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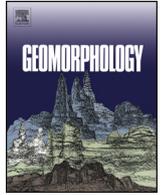
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Headwater valley response to climate and land use changes during the Little Ice Age in the Massif Central (Yzeron basin, France)



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ABSTRACT

The geomorphological response of valley bottoms in eastern France to climatic fluctuations of the Little Ice Age (LIA) was investigated using sedimentological analysis together with optically stimulated luminescence (OSL) and radiocarbon dating. Diachronic mapping of land use since the beginning of the nineteenth century was also carried out. Since A.D. 1500, the valley bottoms experienced three cycles of aggradation and subsequent incision, each characterized by paired periods of high and low detritic activity. While the impact of human activity on the aggradation of the alluvial plain is observed, the vertical dynamics of the valley bottom deposits seemingly were also linked to the hydroclimatic fluctuations during the LIA. The sensitivity to these fluctuations was increased by human activity at the scale of the basin. Variations of the winter North Atlantic Oscillation (NAO) and solar activity from the last five centuries correlate with wet and cold phases during which valley bottoms accumulated, and dry and warm phases during which the streams incised into the valley floors. This fluvial sensitivity to the meteorological conditions induced temporal variations in sedimentary supply originating from either direct input from remnants of periglacial alluvial sheets or local rocky outcrops and/or from indirect input from the erosion of alluvial and colluvial deposits. These two components, combined with the sheet runoff over the ploughlands, express the complex coupling between hillslopes and valley bottoms in the headwater catchments. This caused a cascade-shaped transit of the sediments characterized by alternating phases of storage and removal.

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1. Introduction

The Little Ice Age (LIA) is the last pronounced period of climate cooling, which was defined by historians and Earth Sciences as comprising *stricto sensu* A.D. 1550–1850 (Lamb, 1977; Grove, 1988; Acot, 2005). This episode is marked by a significant advance of Northern Hemisphere glaciers owing to long and severe winters and relatively cool and wet summers. These climatic conditions are particularly well documented by historical climatology studies through the evolution of the grape harvest dates (Dufour, 1870; Angot, 1883; Le Roy Ladurie, 1967; Chuine et al., 2004; Meier et al., 2007; Garnier et al., 2011; Daux, 2012) and the comparison of iconographic representations of glaciers (Le Roy Ladurie, 1967; Nussbaumer et al., 2012; Zumbühl and Nussbaumer, 2012). Some work has also been conducted on the geomorphological

evolution of rivers and valley bottoms since the Medieval Climate Optimum (Bravard, 1989, 2000; Rumsby and Macklin, 1996; Gob, 2005; Gob et al., 2008; Jacob-Rousseau and Astrade, 2010, 2014; Macklin et al., 2012; Notebaert et al., 2014; Lespez et al., 2015). For example, Bravard (1989, 2000) has shown that the braided pattern of most rivers of the French Alps appeared after the increase of sediment production during the LIA, but sometimes with a significant time delay. This trend was not found in the Mediterranean area and the Massif Central, in part because of fewer studies on geomorphological adjustments of watercourses during the LIA (Gob et al., 2008; Cubizolle, 2009). In this regard, Jacob (2003) concluded that southeastern Massif Central rivers experienced some phases of short hydrosedimentary fluctuations, i.e., aggradation of their alluvial floor during periods of high sediment supply followed by incision rather than a bed metamorphosis like the Alpine rivers. Moreover, the manifestation of the LIA does not appear to be homogenous across the Mediterranean region (Berger et al., 2010) because low temperatures were associated with drought in the eastern part as in the Iberian Peninsula (Carozza et al., 2014); such an

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evolution could have decreased sediment production. Finally, Macklin et al. (1994, 1995) reported a negative feedback in semiarid Mediterranean mountainous landscapes, where the wetter climate could have increased the vegetation cover and then decreased hillslope coarse material supply.

In the present work, we focus on the internal secular rhythmicity of the LIA. Notably, the LIA was not a period of continuously disturbed climatic conditions over three centuries, but characterized by quiet phases interrupting the general trend. Indeed, some authors have shown that this period was not characterized by disturbed climatic conditions but known as an alternance of crises and lulls. It has been pointed out first in the southern Alps (Douguedroit, 1979; Jorda, 1980; Neboit, 1983; Gautier, 1992; Pichard, 1995; Miramont and Guilbert, 1997) then in the Languedoc (Berger et al., 2010) and the southeastern Massif Central (Jacob, 2003; Gob, 2005; Gob et al., 2008; Astrade et al., 2011). The fluvial sensitivity to these fluctuations may depend on the size of the basin. The timing of adjustments can also vary because the downstream progradation of debris from headwater streams to lower valleys presumably requires a relatively long time (Bravard, 1989, 1993; Gob et al., 2008; Astrade et al., 2011; Jacob-Rousseau and Astrade, 2014). According to Gob et al. (2008), the three main sedimentation phases of rivers and deltas occurred exactly at the same time as the principal torrential crises that affected the western Mediterranean during the LIA (see discussion below). Conversely, these episodes are interspersed with two multidecennial phases of severe droughts during the second half of the seventeenth and early eighteenth centuries and during the early nineteenth century (Carozza et al., 2014). Nevertheless, Wilhelm et al. (2012) observed a time delay in flood frequencies during the last four centuries between the southern Alps and the Mediterranean coast of Spain and the Cévennes area. According to these authors, these differences could be explained by two northwestern Mediterranean atmospheric circulation paths affecting the area with a frequency of 50 to 150 years.

This article presents a case study from the Yzeron basin based on optically stimulated luminescence (OSL) and radiocarbon dating of valley

bottom deposits in order to understand the relative influence of climate and human occupation during the LIA. The first aim of this paper is to describe the internal secular rhythmicity of the LIA and its geomorphic implications as observed in valley bottom deposits. In light of what has been stated above, the geographical situation (in the northeastern part of the Massif Central) and the size of the studied hydrosystems (headwater basins) should argue for an early and sensitive recording of the internal LIA hydroclimatic fluctuations.

In line with our previous work (Preusser et al., 2011), the second aim is to assess the relative influence of land use evolution in the sedimentary filling of valley bottoms. Our initial hypothesis was that the valley floor in which current incision occurs has been developed during widespread agricultural activity (mainly ploughlands) and that incision could have been triggered by a later decline in sediment supply from cultivated hillslopes. However, Preusser et al. (2011) also highlighted that such small basins show high sensitivity to climate and land use variations. In order to answer the question regarding the forcing factors of sediment dynamics (hillslope soil erosion, valley bottom deposition, remobilization of valley bottom sediments), we require (i) a diachronic mapping of land use since at least the nineteenth century in the four studied subcatchments and (ii) a chronostratigraphic model of these valley bottom deposits. On the latter point, a review of different dating methods has been provided by Lang et al. (1999) showing that radiocarbon dating and dendrochronology are problematic for such sediments, as these methods rely on the dating of reworked material (i.e., wood). As a consequence, such dating approaches may overestimate the true age of sediment accumulation (e.g., Lang and Hönscheidt, 1999; Huckleberry and Rittenour, 2014). Luminescence methods are now frequently used for the dating of colluvial and alluvial sediments, as recently reviewed by Fuchs and Lang (2009).

2. Study area

The Yzeron basin (147 km²) is a right-side tributary of the Rhône River located near the city of Lyon (Fig. 1). From west to east, in the

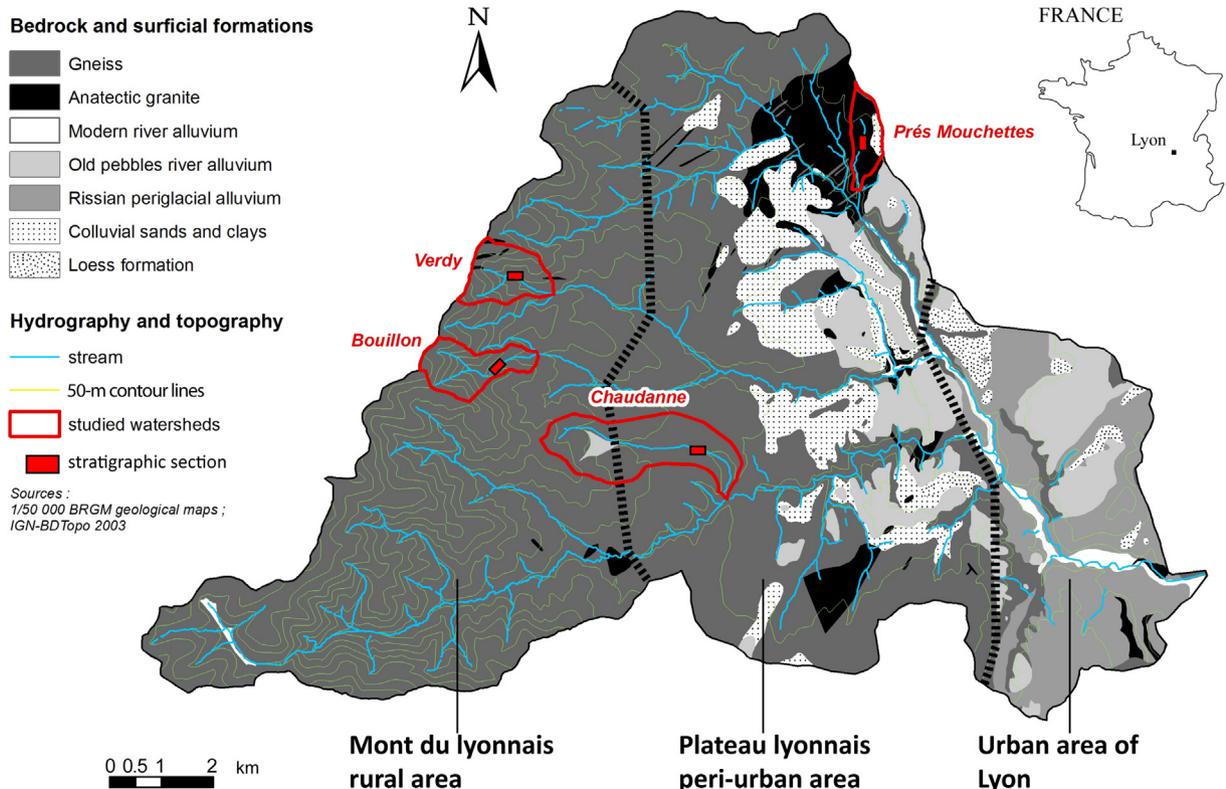


Fig. 1. Location of the four subcatchments studied inside the Yzeron watershed.

