxes in rivers, is highly dependent on human activities whose impact is difficult to quantify compared with that of natural factors, particularly climate (e.g. Judson and Ritter, 1964; Douglas, 1967; Milliman and Syvitski, 1992; Ludwig and Probst, 1998). There are three main questions regarding human impact on sediment yield (Hooke, 2000; Ruddiman, 2003; Wilkinson, 2005). (1) When did it start? (2) How did it evolve? (3) What was its intensity? These questions can be investigated by assessing pre-human and syn-human sediment yields, through studying sedimentary archives stored in favourable basins, particularly lakes (e.g. Campy *et al.*, 1994; Macaire *et al.*, 1997; Dearing and Jones, 2003). Many studies have shown a trend of increasing sediment yield over several thousand years in populated areas (e.g. Zolitschka, 1998; Bichet *et al.*, 1999; Dearing and Jones, 2003). These studies mainly concern solid sediment yield deduced from quantification of detrital sediment stores. Dissolved yield has been more rarely quantified (Einsele and Hinderer, 1998; Gay and Macaire, 1999), although chemical erosion has been found to be of major importance in some lithological or bioclimatic environments (Meybeck, 1987; Berner and Berner, 1987). There is very little information about chemical sediment flux as compared to the detrital fraction because the precipitated fraction

of lake sediments is often difficult to differentiate and quantify. In a catchment of given physiography, the ratio of dissolved versus solid yield depends considerably on runoff and thus on vegetation related to climate and recently to human activities (Walling and Webb, 1986).

An overall increasing sediment yield over the last few thousand years, with some intermittent periods of lower yields, is generally interpreted as the result of human activities (e.g. Zolitschka, 1998; Hooke, 2000; Edwards and Whittington, 2001). This interpretation is based on various proxies of anthropogenic impact. The most usual human-activity proxy is the palynological

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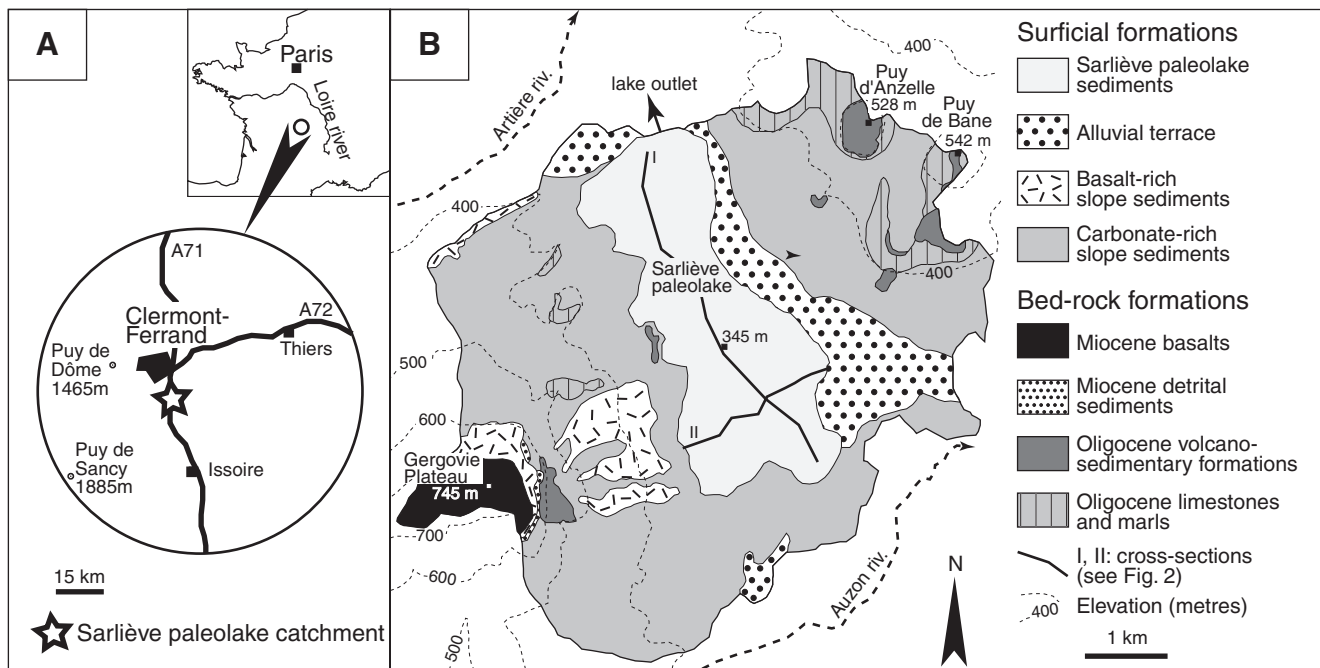
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**Figure 1.** Location (A) and main physiographical characteristics (B) of the Sarliève catchment

record which provides indirect information (deforestation, cereal cultivation, pasture, etc.) from vegetation. Evidence of early human presence is generally provided directly by artefacts, building structures, etc., but data are often very sparse and were not determined in a systematic manner, and so make it impossible to quantify the density of human occupation and compare it with sediment yields at different periods.

The aim of this work was thus: (1) to quantify sediment yield (SY) from lacustrine sediment stores for different periods before and during human impact since the Lateglacial, distinguishing rates of solid sediment yield (SSY) from dissolved sediment yield (DSY), (2) to compare these rates with quantitative data of human settlement (age, density and location of archaeological sites) from detailed and systematic archaeological surveys in the lake catchment; intensity and type of human activities were evaluated from analysis of pollen grains in lacustrine sediments, and (3) finally to evaluate the land surface lowering by catchment-soil erosion which contributed to the sediment yield.

The studied area is a small lacustrine catchment in the centre of France. Lacustrine deposits, stored since the Lateglacial, have been the subject of detailed sedimentological, palaeohydrological and geophysical studies (Bréhéret *et al.*, 2003, 2008; Fourmont, 2005; Fourmont *et al.*, 2006, 2009; Hinschberger *et al.*, 2006). This catchment, located in a major site of French history ('*oppidum* de Gergovie'), contains considerable evidence of human settlement since the Neolithic and has been the subject of systematic archaeological surveys (Trément *et al.*, 2005, 2006, 2007a, b).

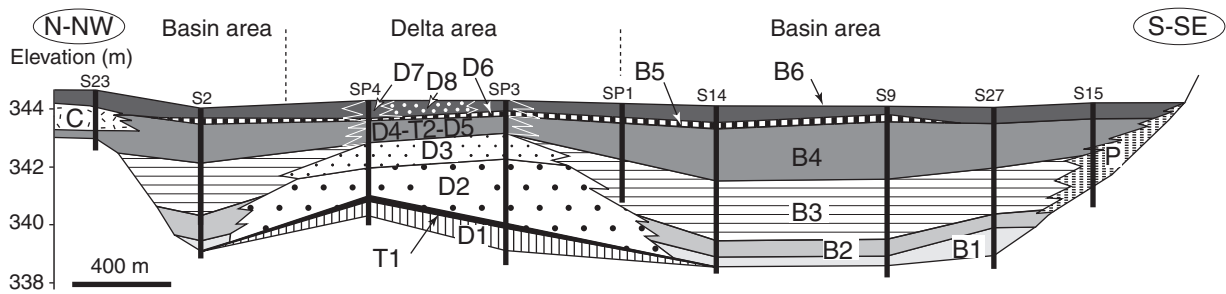
## The Sarliève palaeolake and its catchment: geological setting, sedimentological and palaeohydrological evolution

Here, and in the following sections, all ages are given in calibrated years BP. Calibration of radiocarbon ages is based on the

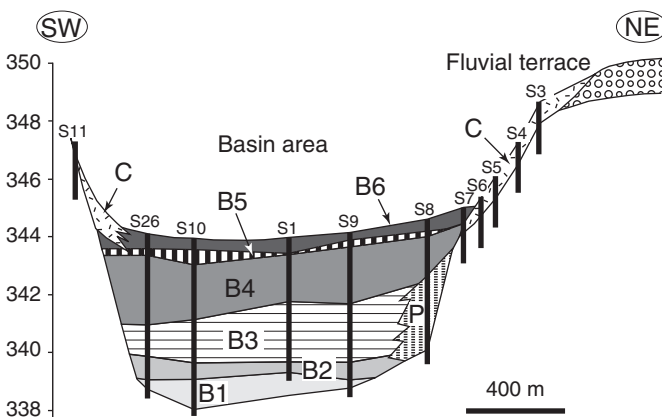
INTCAL04 data set. The 'Marais de Sarliève' is an ancient lake (surface area: 5 km<sup>2</sup> maximum, altitude: approximately 345 m), formed a little before 13 700 yr cal. BP (Fourmont *et al.*, 2006). It is located in the Auvergne region, 10 km southwest of Clermont-Ferrand in the Limagne rift ( $x = 663\ 780$  m;  $y = 2\ 082\ 180$  m in the Lambert Conformal Conic system; Figure 1A). The origin of the lacustrine depression is probably tectonic (Ballut, 2000; Trément *et al.*, 2007b; Fourmont *et al.*, 2009); it can only be drained by evaporation or via the outlet located at the northeastern end of the catchment (Figure 1B). The depression filled with sediments until it was drained by humans during the seventeenth century (Fournier, 1996); it is bordered on the north and east by alluvial terraces. The catchment (total surface area: 29 km<sup>2</sup>) is mainly composed of Oligocene marls and limestones, partly dolomitic and sometimes gypsum-rich, with small outcrops of basaltic rocks on the surrounding hills up to 745 m (Jeambrun *et al.*, 1973). Bed-rock is generally covered with superficial formations derived from Oligocene carbonated rock (Figure 1B). This area is currently characterized by a strong continental climate: mean annual rainfall is less than 600 mm and mean annual temperature is approximately 11°C (min 4°C, max 21°C) (Kessler and Chambraud, 1986).

Lacustrine sediments, studied through deep pits and core drillings, consist of delta and basin deposits (Bréhéret *et al.*, 2003, 2008; Fourmont *et al.*, 2006, 2009). Delta deposits, 4–5 m thick (D1 to D7, Figure 2A), are located in the median part of the depression and comprise several units. From base to top these are: D1, beige to greenish carbonated clayey-silts (CS); T1, black pyroclastic sands; D2, several metres-thick deltaic sands composed of alternating layers of dark tephric sand and light-coloured more carbonated sandy-silt; D3, sandy colluvium topped by a palaeosoil; D4, ochre sands; D5, homogeneous greenish calcitic CS including a thin, pale pink tephra T2; D6, charcoal-rich black calcitic CS; D7, greenish-grey to brown calcitic CS. Basin deposits, 5–6 m thick, observed in the north and south lobes of the depression (B1 to B6, Figure 2A, B), are made up of clayey-silty

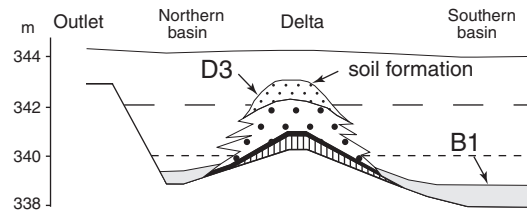
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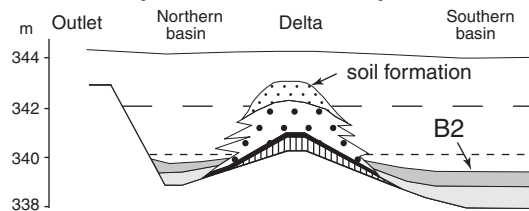
B - Cross-section II



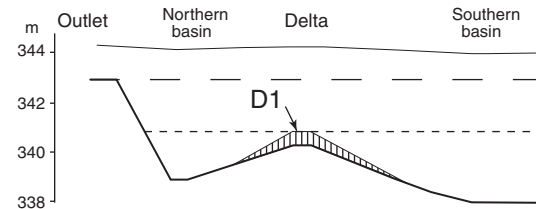
F - Ca. 11.5 kyrs cal BP - ca. 9.8 kyrs cal BP



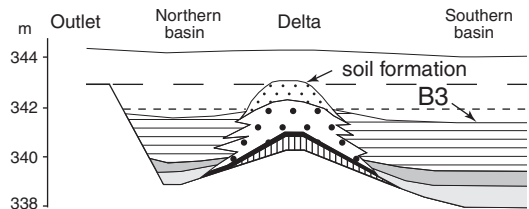
G - Ca. 9.8 kyrs cal BP - ca. 7.5 kyrs cal BP



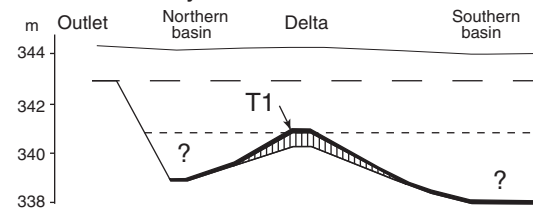
C - Late Glacial up to 13.7 kyrs cal BP



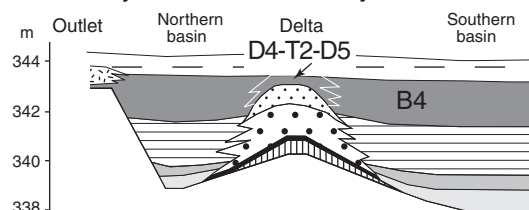
H - Ca 7.5 kyrs cal BP - ca 5.3 kyrs cal BP