downstream direction, the basin drains a subdued, degraded granitic and gneissic mountain (Monts du Lyonnais, a mostly rural area; altitude from 900 to 400 m), a gneissic and partly granitic plateau (Plateau Lyonnais, a mostly peri-urban area in the Lyon neighborhoods; altitude from 400 to 250 m), and some inherited, mostly alpine, fluvial and glacial deposits (part of the urban area of Lyon; altitude from 250 to 165 m). In the last area, the hydrographic network is scarce because of the high permeability of the inherited geological features. Some discontinuous loess covers exist in the eastern part of the basin. Valley bottoms are relatively large and incised into the plateau (Schmitt et al., 2006).

In the Monts du Lyonnais and the Plateau Lyonnais, hillslopes are generally covered by sandy regolith with a typical thickness of about 1 m (Mandier, 1984). This regolith is highly sensitive to soil erosion in the absence of permanent vegetation. The hydrological regime is pluvial oceanic with a Mediterranean influence in the autumn. The high hydrological variability caused by this last influence is strengthened by the low permeability of the substratum and the thinness of the superficial permeable geological features (Chocat, 1997).

Despite the current lack of available palaeoenvironmental data during the last millennia on the Yzeron catchment, we can obtain some insight into past dynamics thanks to the regional studies carried out on the Rhône and the eastern Massif Central. In the Forez Mountains (east of the Monts du Lyonnais), it was during the first Iron Age that the main phase of the highland land-clearing (above 1300 m) occurred (Cubizolle, 2009). Then the transition between the Tene and the Gallo-Roman period is marked by continued deforestation and the intensification of agricultural practices. This is the beginning of a mixed agropastoral economy in the Massif Central (Miras et al., 2004). The Gallo-Roman period is part of a long dry period (from the fourth century B.C. to the fourth century A.D.), which was punctuated by repeated flooding episodes of the Rhône River in Lyon and Vienna from the first century B.C. to the second century A.D. (Bravard and Petit, 2000; Bravard and Salvador, 2009). At Vaise, the first centuries of our era are characterized by a general deterioration of the slopes on which colluviation, torrential activity, and mudslides caused soil erosion. These slope processes are linked to anthropogenic pressures (total disappearance of the forest, cultivation, anthropogenic fires), urbanization, and the increased frequency of rainfall events (Bertran et al., 1998). This morphogenic crisis seems especially important at the end of the Gallo-Roman period when sites were abandoned. In the context of human settlement at that time, the Plateau Lyonnais is considered to be a densely populated space. Evidence for this human occupation is manifold, including tegulae, potsherds, ceramics, remains of large villas, tanks, pipes, walls, ovens, etc. (Lorcin and Housset, 2008).

Palaeoenvironmental research in the Yzeron basin was initiated from problems with current management of river morphodynamics. Significant channel incision is observed for one-third of the headwater streams, and it is characterized by an average lowering of bed channels of 2 m and a maximum of 6 m. We know from public records and dendrochronological analyses of riparian trees that incision began mostly between about A.D. 1970 and 1990. The most significant incision occurred in peri-urban subbasins where urban inflow (UI) and/or combined sewer overflow (CSO) increase peak flow intensity and flood frequency (Grosprêtre, 2011; Schmitt et al., 2011; Navratil et al., 2013). Incision also occurs in the upland rural area, however, where CSO is absent and UI is much less common. This raises the question of the origin of channel degradation in the rural area. Incision has exposed several stratigraphic sections of which four are the subject of this study (Fig. 1). These are located in four subcatchments of the Yzeron basin that are representative of the variety of geographical settings of this catchment: the Bouillon (1.2 km²) and Verdy (0.8 km²) watersheds in the Monts du Lyonnais, and the Chaudanne (3.7 km²) and Prés-Mouchettes (0.4 km²) watercourses in the Plateau Lyonnais (Fig. 1).

More extensive field work, such as coring of the floodplains, was not considered relevant to this study as our main question concerns the

characterization and dating of incised sediments only, in order to predict the occurrence of and mitigate current incisions.

3. Materials and methods

3.1. Sedimentological analyses

We sampled stratigraphic sections to analyze grain size distributions (Delile et al., 2014, for details of the pretreatment) in order to understand the nature of the valley bottom filling and the hydrosedimentary processes. While the sediment fraction >1.6 mm was sieved using several sizes of sieves, the fraction <1.6 mm was measured by a Malvern Mastersizer 2000 laser granulometer. The interpretation of granulometric curves was based on the CM diagram (also called the Passega image), which uses the median (D_{50}) and the coarsest percentile (D_{99}) to determine depositional and transport processes (Salomon et al., 2012; Delile et al., 2015a,b). Magnetic susceptibility (MS) was measured directly on the sections to detect variations in ferromagnetic mineral contents in sediments, mostly Mn- and Fe-oxides, hydroxides, and oxyhydroxides (Dearing, 1999). In fluvial environments, MS reflects the terrigenous flux derived from fluvial hydrodynamics in deltaic (Salomon et al., 2012; Delile, 2014; Delile et al., 2014, 2015a,b) and mountainous areas (e.g., Arnaud et al., 2005, for the Rhône River activity). Moreover, these minerals can be introduced by pedogenetic processes and thereby can be transported, then accumulated in alluvium or colluvium, consecutively to soil erosion events (Dearing et al., 1996; Vannièrè et al., 2000). Magnetic susceptibility was measured three times using a Bartington MS2E1 (Dearing, 1999).

Loss on ignition (LOI) was measured in the muffle furnace from 10 g sediment heated 16 h at 375 °C. LOI gives a crude measure of the sediment's organic content, which tends to increase when fluvial activity is reduced (Arnaud-Fassetta, 2008).

3.2. Radiocarbon dating

Radiocarbon ages for charcoal and vegetal matter were obtained utilizing the linear accelerator at Saclay. Two more radiocarbon ages (tree trunks) were measured at the University of Laval (Table 1). Uncertainties on raw radiocarbon ages BP are reported at the 95% confidence level (2σ). The measured ¹⁴C (BP) ages were converted into B.C.–A.D. calibrated dates by Clam software (Blaauw, 2010) using the continental calibration curve of Reimer et al. (2013).

It is important to state that many taphonomic biases are likely to complicate the interpretation of these radiocarbon dates. We distinguish between two types of disturbance related to post-depositional processes: those intervening at the scale of the charcoal in soils and those relating to the nature of the deposits. In the first case, burial conditions, mixing, and fragmentation of charcoals in soils by biotic (e.g., earthworms) and abiotic (e.g., cryoturbation) agents are likely to modify the charcoals' original stratigraphic positions (Carcaillet and Talon, 1996; Théry-Parisot et al., 2010; Chrzaszewski et al., 2014). Therefore, the dating of soil horizons can be difficult. Moreover, it is possible to date charcoals derived from the same tree and obtain dates differing by up to several centuries, depending on the species of tree dated. That is, charcoals derived from the sapwood and the heartwood of a tree stump will not provide the same dates. Finally, the charcoals could be removed many centuries after their formation, which could make the deposit old. In the second case, taphonomic biases can occur, especially in river valleys where human occupation sites can be buried under several meters of colluvium and/or alluvium caused by hydrological disturbances (Berger, 2011). Hence, because archeological remains preserved in sediments are heavily dependent on river palaeodynamics and the settlement's position in the floodplains (Brown, 1997), knowledge of taphonomic contexts (Holocene colluvial/alluvial deposits, Pleistocene alluvial fans, etc.) and the use of taphonomic corrections can change

Table 1
Summary data of radiocarbon dating of the four stratigraphic sections. Ages were calibrated according to the IntCal13 radiocarbon calibration curve (Reimer et al., 2013) using the Clam software (Blaauw, 2010).

Section	Sample code	Depth (cm)	Laboratory code	Material	¹⁴ C age (BP)	Calendar age (BC–AD) (2σ)
Chaudanne	CHAU 40	40	Lyon-6276 (SacA-16,670)	Charcoal	320 ± 30	1485–1645 AD
Chaudanne	CHAU 165	165	Lyon-6279 (SacA-16,673)	Vegetal matter	305 ± 30	1490–1650 AD
Chaudanne	CHAU 185	185	Lyon-6280 (SacA-16,674)	Charcoal	285 ± 30	1510–1665 AD
Chaudanne	CHAU 230	230	Lyon-6281 (SacA-16,675)	Charcoal	305 ± 30	1490–1650 AD
Chaudanne	CHAU 285	285	Lyon-6282 (SacA-16,676)	Charcoal	380 ± 30	1445–1630 AD
Chaudanne	CHAU-AMONT	220	ULA-1140	Tree stump	285 ± 20	1520–1655 AD
Chaudanne	CHAU-DROITE	310–350	ULA-1141	Tree stump	355 ± 20	1460–1630 AD
Bouillon	BOU 85	85	Lyon-6272 (SacA-16,666)	Charcoal	390 ± 30	1440–1630 AD
Bouillon	BOU 120	120	Lyon-6274 (SacA-16,668)	Charcoal	1235 ± 30	685–880 AD
Bouillon	BOU 135	135	Lyon-6273 (SacA-16,667)	Charcoal	365 ± 30	1450–1635 AD
Bouillon	BOU 195	195	Lyon-6270 (SacA-16,664)	Charcoal	905 ± 30	1035–1205 AD
Bouillon	BOU 230	230	Lyon-6271 (SacA-20,265)	Charcoal	875 ± 30	1045–1225 AD
Près-Mouchettes	PM 95–110	95–110	Lyon-6268 (SacA-16,662)	Charcoal	900 ± 30	1040–1210 AD
Près-Mouchettes	PM 135–145	135–145	Lyon-6269 (SacA-16,663)	Charcoal	1640 ± 30	335–535 AD
Verdy	VER 55	55	Lyon-6266 (SacA-16,660)	Charcoal	595 ± 30	1300–1410 AD
Verdy	VER 80	80	Lyon-6267 (SacA-16,661)	Charcoal	190 ± 30	1650–1865 AD

our perception of the history of human occupation (Verhagen and Berger, 2001; Berger, 2011).

3.3. OSL dating

Altogether, 20 samples have been dated using OSL, of which seven have been already presented in Preusser et al. (2011) where methodological aspects are discussed in detail. The following discussion will summarize the key issues. Material for determination of equivalent dose (D_e) was dried and sieved (see Table 2 for used grain size) and subsequently treated with HCl, H_2O_2 , and Na-Oxalate to remove carbonates and organic matter and to disperse clay particles. The quartz fraction was isolated using heavy liquids (LST fast flow with densities of 2.70 and 2.58 g cm⁻³) and etched with 40% HF for 1 h, followed by treatment with HCl to dissolve fluoride precipitates. Sample PM4 had too little sand to allow application of the above procedure. Here, the fraction 4–11 μm was enriched by settling and etched in H_2SiF_6 for one week to remove feldspar.

All OSL measurements were made using a Risø DA20 TL/OSL reader. Samples were exposed to IR stimulation prior to all measurements, and aliquots that produced any substantial signal response to this stimulation were considered to be contaminated by feldspar and excluded from further analyses. The OSL was recorded during a 60s stimulation

by blue diodes at 125 °C using a Hoya U340 detection filter. The OSL signal from most of the small (2 mm) aliquots is rather bright and dominated by the fast component (Preusser et al., 2011). The first 0.2 s of the signal have been used for analyses. A modified single aliquot regenerative dose (SAR) (Murray and Wintle, 2000) was used for D_e determination. A series of standard performance tests was carried out (Wintle and Murray, 2006), and accordingly samples were preheated at 230 °C for 10 s prior to all OSL measurements. All samples show evidence for the presence of partial bleaching. Preusser et al. (2011) compared different approaches to extract the population of aliquots representing well-bleached grains; we use the minimum age model of Preusser et al. (2007), which has proven to be most robust. This approach cannot be applied to the fine-grained sample PM4 as the large number of grains on the sample carrier will mask the effect of partial bleaching. Hence, the OSL age of this sample will only represent a maximum estimate and it is discarded from further discussion.

Determination of dose rate elements used a low-level, high-resolution gamma spectrometer (Preusser and Kasper, 2001). Following the approach described by Zander et al. (2007) and Preusser and Degering (2007), we did not observe evidence for radioactive disequilibrium in the uranium decay chain. Average water content was estimated based on the sediment moisture measured in the lab, including some uncertainty to account for possible past changes in the

Table 2
Summary data of OSL dating giving sampling code and depth below surface, the concentration of dose rate relevant elements (K, Th, U), measured sediment moisture and the water content (W) used for calculations of dose rate (D), together with the number of replicate measurements (n) and grain size used for equivalent dose (D_e) determination.

Sample	Depth (cm)	K (%)	Th (ppm)	U (ppm)	Mois. (%)	W (%)	D (mGy a ⁻¹)	n	Grain size (μm)	D_e (Gy)	Age (a)	Age AD
CHAU7	26	3.24 ± 0.03	11.94 ± 0.29	3.47 ± 0.12	19.4	20 ± 5	4.06 ± 0.44	51	100–150	0.33 ± 0.02	79 ± 7	1920–1935
CHAU6	60	3.76 ± 0.04	10.69 ± 0.42	3.13 ± 0.02	20.1	20 ± 5	4.37 ± 0.33	50	150–200	0.90 ± 0.05	206 ± 17	1785–1820
CHAU5	105	3.82 ± 0.03	14.07 ± 0.31	4.09 ± 0.06	22.9	20 ± 5	4.78 ± 0.24	40	150–200	1.67 ± 0.17	350 ± 41	1615–1700
CHAU4	150	4.15 ± 0.03	5.59 ± 0.09	1.76 ± 0.02	5.9	10 ± 5	4.52 ± 0.33	45	150–200	1.91 ± 0.18	424 ± 35	1550–1620
CHAU3	210	3.84 ± 0.03	11.67 ± 0.26	3.32 ± 0.09	16.8	20 ± 5	4.43 ± 0.33	44	150–200	0.77 ± 0.04	172 ± 14	1820–1850
CHAU2	252	3.78 ± 0.03	11.24 ± 0.26	3.42 ± 0.05	14.3	20 ± 5	4.43 ± 0.42	43	150–200	0.48 ± 0.05	109 ± 13	1885–1910
CHAU1	295	3.90 ± 0.03	12.23 ± 0.53	3.61 ± 0.07	–	20 ± 5	4.86 ± 0.43	43	150–200	0.71 ± 0.04	154 ± 13	1840–1865
BOU6	20	4.07 ± 0.03	12.05 ± 0.30	4.38 ± 0.06	19.4	20 ± 5	4.67 ± 0.40	45	150–200	0.17 ± 0.01	35 ± 3	1970–1975
BOU2	65	4.12 ± 0.09	7.27 ± 0.17	2.63 ± 0.04	9.8	15 ± 5	4.55 ± 0.30	48	150–200	1.04 ± 0.04	228 ± 17	1765–1795
BOU5	75	4.20 ± 0.03	8.84 ± 0.16	3.26 ± 0.03	20.2	20 ± 5	4.53 ± 0.21	46	250–300	0.68 ± 0.05	152 ± 14	1840–1870
BOU4	160	4.02 ± 0.04	8.63 ± 0.15	4.41 ± 0.07	18.2	20 ± 5	4.78 ± 0.30	46	100–150	2.46 ± 0.19	517 ± 51	1440–1540
BOU3	220	4.17 ± 0.04	6.29 ± 0.26	2.91 ± 0.08	11.0	15 ± 5	4.55 ± 0.27	46	150–200	1.57 ± 0.08	345 ± 27	1635–1690
BOU1	205	4.16 ± 0.09	4.99 ± 0.07	2.15 ± 0.04	8.7	15 ± 5	4.26 ± 0.26	40	150–250	1.54 ± 0.09	360 ± 30	1620–1680
PM4	22	2.65 ± 0.02	16.22 ± 0.20	4.03 ± 0.05	24.3	25 ± 5	5.03 ± 0.48	5	4–11	2.97 ± 0.10	588 ± 61	1360–1480
PM3	65	3.62 ± 0.03	10.14 ± 0.18	2.94 ± 0.08	5.9	10 ± 5	4.67 ± 0.29	49	100–150	1.35 ± 0.04	287 ± 22	1700–1745
PM2	117	2.96 ± 0.02	13.35 ± 0.27	3.50 ± 0.06	10.5	15 ± 5	4.22 ± 0.29	49	100–150	4.74 ± 0.22	1121 ± 91	795–980
PM1	165	2.93 ± 0.03	13.65 ± 0.17	3.69 ± 0.07	12.9	15 ± 5	4.25 ± 0.29	48	100–150	5.21 ± 0.21	1226 ± 95	685–875
VER3	15	3.29 ± 0.03	11.57 ± 0.10	5.10 ± 0.08	20.8	20 ± 5	5.43 ± 0.40	59	100–150	0.20 ± 0.01	34 ± 6	1970–1980
VER2	45	3.94 ± 0.03	8.40 ± 0.22	3.41 ± 0.02	8.0	10 ± 5	5.00 ± 0.35	49	100–150	0.68 ± 0.07	137 ± 17	1855–1890
VER1	75	3.89 ± 0.03	11.22 ± 0.20	4.56 ± 0.03	12.6	15 ± 5	4.96 ± 0.33	49	150–200	0.65 ± 0.05	130 ± 13	1865–1890

hydrological situation. The contribution from cosmic dose rate followed Prescott and Hutton (1994). All age calculations were performed using ADELE software, and dosimetric data is summarized in Table 2.

4. Land use history

Land use history was studied via cadastral documents (Privolt, 2009), photo interpretation of aerial photographs (data collected and analyzed by Jacqueminet et al., 2013), and analysis of old photographs and artworks (Privolt, 2010).