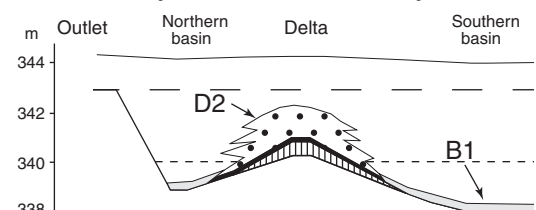
D - At ca. 13.7 kyrs cal BP



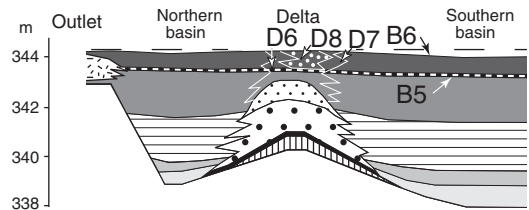
I - Ca 5.3 kyrs cal BP - ca 2.3 kyrs cal BP



E - Ca. 13.7 kyrs cal BP - ca. 11.5 kyrs cal BP



J - Ca 1.8 kyr cal BP - ca 0.3 kyr cal BP



— — — maximum water level      - - - - - probable usual water level

**Figure 2.** Cross-sections through sediments (A, B) and pattern of Sarliève palaeolake evolution since the Lateglacial up to the seventeenth century (C to J) (from Fourmont *et al.*, 2009). Location of I and II cross-sections, see Figures 1 and 4B. S2, S9, core drilling; SP3, SP4, pit section; D1 to D7, delta deposits (T1 and T2, tephras); B1 to B6, distal basin deposits; P, proximal basin deposits; C, colluvium

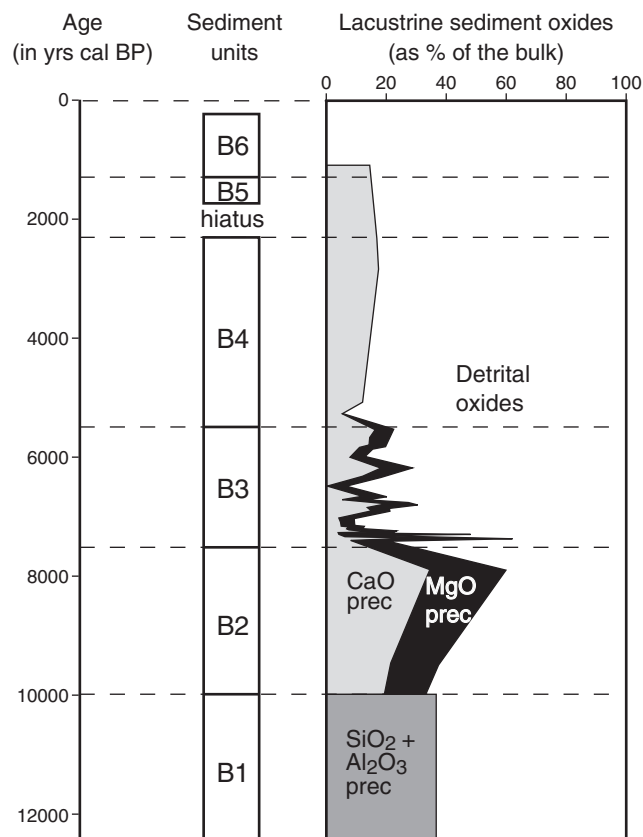
sediments, generally carbonate-rich, showing from base to top: B1 unit, quartz-rich compact yellowish to greenish clayey-silts (CS), characterized by the presence of zeolites; B2, grey to blue clayey-silts mainly composed of authigenic dolomite; B3, alternation of dark calcitic CS (cm-thick layers) with bundles of dolomitic and aragonitic laminae; B4, homogeneous greenish calcitic CS; B5, charcoal-rich black calcitic CS; B6, greenish-grey to brown calcitic CS. The lower part of proximal basin deposits contains a dark sandy layer incorporating reworked pyroclastic particles (similar to T1 and D2).

The following palaeohydrological and sedimentological scheme of the lake's evolution (Fourmont *et al.*, 2009) has been drawn up from distribution and comparison of sedimentary facies,  $^{14}\text{C}$  datings, tephra ages and detailed mineralogical and geochemical analysis.

During the Lateglacial up to *c.* 13 700 yr cal. BP (mainly Bölling), D1 unit sediments, containing *c.* 30% travertine-like precipitated material, were deposited in the delta area; no evidence of coeval sediments was found in basins. Water level was low, with a maximum depth of *c.* 5 m (Figure 2C). At *c.* 13 700 yr cal. BP, at around the beginning of the Alleröd, direct CF1 tephra (Vernet and Raynal, 2000) was deposited (T1 unit, Figure 2D). While it probably covered the whole catchment area, CF1 tephra has only been observed in delta sediments where it was buried under the D2 unit deposited in a fan-type delta during the period 13 700 yr cal. BP–11 500 yr cal. BP (Alleröd and Younger Dryas) (Figure 2E). The D2 unit, exclusively detrital in origin, includes layers of tephra reworked from catchment slopes, suggesting a rise in water level during flood event(s) to more than *c.* 342 m, which probably led to a short-lived opening of the lacustrine depression. However, during the same period, from 13 700 yr cal. BP up to *c.* 9800 yr cal. BP, authigenic zeolites and quartz formed in the distal basin B1 unit, partly because of alteration of CF1 tephra, and indicating endorheic conditions with a generally low water level and reduced detrital input (*c.* 60% of B1 sediments) (Figure 3).

After *c.* 11 500 yr cal. BP (early Holocene), colluvium (D3 unit) was deposited on the emerged delta area (Figure 2F). Soil formed at the top of D3, probably during the early and middle Holocene until the end of the Atlantic period (Figure 2G, H). During this period (9800 yr cal. BP until 7500 yr cal. BP) authigenic dolomite-rich sediments (B2 unit) formed in the basins, indicating perennial endorheic conditions. The biochemical dolomite content increased in the B2 sediments from 30% (bottom) to 60% (top), indicating maximum restriction at around 8000 yr cal. BP (Figure 3). The water level did not reach the top of D3, and the water was probably quite shallow (less than 1–2 m deep).

During the middle Holocene, from *c.* 7500 yr cal. BP until *c.* 5300 yr cal. BP (Atlantic period), when the delta area was never flooded (Figure 2H), unit B3 was deposited in the basins. Interbedding of laminated biochemical sediments (BL facies) with detrital sediments (homogeneous clayey-silts: HCS facies) indicates variations in palaeohydrology and related depositional conditions. Bréhéret *et al.* (2008) identify three phases of BL–HCS facies sedimentation: (1) dolomite authigenesis in BL under restricted conditions similar to B2; (2) aragonite genesis in BL, indicative of  $\text{Ca}^{2+}$ -rich freshwater inputs when facies are composed of 20% to 60% biochemical phases (Figure 3) and deposited while lake waters were salty; and (3) HCS facies, where biochemical phases constituted less than 10%, indicating increased



**Figure 3.** Evolution of contents in detrital and precipitated fractions in Sarliève palaeolake basin sediments (core S17). CaOprec, MgOprec and  $\text{SiO}_2 + \text{Al}_2\text{O}_3$ prec, precipitated CaO, MgO and  $\text{SiO}_2 + \text{Al}_2\text{O}_3$  in percents of lacustrine bulk sediments (from Fourmont *et al.*, 2009).  $\text{SiO}_2 + \text{Al}_2\text{O}_3$  were precipitated from CF1 tephra weathering

detrital input during periods with low water level and salty water, ending with the input of fresh water. This trend could be related to repeated time-limited fluctuations of the water level which was generally below the top of D3 palaeosoil, i.e. *c.* 342/343 m. The duration of one BL + HCS deposition sequence has been evaluated at 150 yr on average in B3 and 470 yr at the maximum between  $7100 \pm 150$  yr cal. BP and  $7260 \pm 160$  yr cal. BP. However, the gradual thickening of detrital HCS facies towards the top of B3 indicates the increasing input of fresh water and the possible temporary opening of the system.

The sediment geometry shows that the water level was high during the late Holocene from 5.3 ka cal. BP: B4 to B6 units accumulated when the lake extended, covering the delta area and border deposits (Figure 2I, J). Water-level altitude must have been at least 343 m at the beginning of the sub-Boreal, and 344/345 m in the seventeenth century. Apart from the D4 sandy transgressive facies and local D8 sandy-gravelly deltaic facies, the upper sediments of the whole delta (D5 to D7 units) and basin (B4 to B6 units) have a homogeneous composition. They contain more than 80% detrital materials, and biochemical calcite is always < 20% (Fourmont *et al.*, 2009; Figure 3). The waters were probably continuously fresh, implying a perennial body of water in the lake, total opening of the depression and continuous water supply from the catchment. However, archaeological data (Gallo-Roman settlements, cemetery and drainage networks in the palaeolake basins) show that the lake dried up between the third century BC and second century AD



because of human activities (Trément *et al.*, 2007b). Moreover, 'catastrophic' flood(s) occurred between the fourth and seventeenth centuries AD, causing sandy-gravelly fan delta deposition (D8 unit), and resulting in the water level rising above 346/347 m. Finally, the lake was drained during the seventeenth century (Fournier, 1996), and since then the water has run in artificial channels.

## Methods

### **Evaluation of catchment physiographical characteristics and calculation of sediment yield rates**

Some parameters of relief and lithology were analysed using GIS. Slope gradient and true surface area of the catchment were calculated from DEM using Arcview 8.2 software and digitizing elevation contour lines of Institut Géographique National (IGN) 2531E and 2532E 1/25 000 maps. Surface areas of main types of rocks were assessed by digitizing XXV-31 'Clermont-Ferrand' 1/50 000 geological map (Jeambrun *et al.*, 1973).

Sediment yielded by catchment was calculated in  $t/km^2$  per yr from stored lacustrine sediment mass. Volumes of main sedimentary units (delta sediments: units D1 to D8, and T1 tephra; basin sediments: units B1 to B6) were calculated from their thickness and extent using different methods. Facies and thickness of sediments were observed directly (1) from 13 pit sections of  $8\text{ m} \times 8\text{ m}$ , carried out up to a depth of 3.3 m by the Institut National de Recherches Archéologiques Préventives (INRAP) for an archaeological survey of the construction site of the 'Grande Halle d'Auvergne', located near by the delta area, and (2) from 31 core drillings retrieved with a percussion sampler (Eijkelkamp) by the geological laboratory of Tours (UMR CNRS 6113 ISTO) in northern and southern distal basins (Figure 4B). Sediment thickness and extent were determined using 56 geotechnical tests (static penetrometry using 100KN penetrometer) carried out by Fondasol-Auvergne: penetrometric data mainly identified hard substratum (resistance to penetration  $R > 6\text{ Mpa}$ ), and with regard to lacustrine sediments, clayey silty (B1 to B6, D1, D4 to D7 units:  $R < 2\text{ MPa}$ ), sandy-silty (T1, D2 and D3 units:  $2 < R < 6\text{ MPa}$ ) and gravelly-sandy (D8 unit:  $R > 6\text{ Mpa}$ ) bodies, according to data of Antoine and Fabre (1980).

In the northern and southern basins about 50 km of electromagnetic profiling was performed using an average recording distance of 7 m along the profiles, a lateral spacing of 20 m to 100 m, an EM 31 instrument, and the slingram method (Mc Neil, 1980) (Figure 4C). Electrical conductivity of surficial deposits up to about 6 m depth was calibrated with lithological facies observed from core drillings. Sixteen electrical soundings were also performed. Based on the geophysical survey, the total thickness of lacustrine sediments in basins and the thickness and extent of sediment units mainly composed of precipitated (B1 to B3) and detrital material (B4 to B6) were determined (Hinschberger *et al.*, 2006). Spatial analysis of these data (elevation of bottom and top, and 3D extent of units) were performed using SIG (Arcview 8.2; Fourmont, 2005). Interpolation by kriging was used to delineate the shape of lacustrine sediment units, based on which sediment volumes were calculated. It was not possible to distinguish the limit between T1 (tephra) and D2 (tephra-rich delta sediments) units, as their grain sizes are similar. Likewise, clayey-silty D6-B5 (charcoal-rich black calcitic CS)

and D7-B6 (greenish-grey to brown calcitic CS) units could not be distinguished (Figure 2).