The document produced by the first centralized cadastration (called *Napoleonic* in France) allows us to reconstruct land use since the beginning of the nineteenth century. It consists of two sets of data: the first map and parcel registration of the early nineteenth century (A.D. 1820 in the present case) and a revised registration about one century later (A.D. 1914 in the Yzeron basin). These documents provide precise information (at the scale of each parcel) concerning land use, which is classified by its nature (e.g., ploughlands, vineyards, orchards, meadows, woodlands, etc.). The revised record of A.D. 1914 registered the changes that had occurred during the nineteenth century, and it can thus be usefully compared with the previous document. In order to follow the more recent landscape evolution, aerial photographs of the studied reaches were collected. These were interpreted using the same land use classification as in the cadastral maps. All land use data were integrated into GIS. In each catchment, each parcel shown by the cadastral map was digitized and associated with a table describing the land use at four dates (A.D. 1820, A.D. 1914, A.D. 1970, A.D. 2008). The use of GIS allows the estimation of surface evolution through time and some semiquantitative or qualitative analysis (level of spatial fragmentation of a type of land use, connectivity) as it is commonly practiced in landscape ecology analyses.

Nevertheless, contrary to aerial photographs, cadastral documents give insufficient precision to reconstitute all characteristics of countryside landscapes. Indeed, at the time of its conception, the land registry aimed to evaluate owners' fiscal contributions and not to describe landscapes. Hence, we paid critical attention to two points. First we had to verify that fiscal classes corresponded to effective land use at the time of registration. The second point concerned parcels' boundaries, which can be occupied by hedgerows, woodbanks, or lynchets and which never appear on cadastral maps. As shown by Rackham (1986), lynchets are the result of soil creep in ploughlands when earth moves downhill and accumulates against the lower field boundary. These features are very common in some European regions. This is a critical point insofar as, after several centuries, these lynchets constitute efficient barriers to downhill sedimentary transfer and can have a strong influence on sedimentary supply to valley bottoms. Field observations showed that no similar features currently exist in the studied catchments. However, taking into account that extensive agricultural alterations occurred in the second half of the twentieth century, we must verify that such lynchets or hedgerows did not exist in the past. For these two reasons, we collected a set of old photographs and artwork representing the local countryside (Privolt, 2010). The set of ancient documents was also studied in order to acquire information about land use before the beginning of the nineteenth century (Privolt, 2010). However, because of the small amount of data few data on these ancient documents, only a qualitative interpretation was possible.

5. Results

5.1. Stratigraphic description

5.1.1. Chaudanne River section

In the Chaudanne River, we investigated a 3.5-m-long sediment section (Fig. 2). The age of the sediment deposits is determined by an in situ tree trunk found 1 m away from the outcrop. Another trunk was found in a similar position about 20 m upstream. These and ten other tree

trunks found along the presently incised channel are *Populus*, *Salix*, and *Alnus glutinosa/incana*, indicating a humid, riverine environment. Radiocarbon dating of the two trees located close to the investigated section gave ages of A.D. 1460–1630 (ULA-1141; Table 1) and A.D. 1520–1655 (ULA-1140; Table 1). This indicates that deposition of the sediment sequence took place after about A.D. 1500. In the field, the stratigraphy has been divided into nine sedimentary units (SU) according to the color, structure, and lithology of deposits.

Units 1 and 2 (350–175 cm) consist of laminated silty-sands wherein ochre coarse layers are stratified with bluish fine layers. The dominant sandy fraction ranges between 63 and 88%, and the fine fraction (silts and clays) from 11 to 29%. These units are intercut by a very coarse layer at a depth of 265–245 cm, wherein the proportion of pebbles is around 20%. Conversely, a layer enriched in fine particles at a depth of 189 cm show a silty-clayed fraction of 62%. The MS values are relatively homogeneous as they fluctuate between 0 and 17 CGS (mean value: 5). Similarly, LOI values vary slightly, between 1 and 3%, except for the thin layer at 189 cm which comprises 8% LOI.

The yellow-orange sedimentary facies of SU 3 (175–130 cm) incorporates very coarse particles; it contains on average more than 70% sands and only 6% fines. The remaining sediments are composed of granules and gravels. This sedimentary facies change is also reflected by a decline of MS and LOI average values, which are –0.2 CGS and 0.5%, respectively.

The bluish SU 4 (130–87 cm) suggests a return toward quieter depositional conditions as indicated by the decrease of the coarse and sandy fractions (respectively, mean values: 1 and 65%) in favor of silts (32%) and clays (2.5%). This change coincides with increasing values of MS and LOI that reach, respectively, 4 CGS and 4%.

The extremely coarse SU 5 (87–75 cm) is composed of grayish sediments containing 42% of particles with grain size exceeding 2 mm, 52% sands, and <7% fine particles (<63 μm). This sharp change in the sedimentary facies is again reflected in the decreasing values of MS and LOI, which respectively fall to averages around 1.3 CGS and 1%.

The darkish SU 6, 7, 8, and 9 (75–0 cm) show a homogeneous facies, with a texture dominated by sands (mean value: 51%) and fines (mean value: 43%). Moderate conditions of transport and deposition are implied by the increasing LOI content, which reaches 9.5%. The maximum MS values in this section are recorded within these units (mean value: 17.4 CGS). This peak could be explained by the development of pedogenic processes in the upper part of the section. Indeed, we suppose these MS values are closely linked to the vertical migration of Fe–Mn oxy-hydroxydes from the upper pedologic layer toward the accumulation horizon.

5.1.2. Bouillon River section

In the Bouillon River we investigated a 2.5-m-long sediment section (Fig. 2). According to OSL dating, basal sediments were deposited during the seventeenth century. These ages are coherent with those from the basal part of the Chaudanne River section. Conversely, we consider that the radiocarbon age of A.D. 1045–1225 (Lyon-6271; Table 1) determined for a charcoal within this section is likely to be reworked material.

The sedimentary unit 1 (250–200 cm) comprises darkish gray sands (79%) incorporating coarse particles (11%) and fines (10%) to a lesser extent. The MS and LOI values are low, respectively, <1 CGS and 1.2%.

The sedimentary environment changes abruptly: unit 2 (200–175 cm) is mostly composed of dark grayish coarse particles (57%) to the detriment of the sand fraction (33%), but the proportion of the fine fraction remains stable (10%). The increase in transport energy suggested by the particle size analysis is not apparent in the MS and LOI values, which remain stable (respectively, 1.5 CGS and 1.9%).

The sedimentary unit 3 (175–65 cm) consists of laminated silty-sands, with interstratified ochre sandy layers and bluish fine layers. While coarse deposits may show up to 93% sands (82 cm), the same level yields only 4% fine particles. In contrast, when fine deposits

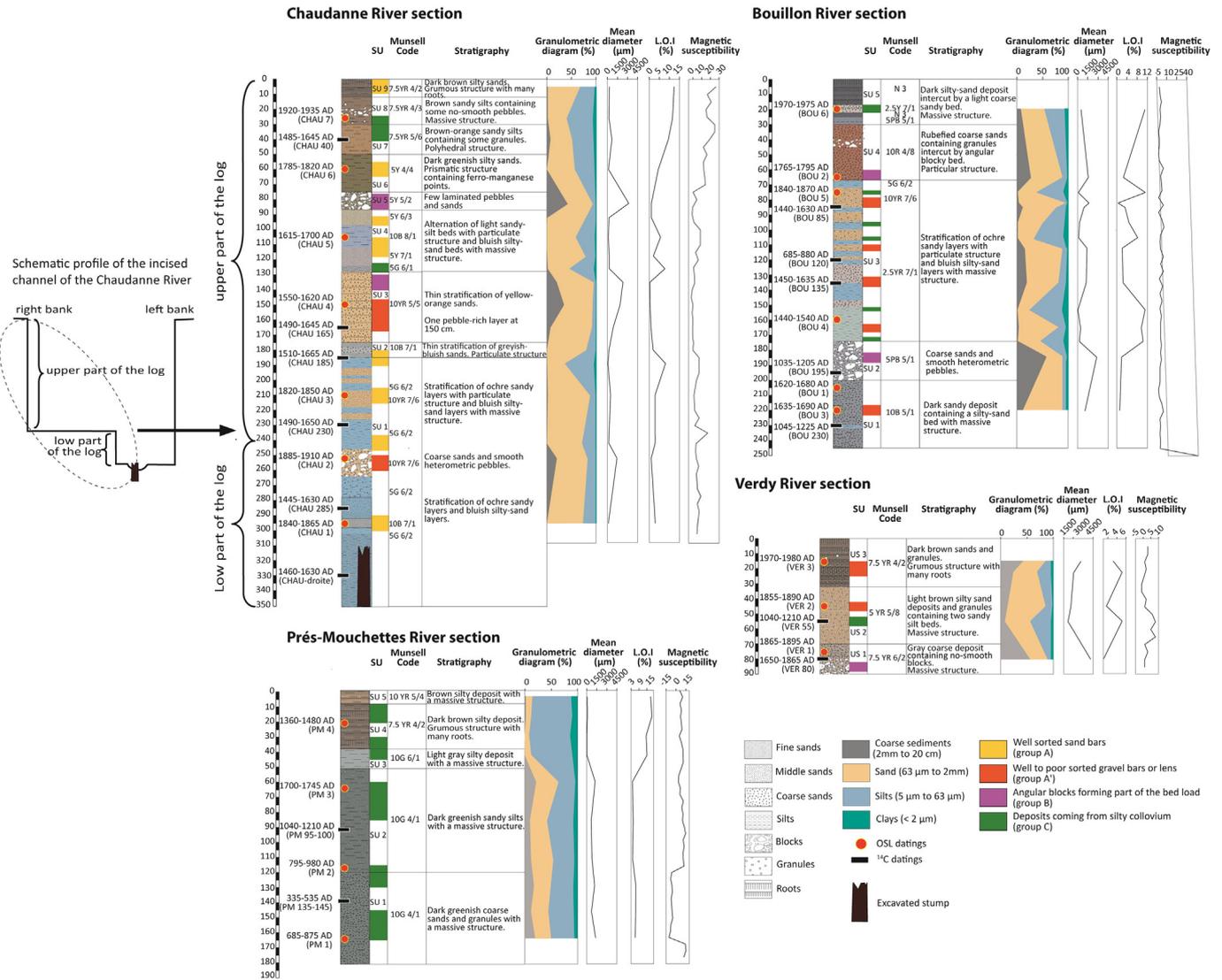


Fig. 2. Stratigraphic log of the Chaudanne, Bouillon, Verdy, and Prés-Mouchettes river sections showing radiocarbon and OSL ages, grain size distribution (%), LOI content (%), and magnetic susceptibility values (in CSG with $SI = CGS \text{ value} * 0.4 * 10^{-5}$). Groups A, A', B, and C, identified by the CM image and respectively symbolized by the colors yellow, orange, purple, and green, are detailed in Fig. 7. SU = Sedimentary Unit.