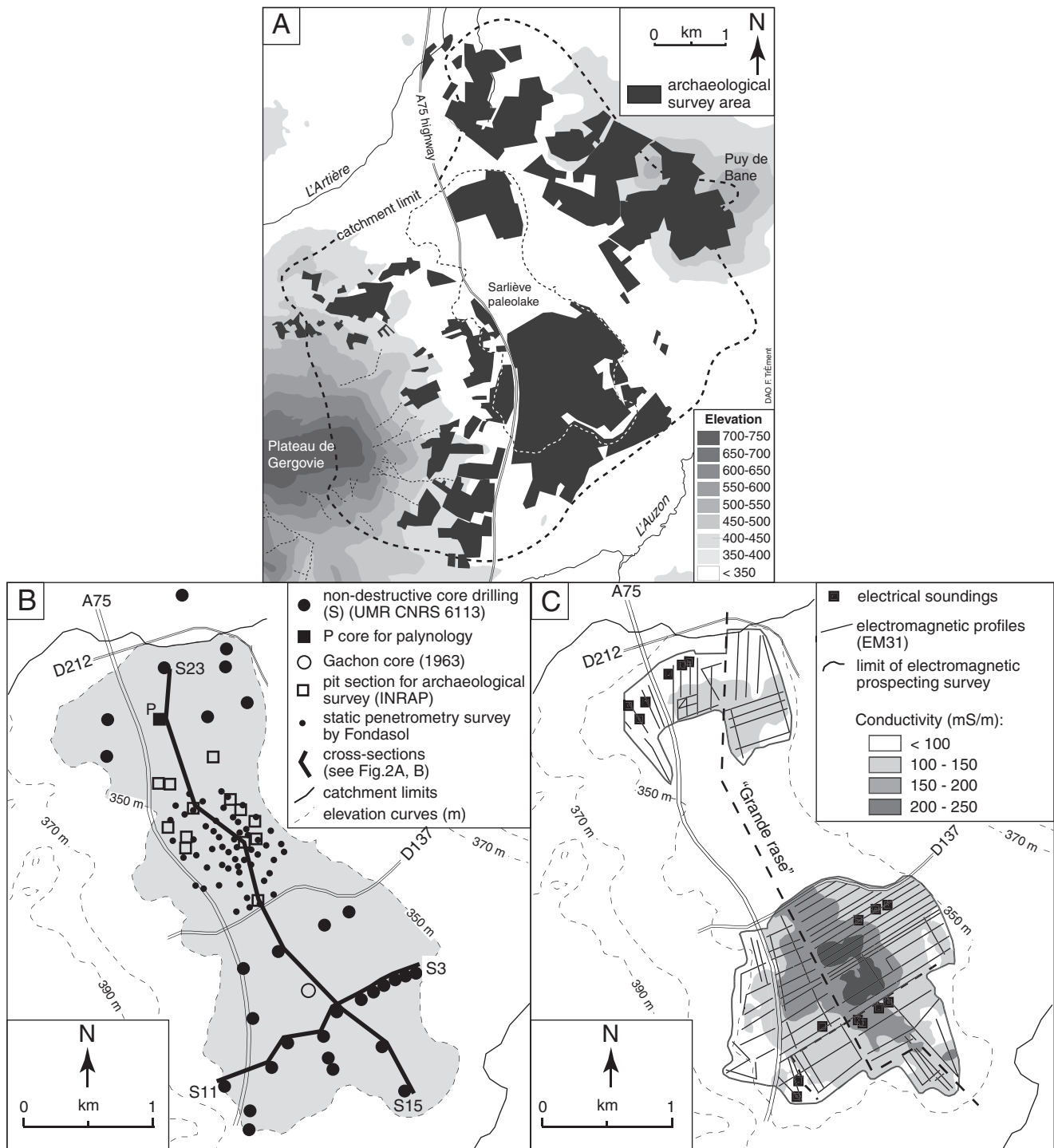
The apparent volumetric mass (dry weight divided by the wet volume, in  $t/m^3$ ) of the basin-unit sediments was calculated by weighing sediments after given volumes of sediments were dried at  $40^\circ\text{C}$  for 48 h. We decided that the apparent volumetric mass of lower sandy delta units, which could not be measured, was  $1.5\text{ t/m}^3$ , based on data of Macaire *et al.* (2006). The sediment mass for each unit was calculated by multiplying the unit's volume with the experimentally derived volumetric mass. From these data we calculated the mass of material (detrital and precipitated) forming each lithological unit, using the data of Fourmont *et al.* (2009). For B3 unit, composed of alternating precipitated material-rich laminae (BL) and detrital material-rich layers (HCS), the whole sediment mass was calculated from the volumetric mass of BL and HCS facies weighted by their relative thickness in the unit. The evolution of the mass of precipitated material compared to detrital material from bottom to top in B3 was deduced from evolution of the thickness of BL compared with HCS facies.

Age and period of formation of each lithological unit were calculated based on the chronological model of Fourmont *et al.* (2009), that is based on 18 calibrated  $^{14}\text{C}$  ages of seeds, charcoal and bulk sediment organic matter, performed by the CDR (Centre de Datation par le Radiocarbone, Lyon 1 University), completed with information from pollen zones, tephrochronology and archaeological data. The base of D1 was arbitrarily chosen as the beginning of the Bölling (15 000 yr cal. BP). Deposition of D3 colluvium was attributed to the Preboreal (duration: 1100 yr), and palaeosol formation on this colluvium to the Boreal and Atlantic (duration: about 5100 yr).

Sediment source area for calculation of the sediment yield was determined for each unit as the difference between the total catchment area and the unit surface area in the lacustrine area. Sediment yield rates were estimated in  $t/km^2$  per yr by dividing the each unit's sediment mass by the surface of sediment source and the time period of formation of the unit. Total sediment yield (TSY) was calculated, as well as solid (SSY) and dissolved (DSY) sediment yields. It was possible to distinguish between detrital and precipitated material in sediments thanks to geochemical, XRD, SEM and EDS analyses. Mineral study suggests that, except in B1, silicates (quartz, feldspars, zeolites and clay minerals) are mainly detrital, and carbonates (calcite, dolomite and aragonite) are both detrital and *in situ* precipitated (biochemical). For each unit, the mass of precipitated MgO and CaO carbonates have been quantified (details in Fourmont *et al.*, 2009), (1) from MgO and precipitated dolomite contents in sediments determined from geochemical analyse and SEM observation, respectively, (2) by comparing CaO contents in sediment and catchment soils for each period. From this investigation, the uncertainty in determination of SSY and DSY values can be evaluated to  $\pm 20\%$ .

### **Pollen study**

Pollen analysis (pollens data used for the chronological model of Fourmont *et al.*, 2009) was carried out on samples collected by increments of 3 cm in P core performed with Russian core sampler in the northern basin (Figure 4B). After eliminating carbonate and siliceous components of sediments, pollen grains were concentrated with 'Thoulet' solution ( $d = 2$ ) (Goeury and de Beaulieu, 1979).



**Figure 4.** Location of surveys. (A) Archaeological survey area in whole catchment; (B) location of core drillings, pit section for archaeological survey and static penetrometry survey in palaeolake area; (C) geophysical survey in palaeolake area

A minimum of 300 pollen grains were identified and counted in each sample. To make it easier to interpret pollen, taxa were separated into two classes: those characteristic of wetland (area in direct contact with the Sarliève palaeolake), and those characteristic of the catchment. The abundance of pollen grains was calculated as a percentage of each class and analysed separately. Chenopodiaceae, which are not strictly related to either class, and Tertiary taxa were calculated as a percentage of the whole pollen grains. Data on non-pollinic microfossils studied on P core were taken from Argant and Lopez Saez (2004).

### **Historical study and archaeological survey**

The history of human settlement was investigated through exhaustive bibliographical study of the nine districts in the catchment. Five systematic archaeological field surveys, with intervals of 10 m and sampling of the whole archaeological material on each site, were performed between 2001 and 2003, in accessible areas with no buildings, representing 40% of the whole catchment area (Trément *et al.*, 2007b; Figure 4A). Four spatial archaeological units were identified for different periods: (1) site, which has a

concentration of artefacts providing evidence of human activity at a precise place, (2) probable site, which has insufficient evidence, (3) isolated artefact, for a notable artefact, and (4) off-site pottery, representing a 'background noise' of scattered and often sub-rounded abundant artefacts resulting from farming-related soil enrichment. Statistical analyses of the sites interpreted as settlements were carried out for each period: number, distribution by elevation and total surface area. In addition, the 13 pit sections carried out by INRAP before the construction of the Grande Halle d'Auvergne (Vernet *et al.*, 2005) were studied; they cover a surface area of 90 ha in the palaeolake delta zone at its eastern and western borders where there is a large site (7500 m<sup>2</sup>) (Figure 4B).

## Results

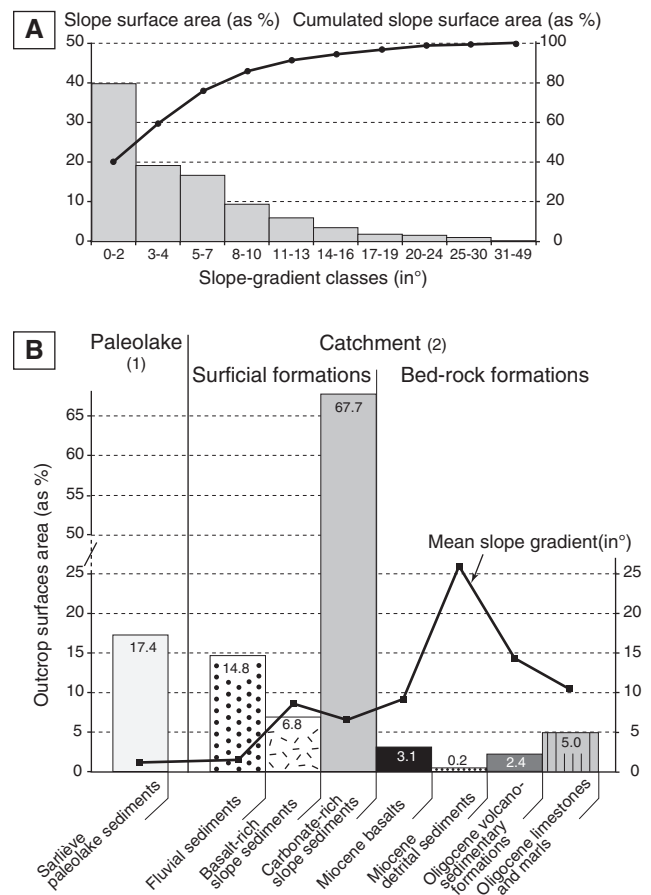
### Catchment physiography

Catchment slope gradients vary from about 0° in the Sarliève depression to 49° on the eastern side of the 'Plateau de Gergovie' (Figure 5A). Slope gradients are lower than 2° on 40% of the catchment area and above 8° on about 20%. Percentages of main rock-outcrop surfaces are shown in Figure 5B: carbonated rocks cover about 75% of the catchment in low to medium slope gradient areas.

### Sediment yield (SY)

Rates of total (TSY), solid (SSY) and dissolved (DSY) sediment yields, and data for their calculation are shown in Figure 6A,B,C and in Tables 1 and 2, respectively. During the Lateglacial and Holocene, SSY and DSY varied from 6 to 203 t/km<sup>2</sup> per yr and from 4 to 44 t/km<sup>2</sup> per yr, respectively. Nine sediment yield phases (SYp1 to SYp9) were identified. During the Bölling and at the beginning of the Alleröd (SYp1), SSY (19 t/km<sup>2</sup> per yr) and DSY (8 t/km<sup>2</sup> per yr) rates were low. During the second part of the Alleröd and the younger Dryas (SYp2), SSY (65 t/km<sup>2</sup> per yr) and DSY (31 t/km<sup>2</sup> per yr) increased significantly. During the Preboreal and at the beginning of the Bölling (SYp3), SSY decreased slightly (52 to 46 t/km<sup>2</sup> per yr), while DSY did not vary. The lowest SY rates appeared during the Bölling and at the beginning of the Atlantic (SYp4): SSY decreased from 11 to 6 t/km<sup>2</sup> per yr, while DSY increased from 4 to 9 t/km<sup>2</sup> per yr. During the Atlantic and at the beginning of the sub-Boreal (SYp5), there was considerable variation between SSY and DSY rates (24 to 55 t/km<sup>2</sup> per yr and 37 to 6 t/km<sup>2</sup> per yr, respectively): SSY and DSY increased alternately during this period, with a general pattern of SSY increase and DSY decrease. During the sub-Boreal and at the beginning of the sub-Atlantic (SYp6), SSY increased considerably (161 t/km<sup>2</sup> per yr), and DSY rose to 40 t/km<sup>2</sup> per yr. The SY rate for the period between 2300 and 1800 yr cal. BP (SYp7) could not be calculated as there were no stored sediments due to lake-water drainage at this time. SY rates were highest during the sub-Atlantic from 1800 to 300 yr cal. BP (SYp8), up to 203 t/km<sup>2</sup> per yr between 1600 and 300 yr cal. BP (SYp8b) for SSY, and 44 t/km<sup>2</sup> per yr for DSY. SY could not be evaluated for the period after 300 yr cal. BP because of the lake drying up.

SSY was generally greater than DSY, except at the end of SYp4 and the beginning of SYp5. The DSY/SSY ratio (Figure 6D) remained close to 0.5 with a slight increase (0.42 to 0.67) between SYp1 and SYp3. This ratio increased sharply to 1.54 during SYp4 (beginning of the Atlantic), then decreased with variations to 0.11 at the end of SYp5. After that, the DSY/SSY ratio did not vary significantly, remaining around 0.25 during SYp6 and SYp8.



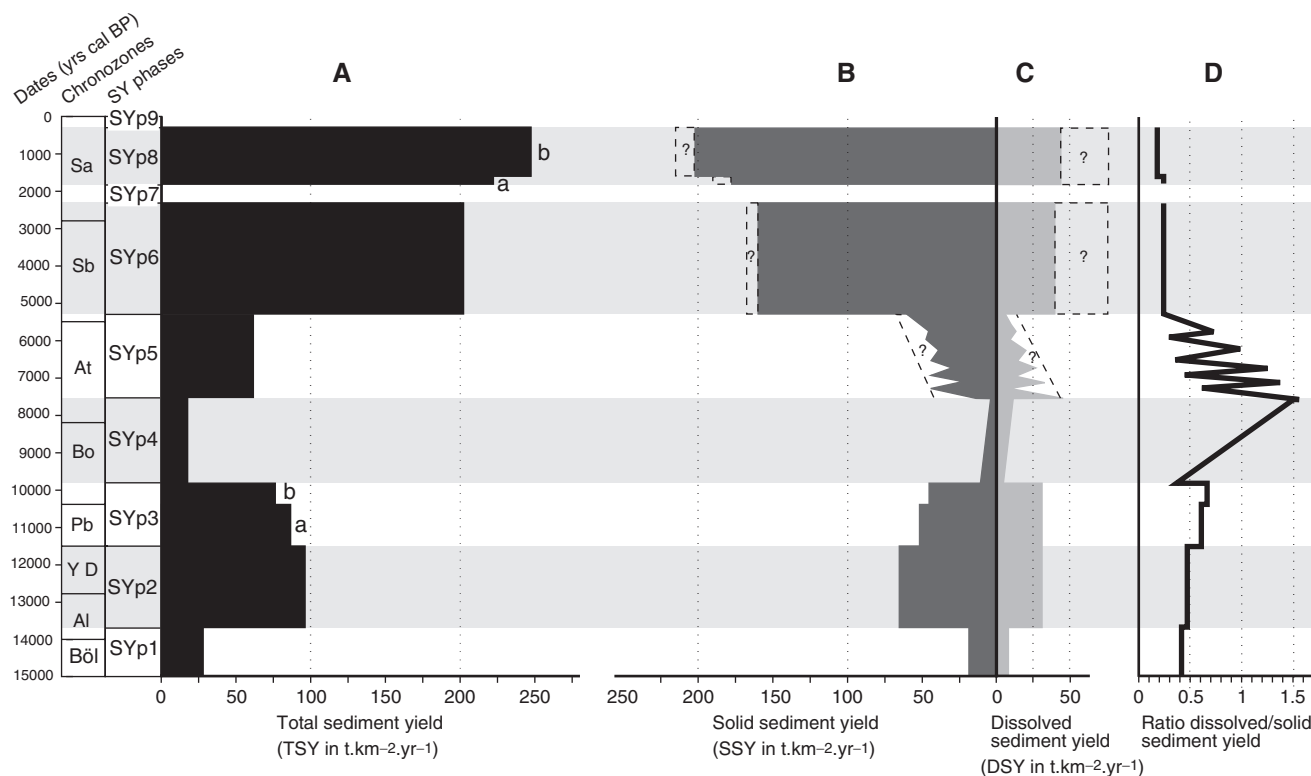
**Figure 5.** Physiographical data of Sarliève catchment. (A) Catchment slope gradients. (B) Lithology and mean slope gradients by lithological area. (1) lithology as per cent of whole catchment area (29 km<sup>2</sup>); (2) lithology as % of sediment-yielding catchment area (24 km<sup>2</sup>)

### Palynology

Palynological data obtained from study of the P core concern B3 to B6 lithological units (Atlantic to late sub-Atlantic). The taxa, described in detail in Argant and Lopez Saez (2004), are presented in this paper in two environments: catchment and wetland (Figure 7). This made it possible to investigate the relationship between SY rates and plant cover during anthropogenic impact periods (Ep5 to Ep8). These elements further Gachon's data (1963) on vegetation in the Sarliève area for the whole Holocene and are in line with Prat's data (2006) for the sub-Boreal and sub-Atlantic.

Catchment plant cover (Figure 7A) was dominated by forest (50–85% of arboreal pollen) up to the end of the sub-Boreal. During the Atlantic, *Quercus* and *Corylus* dominated (pollinic zones a, b and c) with *Ulmus* and *Tilia*; during periods of reduced arboreal pollen grains, *Corylus* decreased more than *Quercus*. After that, *Fagus* and *Abies* appeared (zone d) and developed during the sub-Boreal (zones e, f, g and h), mainly to the detriment of *Corylus*. At the beginning of the sub-Atlantic there was a sharp decline of forest taxa (always lower than 40%: zones i and j), dominated by *Pinus*. Poaceae were always present (5 to 20% of pollen grains in the catchment), but dominated (up to about 50%) only in zone i, at the beginning of the sub-Atlantic. Ruderals (*Plantago*, *Artemisia*, *Centaurea*, Cichorioideae, Asteraceae, *Polygonum*, Lamiaceae, Apiaceae), except Chenopodiaceae, were found from the beginning of the Atlantic (zone a); they were temporarily more abundant in zone c with a marked increase at the sub-Atlantic (up to 45% in





**Figure 6.** Rates of sediment yield (SY) during the Lateglacial and Holocene in Sarliève catchment. Chronozones from Boivin *et al.* (2004). (A) Total sediment yield, (B) solid sediment yield, (C) dissolved sediment yield, and (D) ratio of dissolved/solid sediment yield

zone j). Cereals, not observed in pollinic zone a, appeared as traces in zone b and remained present, with pollen-grain contents temporarily higher during the sub-Boreal in zones e and f and up to about 20% of catchment taxa in zone j.

Wetland vegetation (palaeolake edge) was also characterized by the predominance of arboreal taxa (mainly *Alnus*, with *Fraxinus* and *Salix*) during the Atlantic and sub-Boreal (Figure 7D), with greater and more frequent variations in the abundance of arboreal taxa during the Atlantic (30–80% arboreal pollen grains dominated by *Fraxinus*: zones a to d) than during the sub-Boreal (55 to 85%, dominated by *Alnus*: zones e, f and g). Arboreal taxa decreased sharply at the end of this period (5%, bottom of zone i). During the sub-Atlantic, arboreal taxa first increased (up to 50%, zone i), then decreased sharply (5–20%, zone j). Areas without forest were mainly covered by Cyperaceae which were particularly abundant at the end of the sub-Boreal (zone h) and at the beginning of the sub-Atlantic (zone i). Aquatics sometimes appear.

Chenopodiaceae (Figure 7C) were always present, but more abundant at the beginning of the Atlantic (zone a: up to 15% of total pollen grains), temporarily during the sub-Boreal (zones f and h) and sub-Atlantic (zones i and j). Tertiary taxa (mainly Gymnosperma) were always present (Figure 7B), often forming 10% of total pollen grains, particularly during periods of catchment arboreal taxa decrease, but they were as high as 90% in pollinic zone e at the beginning of the sub-Boreal.

### Archaeology

Surface archaeological survey results have been described in detail by Trément *et al.* (2007b). They are summarized in Figures 8 and 9. Evidence for the Neolithic is found in 21 sites (S), 7 probable sites (PS) and 12 isolated artefacts (IA) observed on the land

surface within the Sarliève catchment (Figure 8A). Evidence for the early Neolithic (Recent Cardial) has been found, although poor, while evidence for the late/final Neolithic, difficult to identify, is sparse and mainly located in high elevation areas. Evidence of the middle Chassean Neolithic dominates (17S, 3PS and 5IA), mainly located on slopes of the Plateau de Gergovie on the west and slopes of the Puy d'Anzelle and Puy de Bane on the east of the catchment.

There is particularly abundant evidence of the ancient Bronze Age (14S, 6PS and 11A), especially on the Plateau de Gergovie and Puy d'Anzelle slopes, and always at an elevation above 360 m (Figure 8B). There is some evidence of the middle Bronze Age (5S, 1PS and 11A) at the same location as evidence of the ancient Bronze Age and above 370 m. There is abundant evidence of the final Bronze Age (10S, 3PS, 11A) and 1 funerary site (FS); they are mainly located on western and eastern catchment slopes, and the funerary site is the first evidence of human settlement in the Sarliève depression at an elevation of 346 m.

Evidence of the first Iron Age is very abundant (17S, 7PS), mainly on slopes, from the eighth century BC. This evidence is not found on the plateau, but in areas close to the palaeolake. There is only a little evidence of the ancient and middle La Tène (fifth–third centuries BC) (7S, 4PS, 11A and 3FS), mainly found at low elevation (387 m on average). Human pressure increased sharply during the final La Tène (second–first centuries BC) (Figures 8C and 9): 24S, 15PS and 2FS, especially at lower elevations (53% of evidence is found below 350 m), at the edge of the eastern alluvial terrace close to the palaeolake and in the northern outlet area, although the whole catchment was settled by humans at that time. Off-site pottery resulting from farming-related soil enrichment is closely associated with sites. Land parcels with boundary markings and drainage ditches, dating from the second half of the first century BC, have been discovered at the bottom of the lacustrine depression.

**Table 1.** Data for sediment yield calculation, and rates of solid and dissolved sediment yield per lacustrine sediment unit. (1) Sediment yield; (2) dissolved sediment yield; (3) solid sediment yield

Sediment units	Age (kyr cal. BP)	Deposition duration (yr)	Precipitated components (%)	Detrital components (%)	Volume (10 <sup>6</sup> m <sup>3</sup> )	Volumetric mass (t/m <sup>3</sup> )	Mass (10 <sup>6</sup> t)	SY (1) surface area (km <sup>2</sup> )	DSY (2) (t/km <sup>2</sup> per yr)	SSY (3) (t/km <sup>2</sup> per yr)
delta basin										
D8	1.6–0.3	1300	0	100	0.516	1.5	0.773	23.8	0	25
D6+D7	1.8–0.3	1500	20	80	4.083	2	8.165	24.5	44	178
D5	5.3–2.3	3000	20	80	8.56	1.75	14.98	24.9	40	160
D4	5.3–2.3	3000	0	100	0.025	1.5	0.038	24.9	0	0.5
B3	7.5–5.3	2200	< 10 to 60 (very variable)	40 to > 90 (very variable)	4.61	0.75	3.457	25.6	6.1(21.5)36.8	24.6(39.9)55.3
B2	9.8–7.5	2300	30 to 60 (from bottom to top)	70 to 40 (from bottom to top)	0.937	1	0.937	26.6	4.6(6.9)9.2	6.1(8.4)10.7
D3	11.5–10.4 ?	1100 ?	0	100	0.102	1.5	0.153	24.9	0	6
B1	13.7–9.8	3900	40	60	0.862	0.95	0.819	27.3	31	46
T1+D2	13.7–11.5	2200	0	100	0.676	1.5	1.014	24.9	0	19
D1	15.0 ?–13.7	1300 ?	30	70	0.526	1.75	0.921	25.8	8	19

The early Roman Empire (first–second centuries AD) is characterized by a sharp increase in signs of settlement (57S, 31PS and 11FS) throughout the catchment (hilltops, slopes, edge and bottom of lacustrine depression); mean elevation of sites is low: 390 m. The off-site pottery area is widespread. Sites were either vast agricultural domains (or *villae*) (Trément, 2007b), or buildings belonging to the *villae*, or small farms. During the late Roman Empire (third–fifth centuries AD) (Figures 8D and 9), only 17 of the former 57 sites remained, mainly located at the edge of the palaeolake (mean elevation: 383 m), in the same place as the main early Roman Empire buildings (*villae*).

During the early Middle Ages, settlements were still few (5S, 4PS, 2IA and 2FS) and always located at very low elevations (mean: 351 m): slopes and plateaus seem to have been deserted. The off-site pottery area was also less extensive than during the early Roman Empire. Four of the five sites were occupied continuously from the final La Tène and became vast seigniorial domains during the Middle Ages.

Archaeological excavations carried out before the construction of the ‘Grande Halle d’Auvergne’ (Vernet et al., 2005; Trément et al., 2007b) discovered a funerary site with a tumulus dating from the final Bronze Age and extensive settlement between the third century BC and second century AD at the northeastern edge of the palaeolake. During the La Tène period, settlement, comprising workshops, wells and burial places, was highly structured with enclosures and drainage networks. There is evidence of human activity (wells, parcels with boundary marking) on the northern lacustrine depression bottom at the time of the Roman conquest (Gergovia battle: 52 yr BC) and during the early Roman Empire (buildings, collection of spring water, funerary sites) up to the third century AD. Evidence of fisheries dating back to the Middle Ages and Modern Times have also been found.