dominate in the section, silts and clays may reach up to 70% (153 cm), and sands fall to 22%. The LOI values reach up to 11% (153 cm) in fine sediments and decrease to 0.5% (82 cm) in sandy layers. The MS values remain similar to unit 2 (mean value: 1.7 CGS).

The sedimentary unit 4 (65–30 cm) is characterized by rubefied coarse sandy layers (62%) containing granules and intercut by a bed of angular blocky particles (27%). The MS values continue to fall, becoming negative (mean value: -1), and LOI content remains relatively low (2.6%).

A change in sedimentary facies occurs with the darkish unit 5 (30–0 cm), which reaches 47% fine particles and 46% sands. This weakening of transport and depositional energy is expressed through the increasing LOI content (11%) but does not affect MS, which remains stable (mean value: 0 CGS).

5.1.3. Verdy River section

Along the Verdy River, we investigated a 0.9-m-long sediment section (Fig. 2). In contrast to the previously described sections, this one does not display a trunk at its base. This is not surprising because of the relatively recent age of this sediment section (eighteenth century).

The sedimentary unit 1 (90–70 cm) consists of a grayish coarse deposit containing angular blocks. Granulometric fractions are divided as

follows: 57% coarse sediments, 33% sands, and 10% fines. This high-energy environment produced weak values for MS and LOI, 1.5 CGS and 1%, respectively.

The sedimentary unit 2 (70–32 cm) is a light brown silty-sand deposit containing two sandy-silt beds. The decreasing transport and depositional energy is characterized by a decrease of the coarse fraction (mean value: 16%) and an increase of the fine fraction (mean value: 29%). This evolution is correlated with MS and LOI values that are elevated with respect to those of SU 1 (mean values: 4 CGS and 1.7%, respectively). It is clear that energy remains relatively high, however, owing to the significant sandy fraction (mean value: 56%) in this unit.

The sedimentary unit 3 (32–0 cm) is a dark brown sandy deposit containing granules, which cause an increase in the coarse fraction (mean value: 35%) and a concomitant decrease in sands and fine sediments (mean values: 43 and 22.5%, respectively). This upper organic deposit is marked by the highest LOI mean value (4%) and the lowest MS mean value (1.4 CGS).

5.1.4. Prés-Mouchettes River section

At Prés-Mouchettes River we investigated a 1.8-m-long sediment section (Fig. 2). This section is nearly a millennium older than the Chaudanne and Bouillon sections, if compared to the deepest samples

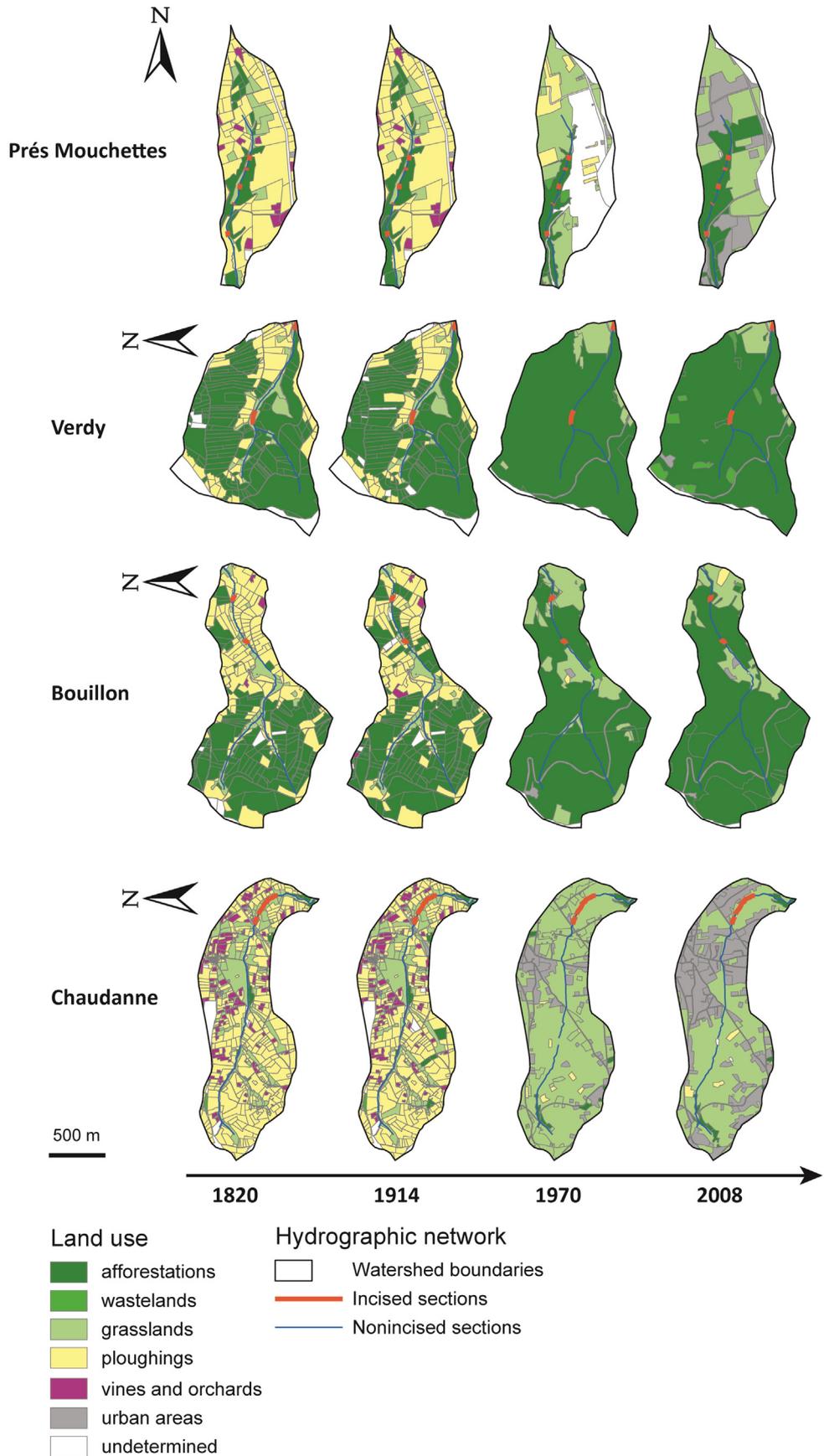
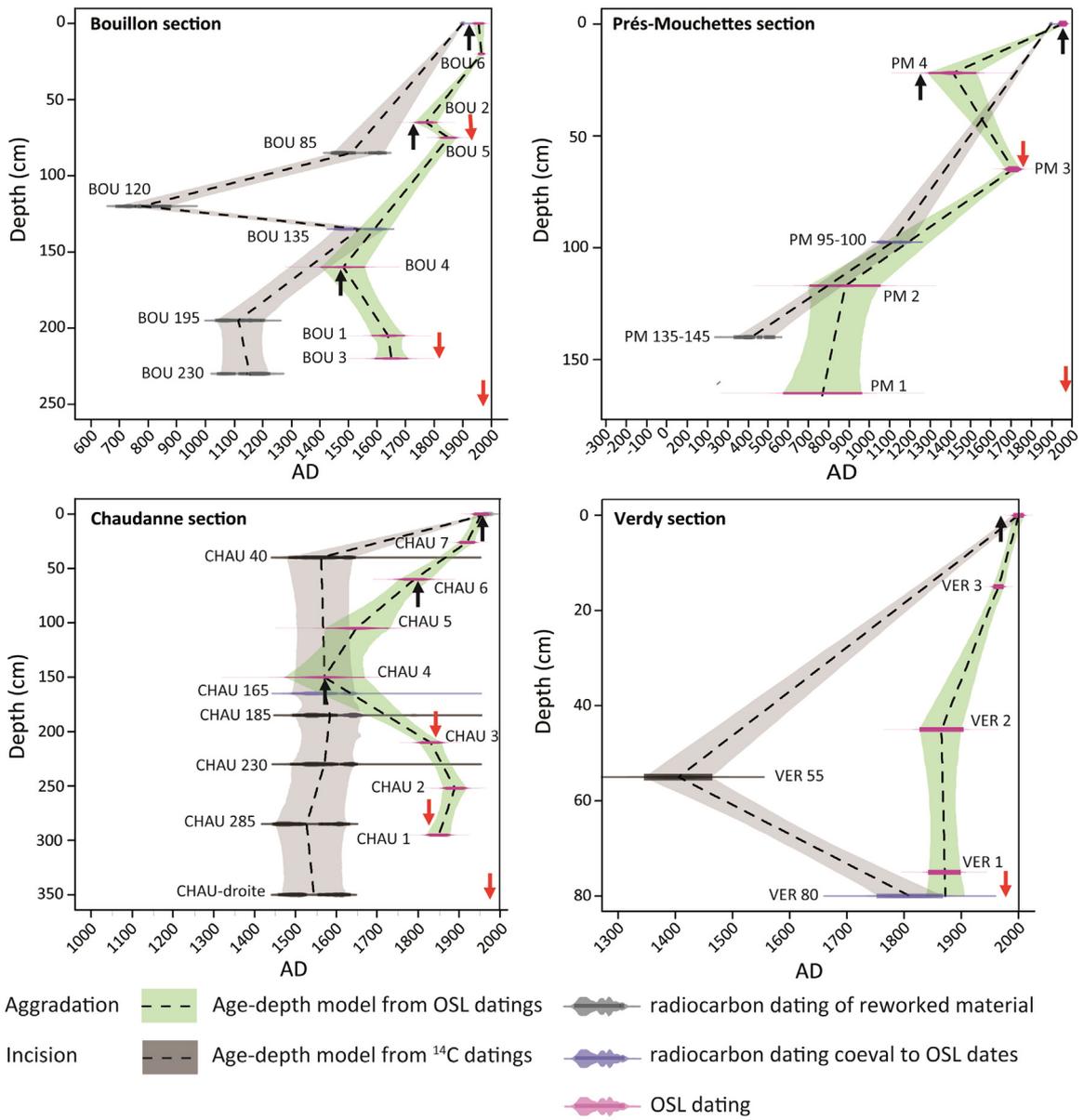
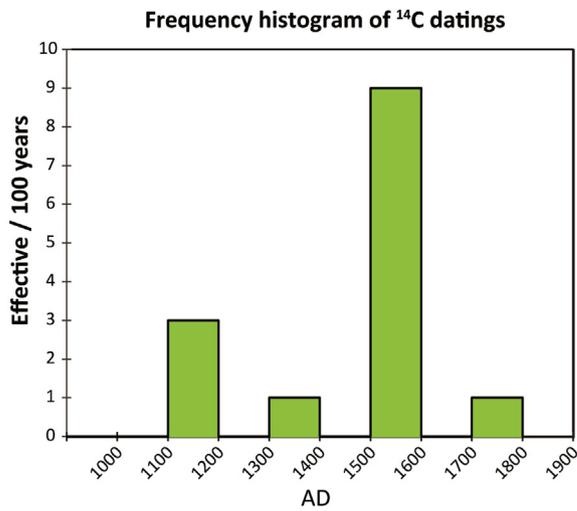


Fig. 3. Diachronic maps of land use since A.D. 1820 of the four subcatchments studied.

A



B



dated by OSL in these locations (CHAU1 and BOU3, respectively). Moreover, the profile of the section is remarkably homogenous, as observed by the extremely weak vertical variations in sedimentological proxies.

The sedimentary units 1 and 2 (180–50 cm) gave OSL ages ranging from A.D. 685–875 (PM1; Table 2) to A.D. 1700–1745 (PM3; Table 2). These dark greenish sandy silts contain on average 16% gravels, 35% sands, and 49% fines, without any major variation. The LOI values also show only weak variations, ranging between 4.1 and 6.6%. Only MS values vary significantly between units 1 and 2. While the values of the first evolve from positive (mean value: 14 CGS) to negative (mean value: -7 CGS), MS is only positive in the SU 2 (mean value: 9.5 CGS).

The depositional environment changes in SU 3 (50–0 cm) as brown fine particles (mean values: 89%) increase and sandy and coarse fractions decrease (mean values: 0.7 and 10.6%, respectively). This low-energy environment is characterized by an increase in LOI content of 16.5% on average, whereas MS values (mean value: 8 CSG) remain high.

5.2. Landscape evolution

Land use mapping reveals that landscape evolution can be divided into two distinct periods between 1820 and 2008 (Fig. 3). During the whole nineteenth century and until the beginning of the twentieth, cadastral data show that a major part of these catchments was covered by cultivated surfaces (principally registered as ploughlands). We can add that these maps hide a significant growth in cereal crops, orchards, and vineyards in the mid-nineteenth century, which is indicated by agricultural statistics and historical studies. Indeed, the agricultural peak occurred around 1860, which also corresponded to a peak in the farming population (De Farcy, 1950). For example, at this time vineyards accounted for 1/5, 1/6, and 1/8 of the municipal areas of Brindas, Craponne, and Francheville, respectively, in the Plateau Lyonnais (De Farcy, 1950). Grasslands were only present in the valley bottoms.

The second trend shared by the four studied catchments is a significant decrease in ploughlands since the second half of the twentieth century (Fig. 3). This decrease, which began slowly at the end of the nineteenth century, gained momentum in the 1960s with an economic reconversion of local agriculture called *révolution fourragère* (Chazal et al., 1955; Housnel, 2006). In order to enhance fodder production, many croplands were gradually converted to grassland (mainly permanent grassland). At the same time, woodland or urban areas replaced some former ploughlands as an effect of agricultural desertion of the steepest hillslopes and Lyon's urban sprawl. Spontaneous or human-induced reforestation occurred mainly in the Monts du Lyonnais, whereas urbanization mostly affected the Plateau Lyonnais (Fig. 3). In the Yzeron basin, ploughlands represented 34% of basin surfaces in 1904 compared to only 12% in 2000. In addition, the general decline of agriculture was very pronounced: in the same period, the proportion of cultivated areas in the basin decreased from 91.7% to 59.9% (Cottet, 2005). In the studied reaches, we can distinguish two cases. In the Chaudanne and Prés-Mouchettes catchments, ploughlands covered 52% to 63%, respectively, of the total basin surface until the beginning of the twentieth century. In the Verdy and Bouillon catchments, ploughlands represented between 32% and 42%, respectively, of the total surface during the same time. In all basins, ploughland proportions quickly decreased after the 1960s and currently range between <1% (Chaudanne) and 0.28% (Bouillon).

Historical mapping also reveals changes in landscape structure that we may consider as important as changes in land use. Since the second half of the twentieth century, ploughlands have become extremely fragmented, existing only as small and isolated patches. By contrast, during the previous century, these ploughlands formed a continuum

along hillslopes, often constituting large patches 500 to 700 m long and well connected to valley bottoms. This spatial setting is favorable to sediment transfer from slopes to riverbeds. The analysis of old photographs and artworks representing the local countryside (Privolt, 2010) reveals that the open landscapes constituted the major fraction of these catchments. In these pictures, only a few hedgerows or woodbanks appear at the boundaries of plowed parcels. We could not distinguish significant evidence for buffers or obstacles along slopes that would be remnants of previous wooded boundaries or colluvial lynchets. Moreover, some artwork dating to the seventeenth and eighteenth centuries and representing the neighborhood of Lyon show the same type of land use. Some hedgerows are present, but most of them are directed toward the slope and they never appear to constitute a closed network. Although the use of paintings or engravings for reconstituting environmental features of the past requires a critical view, the recurrence of previously cited characteristics of local landscapes through three centuries suggests that they might have begun as early as the seventeenth century. This finding is consistent with historical works reporting intense plowing from the end of the Middle Age to the nineteenth century (De Farcy, 1950; Lorcín and Housnel, 2008). This historical information tends to support the hypothesis that past landscapes were quite open and characterized by a good connectivity between slopes and riverbeds. Such features can explain the thick sedimentary fill currently present in valley bottoms.

6. Discussion

6.1. Identification of aggradation-incision phases

The OSL and radiocarbon age-depth models of the four stratigraphic sections exhibit an obvious chronological offset, as radiocarbon dates tend to be earlier than OSL ages (Fig. 4A). This first observation confirms the limits discussed in the introduction concerning radiocarbon dating, which might overestimate the age of deposits (Lang and Hönscheidt, 1999) caused by the presence of reworked materials (Lang et al., 1999). Below we will add information obtained from the radiocarbon ages frequency (Fig. 4B).

The second main observation concerns the S-shape of the OSL model age curves (Fig. 4A), that is, the presence of several chronological inversions in the Bouillon, Chaudanne, and Prés-Mouchettes sections. Indeed, some deposits located at the Bouillon (between ~230 and 190 cm; BOU3, A.D. 1620–1680, 220 cm; and BOU1, A.D. 1630–1690, 205 cm) and the Chaudanne (between ~300 and 200 cm; CHAU1, A.D. 1845–1875, 295 cm; CHAU2, A.D. 1885–1915, 252 cm and CHAU3, A.D. 1825–1855, 210 cm) sections were emplaced later than others located above. This OSL dating inversion also occurs in the top part of the Prés-Mouchettes stratigraphy at 65-cm section depth (PM3, A.D. 1700–1740), where upper sediments have been deposited between A.D. 1360 and 1480 at around 22-cm section depth (PM4). Another inversion near the top of a section occurs on the Bouillon at 75-cm section depth (BOU5, A.D. 1845–1875) with upper sediments dated around A.D. 1760–1800 (BOU2) at 65-cm depth.