## Discussion

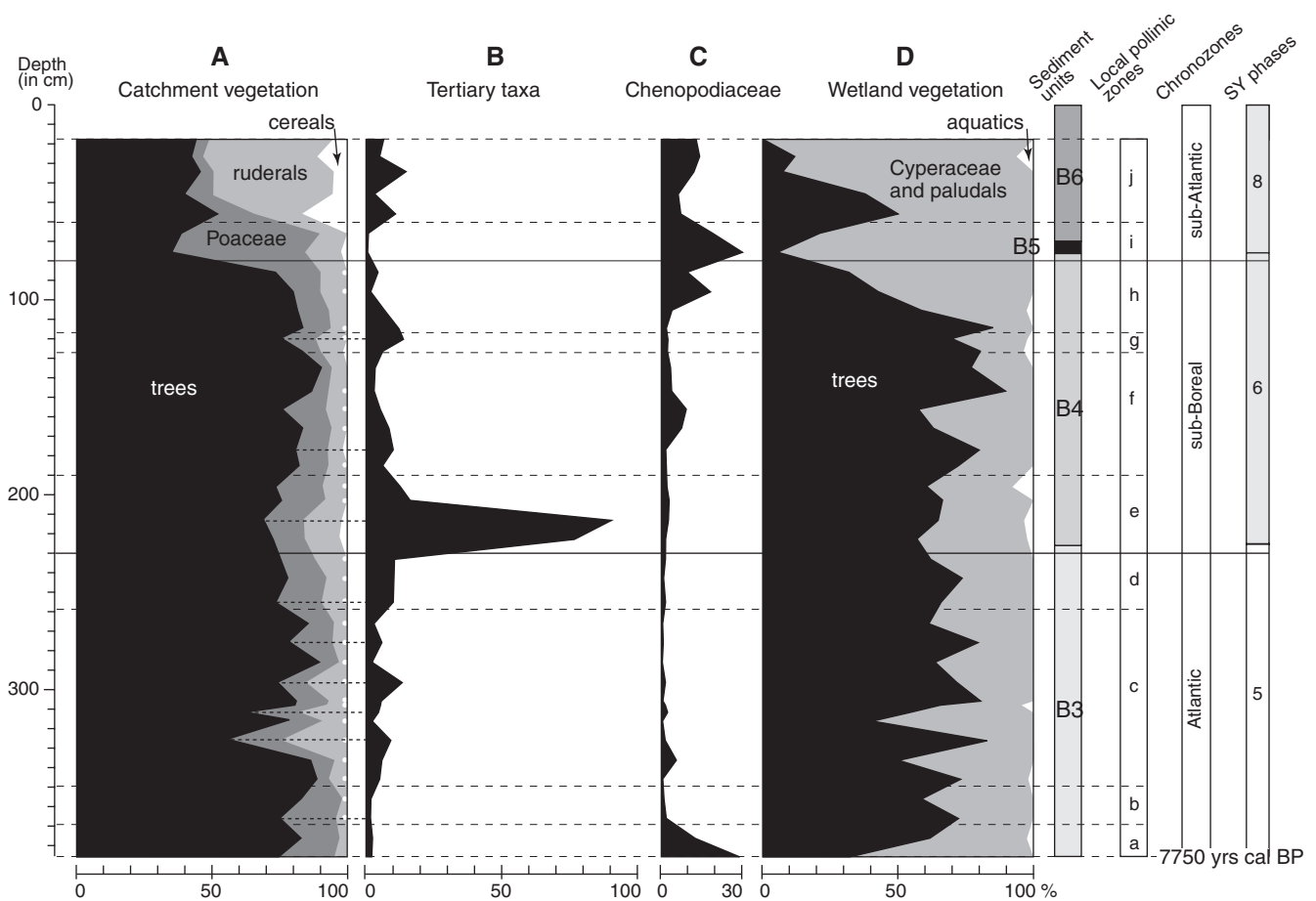
### Significance of rates and phases of sediment yield

Calculated TSY, SSY and DSY rates are averages for the whole sediment yield surface area (27.3 to 23.8 km<sup>2</sup> according to period, Table 1). In the catchment, spatial distribution of SY varied according to earth surface conditions, particularly slope gradient (0–49°) and lithology (dominance of basalt or limestone and marl) (Figure 5). Moreover, SY rates are averages of SY phases whose duration depends on datation possibility and during which SY could vary due to catastrophic climatic events when retention rates of particles in the lake might have been low (Brune, 1953). Nine sediment yield phases (SYp1 to SYp9) were identified covering the main chronozones of the Lateglacial and Holocene (Figure 6).

Calculated SSY rates (Figure 6B) are minimum rates which can be considered close to true rates because many factors are favourable to high palaeolake-trap efficiency (Heineman, 1984; Einsele and Hinderer, 1998): high lake/catchment area ratio (average of 0.16), lake often closed or shallow when open, lake water rich in Ca<sup>2+</sup> and Mg<sup>2+</sup> favouring clay flocculation, and inflow mainly due to runoff with no river. During the Lateglacial and early and middle Holocene (SYp1 to 5), endorheism is shown in basin sediments by abundance of minerals (analcite, dolomite, aragonite) resulting from chemical or biochemical precipitation in salty water. Particle retention in the palaeolake was favoured by

**Table 2.** Rates of solid and dissolved sediment yield per sediment yield (SY) phase. (1) Dissolved sediment yield; (2) solid sediment yield; (3) total sediment yield

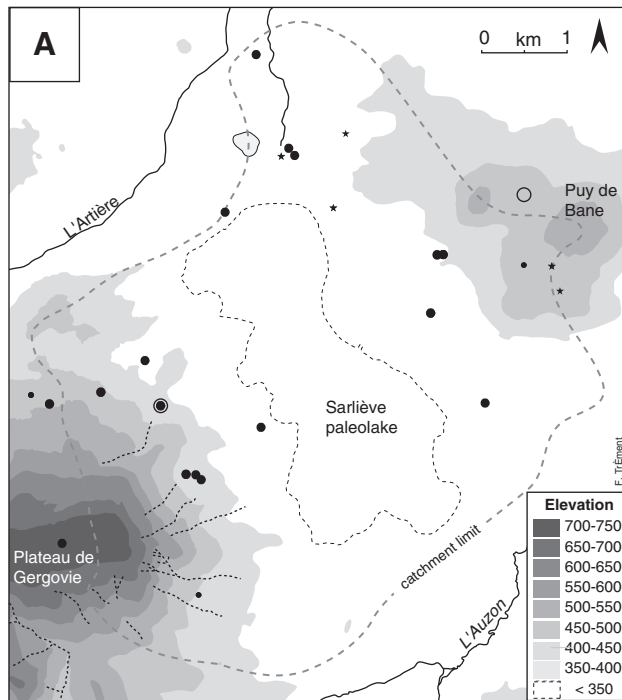
SY phases	Ages (kyr cal. BP)	Sediment units	DSY (1) (t/km <sup>2</sup> per yr)	SSY (2) (t/km <sup>2</sup> per yr)	TSY (3) (t/km <sup>2</sup> per yr)	DSY/SSY ratio
SYp9	0–0.3	<i>no sediments</i>	?	?	?	?
SYp8						
b	0.3–1.6	D6+D7+D8+B5+B6	44	203	247	0.22
a	1.6–1.8	D6+D7+B5+B6	44	178	222	0.25
SYp7	1.8–2.3	<i>no sediments</i>	?	?	?	?
SYp6	2.3–5.3	D4+D5+B4	40	161	201	0.25
SYp5	5.3–5.5	B3	6	55	61	0.11
	5.5–7.5	B3	37	24	61	1.54
SYp4	7.5–8.2	B2	9	6	15	1.50
	8.2–9.8	B2	4	11	15	0.36
SYp3						
b	9.8–10.4	B1	31	46	77	0.67
a	10.4–11.5	D3+B1	31	52	83	0.60
SYp2	11.5–13.7	T1+D2+B1	31	65	96	0.48
SYp1	13.7–15.0	D1	8	19	27	0.42



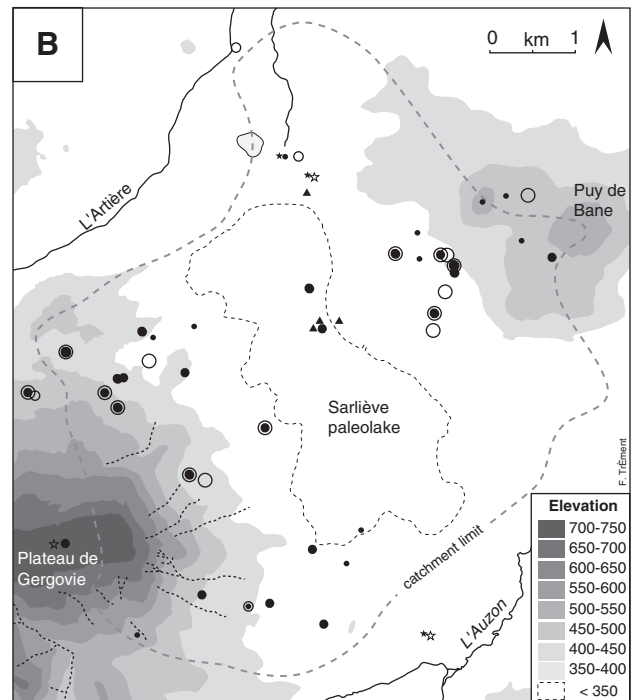
**Figure 7.** Pollen diagrams from P core (location, see Figure 4B). (A) Catchment vegetation as per cent of total catchment taxa. Trees: *Corylus*, *Quercus*, *Ulmus*, *Tilia*, *Betula*, *Fagus*, *Abies*, *Juniperus*, *Hedera*, *Acer*, *Picea*, *Pinus*. Ruderals (except Chenopodiaceae): *Artemisia*, Asteraceae, *Carduus*, *Centaurea*, *Cuscuta*, Brassicaceae, Cichorioideae, *Convolvulaceae*, Caryophyllaceae, Malvaceae, *Apiaceae*, *Plantago*, *Rumex*, Rubiaceae, Fabaceae, Lamiaceae, *Urticaceae*, *Polygonum*. (B) Tertiary taxa as per cent of total pollen grains. (C) Chenopodiaceae as per cent of total pollen grains. (D) Wetland vegetation as per cent of total wetland taxa. Trees: *Alnus*, *Salix*, *Fraxinus*, *Ligustrum*, *Viburnum*, *Myrica*, *Sambucus*, *Vitis*. Cyperaceae and paludals: *Filipendula*, *Thalictrum*, Typhaceae. Aquatics: *Potamogeton*, *Lemna*

endorheic conditions (Einsele and Hinderer, 1998) which were continuous until the beginning of the Atlantic and then intermittent until the beginning of the sub-Boreal (Bréhéret *et al.*, 2003, 2008; Fourmont *et al.*, 2006). During the late Holocene (SYp6 and 8),

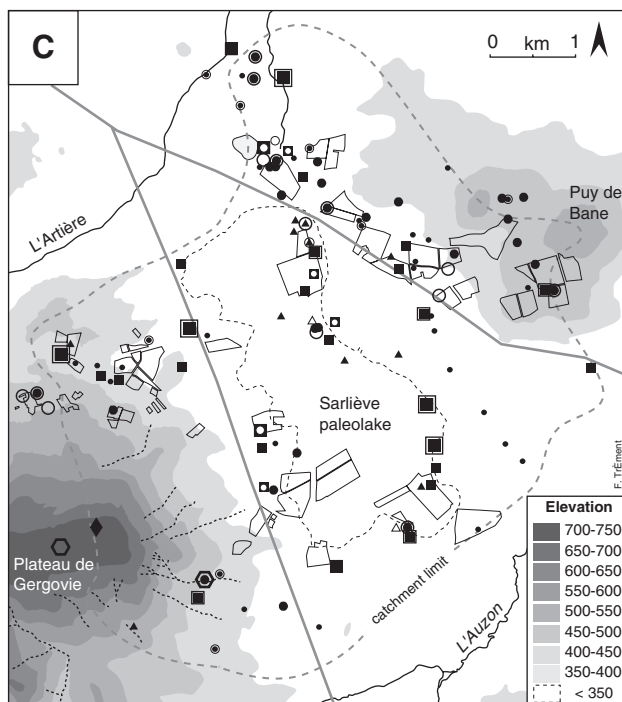
the fact that only precipitated low-Mg calcite is found in sediments is the consequence of open conditions – an extensive freshwater lake with fluctuating water level, as shown by non-pollinic microfossils (Argant and Lopez-Saez, 2004), and probable frequent



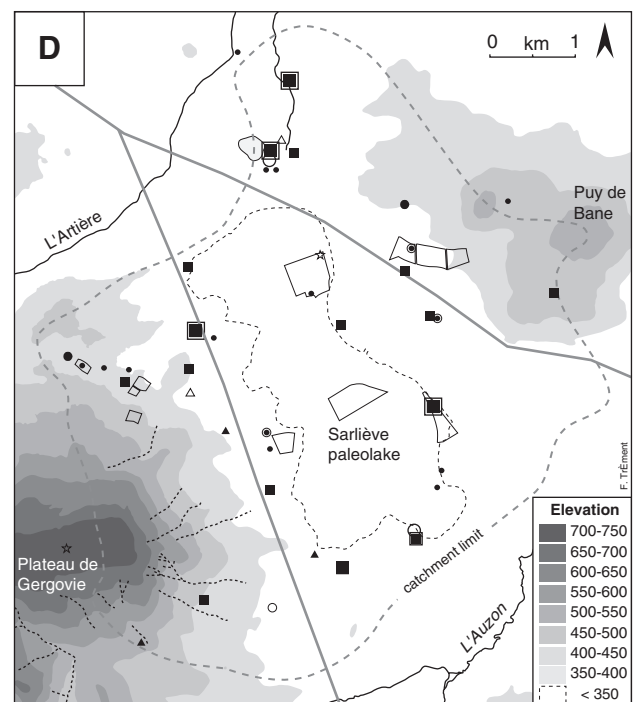
Ancient Neolithic: ○ Probable site  
 Middle Neolithic: ● Site ● Probable site ☆ Isolated artefact



Ancient and Middle Bronze Ages: ○ Site ○ Probable site ☆ Isolated artefact  
 Final Bronze Ages until Ancient La Tène: ● Site ● Probable site ☆ Isolated artefact  
 ▲ Funerary site



Final La Tène: ○ Agglomeration ○ Site ○ Probable site △ Funerary site  
 Early Roman Empire:  
 ■ Large villa ■ Small villa ● Site ● Probable site ▲ Funerary site  
 ◆ Sanctuary □ Large villa with Final La Tène traces ☆ Isolated artefact  
 □ Small villa with Final La Tène traces — Roman road □ Off-site pottery

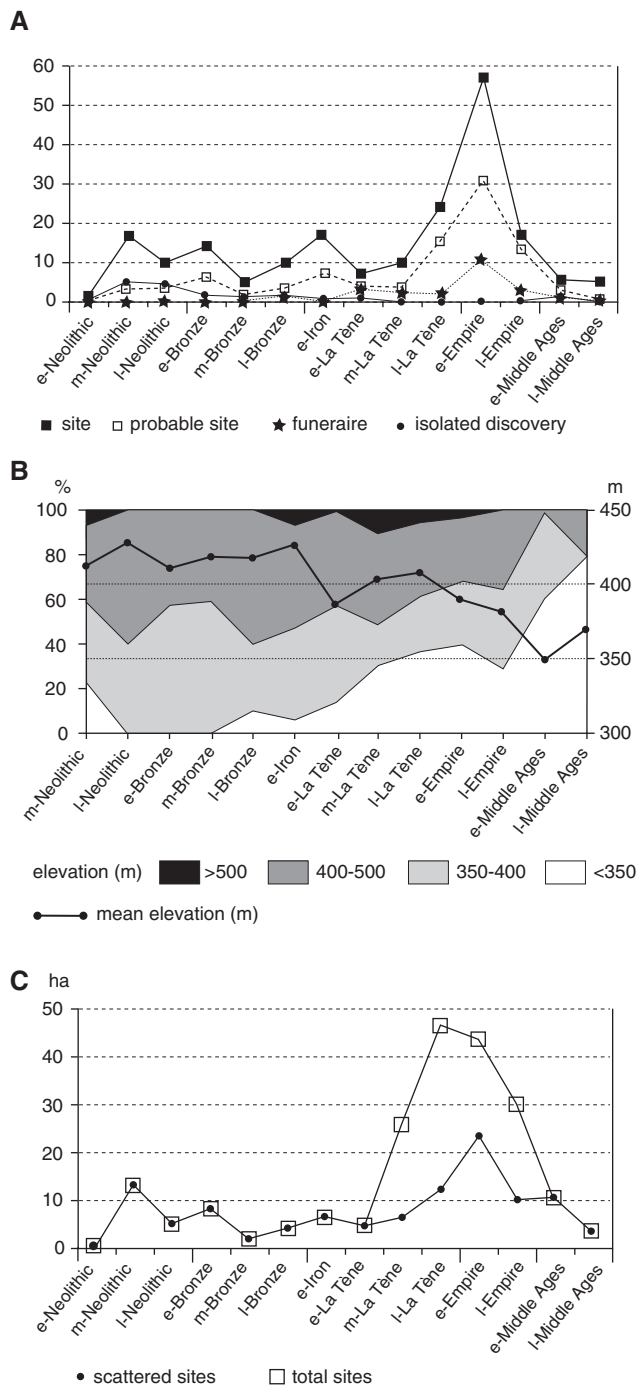


Late Roman Empire:  
 ■ Large villa ■ Small villa ● Site ● Probable site ▲ Funerary site  
 — Roman road □ Off-site pottery  
 Early Middle Ages:  
 ○ Site ○ Probable site △ Funerary site ☆ Isolated artefact

**Figure 8.** Location maps of human settlements in Sarliève catchment at different periods. (A) Ancient and middle Neolithic; (B) Bronze Ages up to ancient La Tène; (C) final La Tène and early Roman Empire; (D) late Roman Empire and early Middle Ages

outflow and loss of solid matter downstream of the lake during highstand periods. Although sediment storage increased markedly at this time (Table 1), SY may be slightly underestimated. Very

abundant slope formations (74.5% of catchment area: Figure 5B) are mainly due to periglacial processes (rock fall, solifluxion: Jeambrun *et al.*, 1973) and thus prior to lake formation. Colluvium



**Figure 9.** Statistics of archaeological sites by period. e, early; m, middle; l, late. (A) Site numbers; (B) abundance of sites as per cent of elevation class, and mean elevation of sites in metres; (C) cumulated surface area of sites in ha

rich in organic matter containing archaeological artefacts (Vernet *et al.*, 2005) and clearly the result of Holocene soil erosion, is mainly located on the edge of the palaeolake. As it is not widespread in the catchment, it was not quantified.

Evaluating real DSY rates is difficult because of high discharge of dissolved matter downstream of the lake during high-water periods (Fourmont *et al.*, 2009). DSY rates during the Lateglacial and early Holocene (SYp1 to SYp4) are probably close to gross rates resulting from the endorheic conditions of the palaeolake (Einsele and Hinderer, 1998). During the middle and particularly the late Holocene, because the basin was open more often, first for

short periods (SYp5), then more continuously (SYp6 and 8) when the palaeolake spread out and detritism increased, DSY rates are probably grossly underestimated, although they were high during the sub-Boreal and sub-Atlantic (Figure 6C).

The Sarliève catchment is located in medium-sized mountains where slope gradients are low ( $< 5^\circ$  for 60% of the catchment area; Figure 5) and carbonated rocks dominate (about 75% of the area; Figure 1B). SSSY and DSY rates for the most recent period (178 to 203 and 44 t/km<sup>2</sup> per yr, respectively for SYp8) are a little higher than those assessed from current river flux (Meybeck, 1979; Milliman and Meade, 1983) and as high as soil erosion rates (Cerdan *et al.*, 2006) in similar physiographic and bioclimatic environments. Nevertheless, because of the climate characteristics of the Sarliève environment, lower rates could be expected. This suggests that SY rates calculated from Sarliève sediment stores, although minimum, are quite close to gross erosion rates.

Sediment yield is mainly related to soil erosion. Assuming that the mean volumetric mass of eroded soils is 2 g/cm<sup>3</sup>, it is possible to convert the sediment yield (in t/km<sup>2</sup> per yr) in catchment-soil erosion rates (in mm/yr). During SYp1 to 5 as there is no colluvium of this time on slopes and SY calculated values are close to true sediment flux values, we assumed that SY rates correspond to erosion rates. During SYp6 and 8, because of colluvium stores on slopes and matter delivery downstream the lake, erosion rates deduced from SSSY rates are evidently underestimated, especially DSY.

During the Lateglacial and Holocene, TSY, SSSY and DSY varied greatly (Figure 6). Examination of archaeological and palynological data provides clear indication of two periods in the evolution of the palaeoenvironment: the first before 7500 yr cal. BP during which SY was due only to natural bioclimatic conditions (SYp1 to 4), and the second, after this date, during which SY was also due to human impact (SYp5 to 9).

### **Sediment yield evolution before evidence of human impact (Lateglacial and early Holocene)**

While there is evidence of human settlement in the Sarliève catchment prior to the Neolithic, it is sparse (Pomel, 1853; Pommerol, 1877; Trément *et al.*, 2007b). Palynological data show no evidence of farming before the Atlantic (Gachon, 1963): cereals only appear in pollinic zone b (Figure 7A). Although ruderals were present from the beginning of the Atlantic, it is likely that variations in vegetation and hydrological processes influencing erosion prior to about 7500 yr cal. BP were only due to natural processes and climate change. During the Lateglacial and early Holocene, TSY was lower (mean 55 t/km<sup>2</sup> per yr) than subsequently, but variable (Figures 6A and 10): from 6 to 65 t/km<sup>2</sup> per yr for SSSY and 4 to 31 t/km<sup>2</sup> per yr for DSY, with a DSY/SSSY ratio of about 0.5.

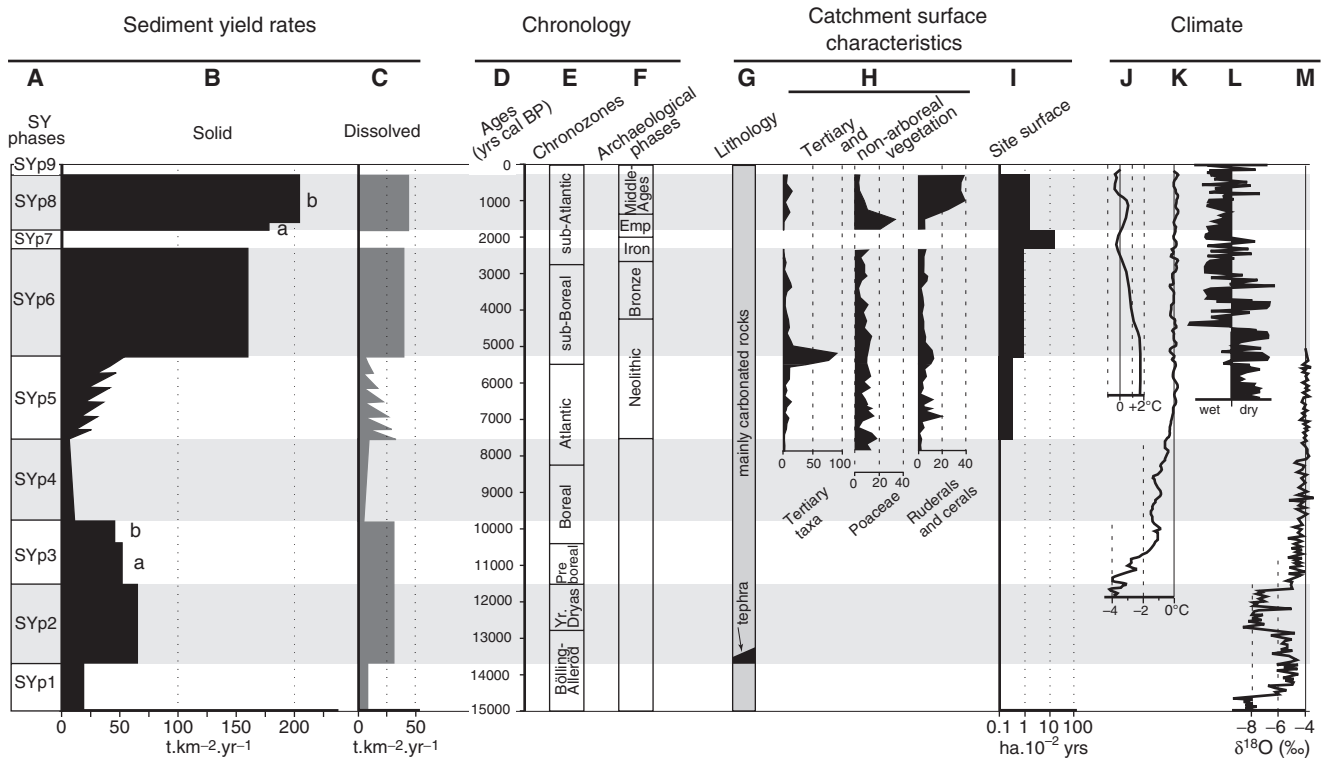
#### **Sediment yield phase 1 (SYp1)**

During SYp1 (Bölling and beginning of the Alleröd), very low SSSY and DSY rates could be due to the first postglacial development of arboreal cover with *Juniperus* and *Betula* (de Beaulieu *et al.*, 1988) which limited mechanical and chemical erosion during a cool period (Johnsen *et al.*, 1992).

#### **Sediment yield phase 2 (SYp2)**

Increased SSSY (65 t/km<sup>2</sup> per yr) during the Alleröd at 13 700 yr cal. BP, despite the continuation of previous bioclimatic conditions,





**Figure 10.** Comparison of sediment yield rates, chronology, catchment area characteristics and climate. (D) Ages in yr cal. BP; (H) tertiary taxa as per cent of total pollen grains; Poaceae, and ruderals and cereals as per cent of catchment-taxa pollen-grains; (J) temperature from Greenland ice-core (Johnsen *et al.*, 2001); (K) temperature from pollen data (Davis *et al.*, 2003); (L) humidity from bog (Barber *et al.*, 1994); (M) temperature from lake record (von Grafenstein *et al.*, 1999)

seems to be due to CF1 tephra fallout, with a mean depth of 15 cm (Vernet and Raynal, 2000). Tephric cover could have favoured mechanical erosion over several decades or centuries (Figure 10G) because of the temporary destruction of vegetation dominated by *Betula* and *Pinus* on slopes (de Beaulieu *et al.*, 1988), but mainly because of the high susceptibility of tephra to mechanical erosion (Chorley *et al.*, 1984; Collins and Dunne, 1986). Likewise, increased DSY (31 t/km<sup>2</sup> per yr) can be explained by high susceptibility to dissolution of tephra silicates, mainly glass (Fourmont *et al.*, 2006). These higher SSS and DSY rates continued during the Younger Dryas up to about 11 500 yr cal. BP, although tephric cover had probably been completely eroded by that time; Tertiary pollen-grain abundance in lacustrine sediments (Gachon, 1963) shows that mechanical erosion mainly cut into the Oligocene bedrock. During the cold and dry Younger Dryas (Petee, 1995; Anderson, 1997) (Figure 10M) mechanical erosion was favoured by tundra (de Beaulieu *et al.*, 1988), which does not provide efficient protection of the earth surface against erosion, as observed in the Lac Chambon catchment located in a granitic and volcanic area close to the Sarliève catchment (Macaire *et al.*, 1995, 1997). Nevertheless, high DSY indicates that the climate was fairly humid, and the dissolution of carbonated rocks could have been favoured by the cold climate.