At first sight, these inversions could be the result of a lower alluvial terrace forming in the channel at the bottom of the banks. This terrace would correspond to a stage of fluvial incision (consequently leading to the presence of younger deposits at the bottom of the sections investigated). Logically, such a pattern would require that this lower terrace yielded the most recent age in the entire stratigraphy. However, this does not seem to be the best explanation, for several reasons. First of all, in the Chaudanne and Bouillon Rivers, the OSL ages for the upper part of the deposits (e.g., Chau7, BOU 5, 2, and 6) give posterior dates

Fig. 4. (A) Age-depth models for the four stratigraphic sections deduced from radiocarbon (gray fields) and OSL dating (green fields), and (B) frequency histogram of radiocarbon ages. The four age-depth models presented in Fig. 4A provide methodological perspectives rather than practical purposes like constructing a continuous sedimentation model. Indeed, while it was impossible for sediment to accumulate backwards in time, these inverted age-depth models suggest a more complex process than a simple continuous sedimentation, which is conventionally observed in this kind of graph. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to those from the bottom. Another key to interpretation is given by the observation of current processes in channels of the studied basin. Indeed, the present-day conditions of fluvial incision does not allow the development of low terraces but rather favors the formation of frequent underbank scours, as we show in Fig. S1. This kind of evolution can easily be explained by the narrowness of the valley bottoms where the shear stress is high and the lateral erosive dynamics are efficient.

Rather, the radiocarbon and OSL dates suggest alternating, rapid incision and deposition processes (Figs. 5 and 6). Except for the particular case of samples CHAU1-2 (see below), the inversions related to the samples CHAU3, BOU3, BOU1, BOU5, and PM3 can be interpreted as short incision phases that have been quickly followed by sediment deposition into underbank excavations (Figs. 5 and 6). The latter, which are common in nonbedrock channels, are explained by the fact that riparian tree roots are highly efficient at controlling lateral erosion and mass failure (Zaimes et al., 2004; Wynn and Mostaghimi, 2006). Consequently, when incisions are deeper than roots (current incision depths are around 3.50, 2.50, 1.80, and 0.90 m for the Chaudanne, Bouillon, Prés-Mouchettes, and Verdy rivers, respectively), underbank scour is frequent. This scouring process is particularly active and widespread during the incision stage (Figs. 5 and 6). It can also be observed currently in many entrenching channels of the Yzeron basin (Fig. S1), and this process has already been suggested by Preusser et al. (2011) to explain sample CHAU3. Therefore these chronological inversions may result from previous incision phases where subsequent and dated aggradational phases constitute the *terminus ante quem* of the incision phases. The OSL dating can therefore be used to determine the chronology of the phases of sediment deposition and incision in headwater sub-basins (Figs. 5 and 6). Indeed, they are extremely sensitive to external factors (land use, climate, etc.) and the lateral development of underbank scourings can attain a relatively high dimension compared to the channel width, especially as the width to depth ratio is comparatively low in this kind of channel (Schmitt et al., 2001).

Concerning the particular OSL dates of CHAU1-2, Fig. 2 indicates that the shape of the bank presents a bench at a depth of 240 cm with a width of 188 cm. While OSL samples CHAU1-2 have been taken from a lower bank in the channel, samples CHAU3-7 are from the main exposure. After a first incision on the Chaudanne, a subsequent phase of aggradation followed by a second incision, which reached a lower level than the first incision, led to the deposition of samples CHAU1-2 (Fig. 5). The inversions of these samples are not linked to underbank excavation like other inversions mentioned above but to the successive incision/aggradation phases and the particular bank morphology (bench) of the Chaudanne section during sample collection (Preusser et al., 2011).

Incision phases operate at different times in the four stream channels studied. The Bouillon River was incised during the seventeenth century (Fig. 6) whereas it occurred in the eighteenth century for the Prés-Mouchettes River, and in the nineteenth century for the Chaudanne River (Fig. 5). This latter phase in the nineteenth century could have taken place also on the Bouillon River (BOU5, A.D. 1845–1875; Fig. 6). The absence of any incisions dated to the seventeenth century in the Chaudanne River section (Fig. 5) could be explained by upstream sedimentary removal (from the Monts du Lyonnais and partly the Plateau Lyonnais) at this time causing downstream infilling (Plateau Lyonnais). This correspondence between upstream headwater channel incision and downstream river fine deposits is currently observed in the Yzeron's catchment, the disturbing effects of which (biocenoses, flooding) are precisely the reason for the geomorphic studies conducted in this basin over the past 10 years (Grosprêtre, 2011). Only the OSL ages measured on the Verdy River sediments do not display chronological inversions, as sedimentation was continuous (Fig. 4A). This state is consistent with results obtained on the three other watercourses, which do not show any incisions after the end of the nineteenth century (except modern incision); the studied section of the Verdy River is younger than this period.

Incision phases cited above are preceded by an aggradation phase in the valley bottoms that began in the early sixteenth century (Figs. 5 and 6). At this point, OSL and radiocarbon ages seem to agree: they are similar with regard to the stratigraphic sections of the Chaudanne (around 150 cm) and Bouillon rivers (between 160 and 135 cm) (the gray and green fields of the age–depth models overlap as early as A.D. 1500; Fig. 4A). In other words, OSL dating, in concert with radiocarbon ages and the absence of palaeosoils within the sequences, indicates rapid aggradation at valley bottoms owing to a substantial flux of sediment from hillslopes. Deposition began shortly after A.D. 1500 at the valley bottoms of the Chaudanne and Bouillon rivers (Figs. 5 and 6), probably before those of the Prés-Mouchettes River, and continued until about A.D. 1800 for the Chaudanne River, A.D. 1700 for the Prés-Mouchettes River, and A.D. 1600 for the Bouillon River. The dating of this thick sedimentary filling appears consistent with the characteristics of land use we described above. Indeed, the weak resistance of cultivated surfaces to erosion is explained by the significant runoff over these areas that do not benefit from a protective vegetation cover. This process is related to the development of diluted or concentrated flows on the stripped surfaces causing colluviation on the footslopes up to several centimeters per year (Bertran and Texier, 1997).

High sedimentation rates during this period were also found in southern, southwestern, and central France (Allée, 2003; Bertran, 2004; Miras et al., 2004) as in other regions (Lespez et al., 2015). In the Belgium Ardennes massif, Notebaert et al. (2013) showed that the floodplains' contemporary storage was accumulated during the last 600 years because of increased sedimentation rates related to agricultural activities. In the Lyon region, the first evidence for valley bottom aggradation is observed from the sixteenth century, though the development of agriculture has occurred since at least the early fourteenth century (Lorcin, 1974). Therefore human activity anterior to the LIA could have already destabilized the hillslopes, and thereby subsequently amplified the LIA climatic signal. In this regard, Macklin and Lewin (2003) noted that climatic signals can be amplified or attenuated by human land use, particularly in small-sized river basins.

While the history of land use of the four studied subcatchments since A.D. 1820 (Fig. 3) supplies detailed information concerning catchment-scale human activities, the frequency of radiocarbon ages is also highly instructive for prior periods. Fig. 4B shows two relatively important modes in the radiocarbon age distribution that are centered on the twelfth and sixteenth centuries. The radiocarbon age frequency of the latter period is much higher than that of the former period. As specified above, these charcoals from the sixteenth century are coeval with deposits dated by OSL, as OSL and ^{14}C age–depth models overlap. Such nonuniform distribution could result from a release of charcoal as a result of land-clearing (Horn and Sanford, 1998; Clement and Horn, 2001) intended to increase cropland area (Berger et al., 2002; Vannièrè and Laggoun-Defarge, 2002; Franc, 2005; Bertonecello, 2008).

The smaller mode centered on the twelfth century (Fig. 4B) could be related to the rapid population growth and land-clearings in the Monts du Lyonnais and the Plateau Lyonnais (Lorcin and Housset, 2008; Rubellin, 2009) during the time of the Medieval Agricultural Revolution (Duby, 1954). In contrast to the sixteenth century mode, this lower radiocarbon age frequency represents charcoals that are not coeval with the timing of sediment deposition because the OSL and ^{14}C age–depth models do not overlap during the twelfth century for the Bouillon section (Fig. 4A). This period corresponds to the large deforestation phases operating at the European scale (Monna et al., 2005). The occurrence of this phase of land-clearings during the twelfth century was likely to have caused an early aggradation stage of the bottom valley of the Bouillon River, as was the case during the sixteenth century.

When the number of radiocarbon dates is large enough, inspection of the dates' frequency histogram is particularly instructive to discriminate potential aging effects. Indeed, the aging of radiocarbon dates can also be caused by the burning of tree rings located in the heart of the stump rather than those toward the exterior. This process, occurring