#### Sediment yield phase 3 (SYp3)

At the beginning of the Holocene, between 11 500 yr cal. BP and 9800 yr cal. BP, SSS and DSY remained high, although the former fell to 46 t/km<sup>2</sup> per yr (Ep3b). At this time, forest developed, dominated first by *Corylus* and then *Quercus* and *Ulmus* (Gachon, 1963; de Beaulieu *et al.*, 1988), and the climate became warmer

(Johnsen *et al.*, 2001; Davis *et al.*, 2003) (Figure 10K,M). Gachon (1963) suggested that the abundance of *Chenopodiaceae* pollen grains in Sarliève sediments during the Lateglacial and early Holocene could have been due to slope-mass movement by solifluction, which could have contributed to the development of these pioneering taxa. The abundance of *Chenopodiaceae* at the beginning of the Atlantic (zone a, Figure 7C), when SSS was very low (6 t/km<sup>2</sup> per yr), indicates that there is no relationship between the abundance of this taxa and the intensity of mechanical erosion. On the other hand, *Chenopodiaceae* could have colonized the bottom of the lacustrine depression during drought periods, providing evidence of the presence of salt water as shown elsewhere by Valero-Garcés *et al.* (2000). Salt, also testified by precipitated minerals in B1 to B3 lacustrine units (Fourmont *et al.*, 2006; Bréhéret *et al.*, 2008), was produced by dissolution of gypsum forming a small part of Oligocene limestones and marls (Jeambrun *et al.*, 1973). Dissolution of catchment bedrock gypsum and calcite during SYp3 could indicate the beginning of pedogenesis during the early Holocene and is in accordance with a relatively high value of DSY (31 t/km<sup>2</sup> per yr). However, it was not possible to evaluate precisely the evolution of DSY rates from SYp2 to SYp3.

#### Sediment yield phase 4 (SYp4)

During the Boreal and the Atlantic before 7500 yr cal. BP, erosion rates, much lower than before and similar to SYp1, did not change significantly (SSS = 6 to 11 t/km<sup>2</sup> per yr and DSY = 4 to 9 t/km<sup>2</sup> per yr), although the DSY/SSS ratio increased (0.36 to 1.50; Figure 6D). This trend could be explained by extensive development of forest cover, dominated by *Corylus* and *Quercus* (de Beaulieu *et al.*, 1988; Gachon, 1963), related to climate warming

(Figure 10K,M), which provided efficient protection of the earth surface against mechanical erosion. Higher temperatures and less precipitation during the Boreal, testified in western Europe (Andrews, 2006) with minimum temperatures and dryness at about 8200 yr cal. BP in the Northern Hemisphere (Carrion, 2002; Alley and Agustsdottir, 2005; Macklin *et al.*, 2006), may have been more marked in the drier microclimate of Sarliève and could explain the low absolute value of DSY. Nevertheless, the sharp rise of the DSY/SSY ratio at this period, marked by catchment-slope stability, indicates a matter budget promoting an increase in soil depth.

### **Sediment yield evolution during periods of human impact (middle and late Holocene)**

TSY increased dramatically after 7500 yr cal. BP (average for SYp5, SYp6 and SYp8: 165 t/km<sup>2</sup> per yr): from 24 to 232 t/km<sup>2</sup> per yr for SSY and from 6 to 44 t/km<sup>2</sup> per yr for DSY. The DSY/SSY ratio decreased to close to 0.25, with considerable fluctuations during the Atlantic (SYp5) (Figure 6). This rise in sediment yield rate appeared concomitantly with the growth of human settlement in the Sarliève catchment (Figure 10I). Pottery dated from the end of the Ancient Neolithic, although scarce (two probable sites), provides evidence of human activity in the catchment; similar activity has also been observed in many places around Clermont-Ferrand from 7500 yr cal. BP (Georjon *et al.*, 2004; Pouenat, 2007). Human activity increased considerably after that period, with some fluctuations (Figures 8 and 9). Evidence of ruderals (zone a, Figure 7A) and cereals (zone b, Figure 7A) from the beginning of the Atlantic show that vegetation and earth surface conditions were modified by human activities from about 7500 yr BP. Human activity and climate together influenced erosion processes and intensity (Figure 10H–L).

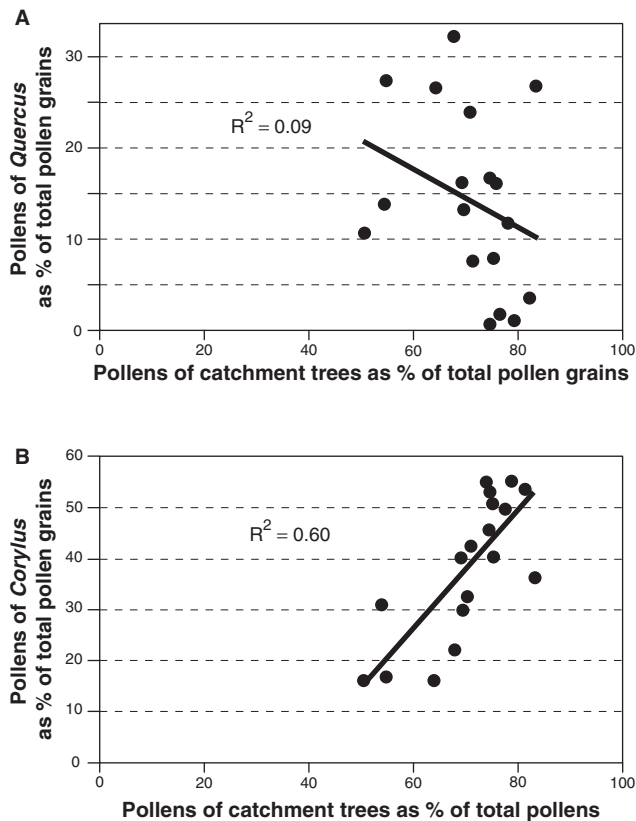
#### **Sediment yield phase 5 (SYp5)**

From the Atlantic after 7500 yr cal. BP to the beginning of the sub-Boreal at about 5300 yr cal. BP, sharp TSY increase (61 t/km<sup>2</sup> per yr) is characterized by strong variations in DSY/SSY ratio. Marked SSY increase (by a factor of nine maximum relative to SYp4) together with lower variation in DSY (increase by a factor of four maximum) is an indication of human impact (Dearing and Jones, 2003), although climate became a little more humid than before. SYp5 corresponds to the development of the Neolithic society and arable farming in the Massif Central (Georjon *et al.*, 2004), particularly widespread in the Sarliève catchment during the Chassean Middle Neolithic (Figures 8A, 9A). Evidence of farming is provided by cereal pollen grains (Figure 7A). Farming seems to have occurred mainly at elevations of 350 to 500 m (average 400–450 m, Figure 9B) where ancient and middle Neolithic sites cover a total area of about 13 ha (Figure 9C), corresponding to a mean time-weighted settlement area of 0.65 ha per century (Figure 10I). It is difficult to explain high variations of arboreal pollen grain contents in slope vegetation during the Atlantic (zones a, b and c Figure 7A) by climate change, which, although not marked, did occur (Aaby, 1976; Bond *et al.*, 2001; Douglas *et al.*, 2007). On the other hand, a sharp increase in ruderals (Figure 7A) and preferential decrease in *Corylus* (Figure 11B), which is more easily cut than *Quercus* (Figure 11A), during periods of slope arboreal pollen regression, could indicate human impact on deforestation. This seems to be confirmed by frequent

simultaneity between periods of deforestation and periods of high Tertiary pollen grain content (Figure 7B) and detrital layer deposition (HCS facies in B3), indicating increased mechanical erosion. In the lacustrine depression during SYp5, a marked variation of arboreal pollen contents (mainly *Alnus*) compared to Cyperaceae and paludals (Figure 7D), appears to be related to an alternation of biochemical dominated BL facies and low water level in the palaeolake on the one hand, and detrital dominated HCS facies and high water level observed in lacustrine sediments on the other (Fourmont *et al.*, 2009). Non-pollinic microfossils indicate the occurrence of livestock farming as early as pollinic zone c, which could explain the mesotrophic to eutrophic character of the palaeolake waters (Argant and Lopez-Saez, 2004). These marked variations in vegetation, hydrology and sediment supply in the lacustrine depression are similar to variations in the catchment vegetation. Low water level in the lake could be the result of increased evapotranspiration during afforestation in the catchment, and high water level due to increased runoff during deforestation. However, the relative impacts of climate versus human activity on hydrology and sediment yield are not yet clear because of the marked variability of sedimentary facies in unit B3. High resolution multiproxy analysis (at a centimetric scale) of this unit is in progress.

#### **Sediment yield phase 6 (SYp6)**

From the sub-Boreal after 5300 yr cal. BP up to 2300 yr cal. BP in the sub-Atlantic, increased TSY (201 t/km<sup>2</sup> per yr) and rising water level (Fourmont *et al.*, 2009) are in keeping with changes in the climate which became more humid between 5200 yr cal. BP and 4500 yr cal. BP (Barber *et al.*, 1994; Magny *et al.*, 2006) and cooler (Johnsen *et al.*, 2001), with greater cooling at about 2800 yr cal. BP (van Geel *et al.*, 1998) (Figure 10J,L). Nevertheless, a greater rise in SSY and DSY during SYp6 than SYp5 (by factors of 2.9 and 6.6, respectively, Figures 6B and C) cannot be explained solely by climate change which was not marked. The rise in SSY is synchronous with increased human settlement between the end of the Neolithic and the ancient La Tène as shown by the abundance of sites, particularly during the ancient Bronze Age, final Bronze Age and first Iron Age (Figures 8B and 9A): total surface area of sites varies between archaeological periods (Figure 9C), but the mean time-weighted site area increased more during SYp6 (0.92 ha/century) than SYp5 (0.65) (Figure 10I). These sites, located at elevations between 350 and 500 m from the final Neolithic until the middle La Tène (Figure 9C), were scattered between 700 m and the edge of the palaeolake (< 350 m) from the final Bronze until the middle La Tène, promoting transit of solid flux from top to bottom of slopes. During SYp6, forest cover on slopes, marked by the replacement of *Corylus* by *Fagus* (zones e to h, Figure 7A) was more continuous than during SYp5. Nevertheless, several maximum cereal-pollen contents, often synchronous with increased Tertiary taxa and slight forest regression (Figure 7A, B), show that human impact and mechanical erosion of bedrock could have been intense during certain periods (pollinic zone e in particular). These periods could correspond to rapid human population growth, as during the ancient Bronze Age (pollinic zone e) and ancient Iron Age (zone g) and explain the high overall SSY value during SYp6. The palaeolake water level, which was probably higher because of the more humid climate, varied as shown by non-pollinic microfossils (Argant and Lopez-Saez, 2004). At the edge of the palaeolake, where vegetation varied



**Figure 11.** Correlations between catchment arboreal taxa from total pollen grain percentages. (A) *Quercus* versus catchment trees; (B) *Corylus* versus catchment trees

more than on catchment slopes (Figure 7D), periods of Cyperaceae and paludal increase and arboreal taxa decrease can be explained by frequent variations in water level, recently emerged areas being colonized by hygrophilous herbs. Nevertheless, Cyperaceae probably indicate above all the occasional but increasing deforestation of the edge of the palaeolake by humans during SYp6, especially during the ancient La Tène (Figure 9B,C, and zone h Figure 7D), a period of extensive human settlement confirmed by increasing eutrophication of palaeolake water and evidence of livestock farming (Argant and Lopez-Saez, 2004). Periods of high deforestation round the palaeolake do not seem to be synchronous with that on catchment slopes (Figure 7A, D), indicating possible differences in land use from one area to another; as a result, matter produced by mechanical erosion could have moved spasmodically toward the lake.

Although calcite dissolution is favoured by a humid climate, the very high increase in DSY during SYp6 cannot be explained only by climate change. Dissolved matter is mainly composed of carbonate ions because of weathering of marly-calcareous bedrock. It is probable that strong soil rejuvenation by mechanical erosion reactivated the weathering of parent-rocks, and thus DSY, as suggested by Carson and Kirkby (1972) and observed in the nearby Chambon catchment by Gay and Macaire (1999). Low DSY/SSY ratio (# 0.25) expresses this imbalance in soil evolution.

#### Sediment yield phase 7 (SYp7)

It is not possible to evaluate sediment yield rates during SYp7, corresponding to the middle and final La Tène and the early Roman Empire (2300–1800 yr cal. BP), because there are no

sediment stores dating from these periods. Archaeological evidence such as drainage ditches, buildings, funerary sites, and off-site pottery for soil enrichment observed at the bottom of the lacustrine depression show that it was dry and mainly settled by humans at the end of the La Tène and during the early Roman Empire (Figure 8C). These dry conditions could have been partly due to a less humid climate at this time (Barber *et al.*, 1994; Magny, 2004) (Figure 10L), but were mainly the result of human activity as shown by drainage ditches and parcels with boundary markings in the depression (Trément *et al.*, 2007b). A marked rise in settlements on catchment slopes is shown by very abundant sites of the La Tène and early Roman Empire (Figure 9A), especially at low elevations (Figure 9B), and the high value of time-weighted surface area of sites (21 ha/century) (Figures 9C and 10I). Archaeological data (Trément *et al.*, 2007b) and the increasing extent of enriched soils (Figure 8C) indicate intense arable farming, suggesting a high erosion rate. The lack of deposits is due to the discharge of most solid and dissolved matter downstream of the catchment through efficient drainage ditches.

#### Sediment yield phase 8 (SYp8)

During the sub-Atlantic, from 1800 yr cal. BP until 300 yr cal. BP, TSY (222 to 247 t/km<sup>2</sup> per yr) increased slightly relative to SYp6 (by a factor of 1.1 to 1.2) (Figure 6A). After the great development of the final La Tène and early Roman Empire societies (SYp7), similar SY rates could be explained by a sharp reduction in the number and total surface area of sites (time-weighted surface area = 3.5 ha/century) during the late Roman Empire and early Middle Ages (Figures 8D and 9A,C), down to rates close to those for SYp6. Nevertheless, during SYp8, there was a marked decrease in *Pinus*-dominated forest on slopes (less than 50% of arboreal pollen grains, Figure 7A). Moreover, the increase in Chenopodiaceae initiated during the La Tène (Figure 7C) cannot be attributed to water salinity, as during the Lateglacial and early Holocene, within the context of high water levels and greater humidity, particularly during the last millennium (Barber *et al.*, 1994; Magny, 2004; Magny *et al.*, 2008) (Figure 10L); this taxa, with the increase in other ruderals, more likely indicates a strong anthropogenic impact on vegetation. The presence of pyrofusinite-type charcoal fragments (Fourmont, 2005) and fungi growing on charred tissue (Argant and Lopez-Saez, 2004) in black clayey-silty B5 unit, are also evidence of frequent fires during the late Roman Empire, probably for soil enrichment rather than due to forest clearing for farming which was already extensive. The deforested area was first colonized by grassland (zone 1, Figure 7A) for livestock as shown by coprophilous fungi and evidence of palaeolake eutrophication. Despite this high anthropogenic impact on vegetation, low SSY increase during the late Roman Empire (SYp8a) could be explained by the development of grassland at different slope elevations (Figure 9B) down to the edge of the palaeolake where trees almost disappeared (Figure 7D); pastureland provides efficient protection of the earth surface against mechanical erosion, except when overgrazed (Ursic and Dendy, 1965; Pimentel *et al.*, 1995; Hooke, 2000).

From the beginning of the Middle Ages, croplands developed on catchment slopes, as shown by increased cereal and fallow-land taxa (zone j, Figure 7A), while palaeolake eutrophication was at its highest (Argant and Lopez-Saez, 2004). Settlement sites, less numerous and extended than before, were concentrated around the palaeolake (Figures 8D and 9B). During SYp8b (the Middle Ages

and Modern Times), high SSY (203 t/km<sup>2</sup> per yr) mainly due to mechanical erosion of sandy-gravelly sediments from the alluvial terrace east of the palaeolake (Figure 1), which produced D8 deltaic unit, could be the result of agricultural concentration in this area. Moreover, colluvium overlying archaeological sites of the late Roman Empire and early Middle Ages at the slope bottom indicates increased mechanical erosion after these periods. This colluvium storage could have been promoted by temporary afforestation (*Alnus*) round the palaeolake (first part of zone j, Figure 7D). These colluvium stores were not taken into account when quantifying SYp8b SSY which is thus underestimated. Rates of DSY (minimum of 44 t/km<sup>2</sup> per yr) and the DSY/SSY ratio (# 0.25) do not differ much from SYp6 rates, showing similar pedogenetic conditions with high soil rejuvenation by mechanical erosion.

#### *Sediment yield phase 9 (SYp9)*

SY cannot be evaluated for the last three centuries as sediment yield has been discharged downstream of the Sarliève catchment through ditches, called 'rases', since the palaeolake was drained during the seventeenth century (Fournier, 1996).

### **Balance of climate change versus human impact on sediment yield, earth surface lowering and soil evolution**

During the Lateglacial and early Holocene (SYp1 to SYp4), SSY and DSY rates, lower on average than later, depended mainly on strong climate change, from cold to warm, with a general trend towards dryness (Figure 10). Highest SSY rates (SYp2 and SYp3) correspond to the coldest periods (essentially the Younger Dryas and Preboreal), while lowest rates (SYp1 and SYp4) correspond to vegetation development during warmer periods (Bölling-Alleröd and Boreal). These erosion trends are similar to those observed in the Lac Chambon catchment (Macaire *et al.*, 1997; Gay and Macaire, 1999), located close to the Sarliève catchment but at a higher elevation and in a crystalline bedrock area, confirming regional climate impact on sediment yield. The trend in SSY values at Sarliève differs from that observed in mountainous areas where abundant inherited glacial deposits induced high SSY after glacier retreat (Church and Ryder, 1972; Bichet *et al.*, 1999; Hinderer, 2001). However, in the Sarliève catchment, climatic impact on SY was disturbed by CF1 tephra fallout at 13 700 yr cal. BP, leading to increased SSY from the Alleröd, before the climate change of the Younger Dryas, confirming strong and short-term impact of surface formations on mechanical erosion. The trend in DSY values is fairly similar to SSY (Figure 10B and C), with an increase during cold periods. However, temperature, relative to precipitation, is not the main factor of carbonate dissolution (Gombert, 1997), and the similar DSY and SSY trends suggest that mechanical erosion favoured chemical erosion through soil rejuvenation, so that parent-rocks, which are more susceptible to dissolution, were found close to the earth surface (Carson and Kirkby, 1972; Berner and Berner, 1987; Gabet and Mudd, 2009); carbonated rocks, and temporarily tephra, were particularly reactive to this process.

During the late Holocene (SYp6 and SYp8), increasing SSY and DSY are in keeping with lower temperatures and rising precipitation after 5200 yr cal. BP (Johnsen *et al.*, 2001; Barber *et al.*, 1994). However, SSY and DSY during the Holocene (SYp4–SYp8), when there was no marked climate change, varied extensively

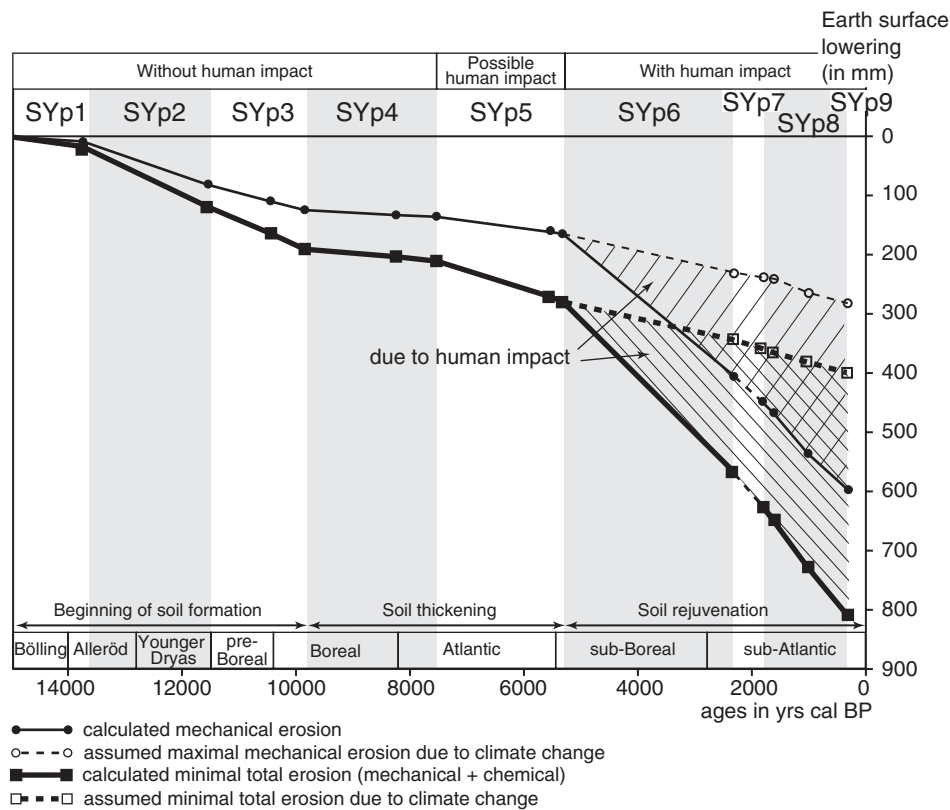
(by factors of > 38 and > 11, respectively), while they varied less (by factors of 11 and 8, respectively) during the Lateglacial and early Holocene (SYp2–SYp4) which was marked by considerable climate change. Thus, increased SY rates during SYp6 and SYp8, particularly SSY, seem to be highly related to the growth of human activity.

SSY (174 t/km<sup>2</sup> per yr on average for SYp6 and SYp8) rose by a factor of 6.4 (i.e. 540%) during the late Holocene compared with earlier Holocene periods (27 t/km<sup>2</sup> per yr on average for SYp3 to SYp5), while precipitation is assumed to have risen by 50 mm to 100 mm (Guiot *et al.*, 1989), i.e. about 10%, during the sub-Boreal and sub-Atlantic. Any increase in rainfall may directly exacerbate erosion (Boardman, 1990; Bullock, 1991), but the relationship between these two factors is not linear: a 10% increase in winter rainfall can induce an increase in mechanical erosion of up to 150% (Favis-Mortlock and Boardman, 1995). Nevertheless, this assessment concerns currently tilled soils which are particularly susceptible to mechanical erosion, while precipitation at the beginning of the Holocene rose in extensively forested environments. SSY does not seem to have increased by more than 150% as a result of rising precipitation and erosion, taking all other environmental parameters as constant. SSY could have increased by at least 390%, i.e. 75% of total increase, as a result of human activity during the final Neolithic, probably exacerbated by climate change. SSY increased more in SYp5 than SYp6, and less in SYp6 than SYp8, with a break in the intensity of erosion during the final Neolithic, which is a little earlier than the break observed by Miras *et al.* (2004) in the higher Massif Central. As there are few final Neolithic sites at Sarliève, this break could be a delayed effect of human settlement during the middle Neolithic, as observed elsewhere (Edwards and Whittington, 2001); forest cover was still abundant at this time and could have slow down the solid flux delivery to the palaeolake. Soil use changes during the Protohistorical and Historical periods do not seem to have significantly affected mechanical erosion intensity before the seventeenth century.

DSY increase during the late Holocene is more difficult to explain, as their rates are certainly strongly underestimated for the sub-Boreal and sub-Atlantic. Taking all other environmental parameters as constant, a 10% increase in water infiltration into the soil and a 1.5°C drop in the mean temperature at about 4500 yr cal. BP could have led to an increase in chemical erosion (calcite dissolution) of less than 15%. Thus, at least 90% of the DSY increase (overall 180%) between SYp5 and SYp6 could also be anthropogenic, increased SSY reactivating DSY. The impact of climatic versus anthropogenic factors on SY during SYp5, a period characterized by very variable SSY and DSY rates and the development of ancient and middle Neolithic society, is currently being investigated.

From estimation of mean eroded soil thickness from SSY and DSY rates and duration of each SY phase, three distinct periods can be identified (Figure 12): (1) from the Bölling to the beginning of the Boreal (SYp1 to SYp3), total earth surface lowering in the catchment was about 20 cm thick; soil thickness was low as shown by relatively constant and low DSY/SSY ratio (# 0.5) in environments marked by cold and dry climate and sparse vegetation; (2) during the Boreal and Atlantic, during which erosion rates were probably still close to SY rates, total erosion was low (8 cm thick) with rise in soil thickness shown by high DSY/SSY ratio (up to 1.5) as a result of vegetation cover growth and warmer climate, although the lower ratios during SYp5 could indicate the beginning of anthropogenic impact; (3) during the sub-Boreal and





**Figure 12.** Evaluation of earth surface lowering and soil thickness from sediment yield rates since the Lateglacial

sub-Atlantic, soil erosion rates were much higher than SY rates: total erosion greatly increased (55 cm thick at least) with extensive soil rejuvenation and thinning characterized by a pronounced lowering of the DSY/SSY ratio (# 0.25). This trend appears to be a consequence of human activity which is assumed to have accounted for more than 75% of SSY and 90% of DSY, compared with SY rates resulting only from climate during the late Holocene.

### Conclusion

By quantifying stored sediment mass in the Sarliève palaeolake it was possible to calculate minimum solid (SSY) and dissolved (DSY) sediment yield rates for seven phases (SYp1 to SYp6 and SYp8) between about 15 000 yr cal. BP and 300 yr cal. BP; phases SYp7 and SYp9 were marked by anthropogenic drying of the lake and lack of sediment stores. During the Lateglacial and early Holocene up to 7500 yr cal. BP, SSY and DSY rates, lower on average than later, varied mainly in relation to climate change: higher rates (SYp2 and SYp3) correspond to colder periods (Younger Dryas and Preboreal), while lower rates (SYp1 and SYp4) correspond to periods of warmer climate (Bölling-Alleröd and Boreal). However, CF1 tephra fallout at 13 700 yr cal. BP induced greater SY during the Alleröd. After 7500 yr cal. BP, the middle and late Holocene are marked by a sharp increase in SSY and DSY, reaching a peak during the final Neolithic after 5300 yr cal. BP. Comparison of SY rates with quantified data of human settlement, and palaeoclimatic and palynological data, indicates that after 5300 yr cal. BP, when the climate became cooler and more humid, at least 75% of SSY increase and more than 90% of DSY increase were due to human activities. Changes in soil use during the Protohistoric Times (SYp6) and the Historic Times up to the seventeenth century (SYp8)

did not significantly alter SY rates. Extensive vegetation clearing due to climate change during the Younger Dryas and to human activity during the Historic Times can explain periods of severe mechanical erosion at some places (delivery of coarse-grained deltaic sediments) during SYp2 and SYp8. Catchment-soil evolution deduced from DSY and SSY rates and DSY/SSY ratio indicate that soils began to be formed during the Lateglacial and Preboreal, then thickened considerably during the Boreal and Atlantic, and finally became thinner (rejuvenation) mainly as the result of human-induced erosion during the sub-Boreal and sub-Atlantic. Severe mechanical erosion during the late Holocene induced a sharp rise in chemical erosion, which was favoured by the presence of mainly carbonated rocks in the catchment.

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