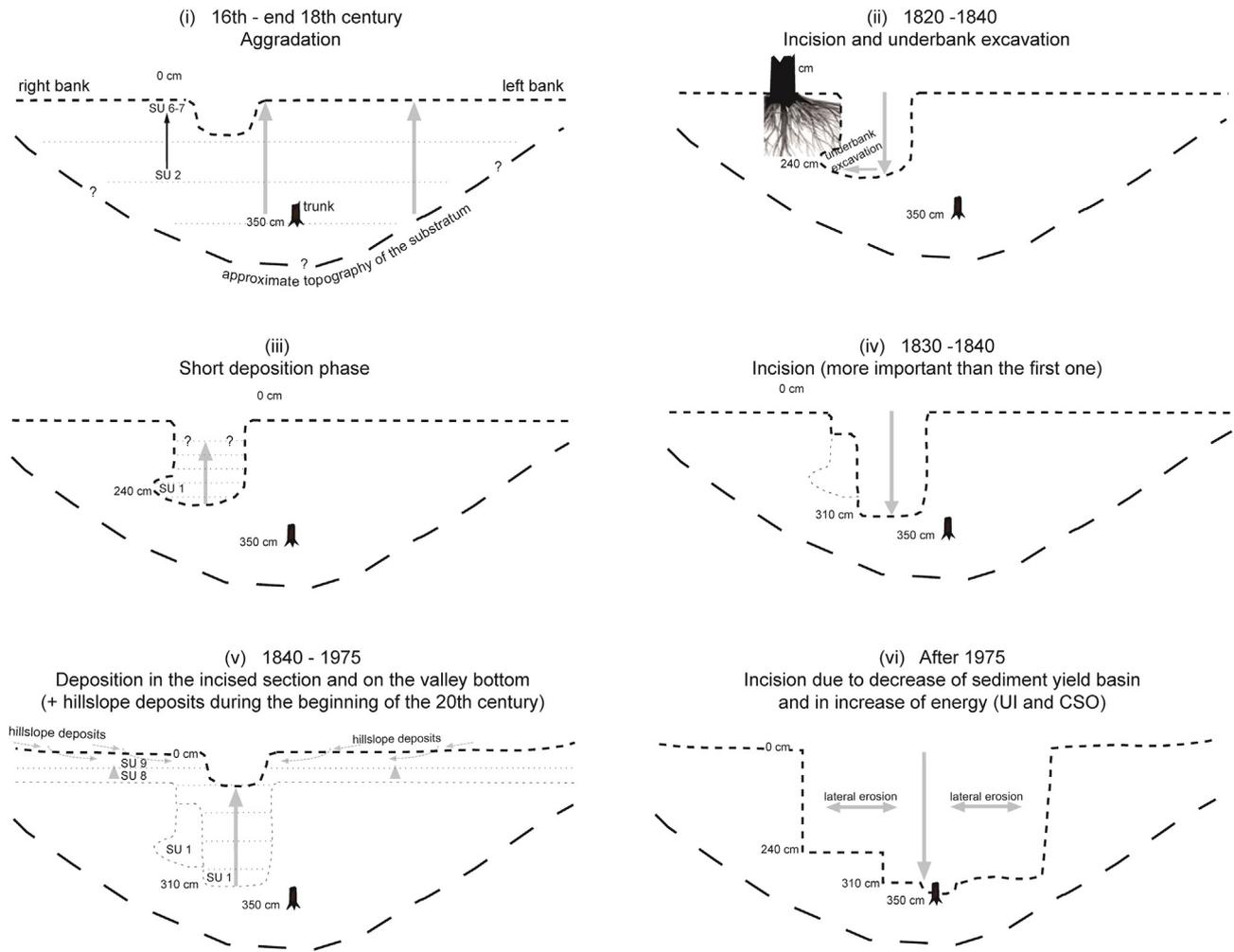


Fig. 5. Scheme of the aggradation and incision phases of the Chaudanne channel and valley bottom since the sixteenth century. This model of the sedimentary history has been made with ^{14}C and OSL datings.

Modified from Preusser et al. (2011).

randomly within the tree stump, is recognizable by the occurrence of older and isolated radiocarbon dates, which do not lead to the formation of a specific mode in the histogram. As an illustration of this effect, we can cite the example of the charcoal BOU 120, which shows a particularly significant age offset. We do not believe this can be attributed to ancient land clearings because of the lack of other charcoals from the eighth/ninth centuries.

Afterwards, the demographic decrease of the fourteenth and fifteenth centuries, from the plague and the Hundred Years War (Lorcin, 1974; Lorcin and Housnel, 2008), could indirectly explain the low frequency of the recorded radiocarbon ages for this period (Fig. 4B). Finally, the major peak in radiocarbon ages detected for the sixteenth century (Fig. 4B) could be associated with the modern demographic rise, the resumption of land clearing and the conquest of new agricultural surfaces. This trend is perceptible not only in the Lyon neighborhood but also in major parts of the kingdom of France, where it was accompanied by a significant decrease of woodlands (Garnot, 1998).

6.2. Assessment of sediment-transport processes

A common technique employed in geomorphology to assess sediment-transport processes is to analyze samples via the CM diagram of Passega (1957), which is based on grain size data (Bravard and Peiry, 1999; Bravard et al., 2014; Delile et al., 2015a,b). Fig. 7 shows this kind of data representation for all samples taken from the

four stratigraphic sections. The resulting image differs strongly from the original defined by Passega (1957) or that obtained for large rivers such as the Rhône River (Bravard, 1985; Macé et al., 1991). This singular image encompasses the contrast between two main components that reflect the influence of fluvial (red field) and colluvial (green field) processes (Fig. 7). Hillslope processes are more pronounced in the small watersheds studied (Preusser et al., 2011) where Holocene deposits are typically stored in colluvial fans and hillslope foots (Notebaert et al., 2013). Four groups are easily identifiable within these two components.

The green field integrates deposits coming from silty colluvium with granules mainly from diffuse runoff over plowed lands (C group) and a small part of the B and A' groups (Fig. 7). The C group is clearly dominated by the samples of the Prés-Mouchettes River section whose valley bottom is narrower and hillslopes are steeper.

The colluviation is characterized notably by a lower velocity of particle transport, which could explain, at least partly, the older age of the Prés-Mouchettes deposits. We can establish a parallel with Berger et al. (2002) who estimated, in their comparative study of alluvial and colluvial records from the watershed of the Citelle River (middle Rhône valley, left side), that hydrological fluctuations in the colluvium is 10 times lower than in alluvium. The occurrence of colluvium in these deposits is not surprising because this process is enhanced by runoff over croplands (Auzet, 1987, 1990; Bertran and Texier, 1997; Bertran et al., 1998), which were significant from the sixteenth to the early

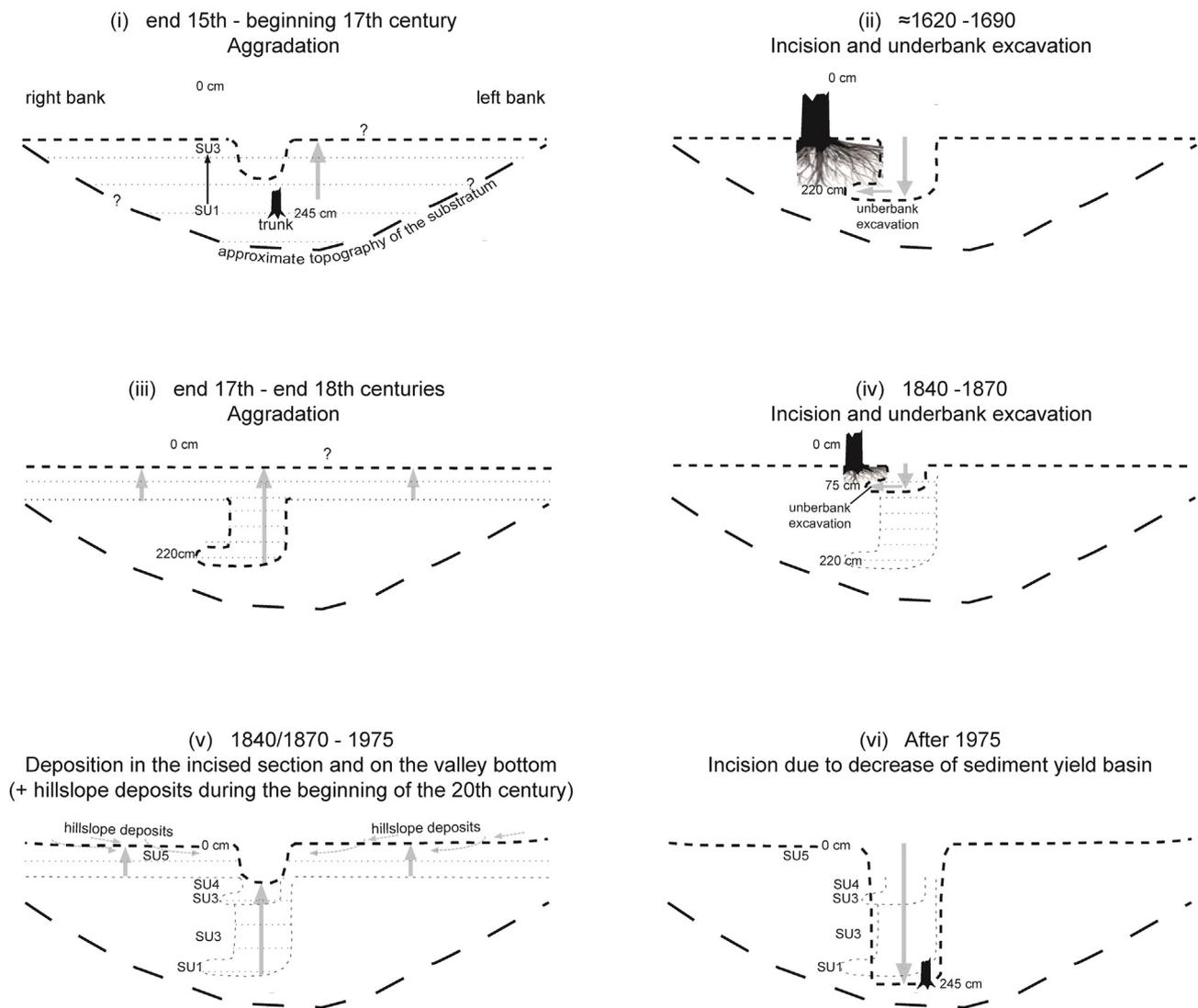


Fig. 6. Scheme of the aggradation and incision phases of the Bouillon channel and valley bottom since the end of the fifteenth century. This model of the sedimentary history has been made with ^{14}C and OSL datings.

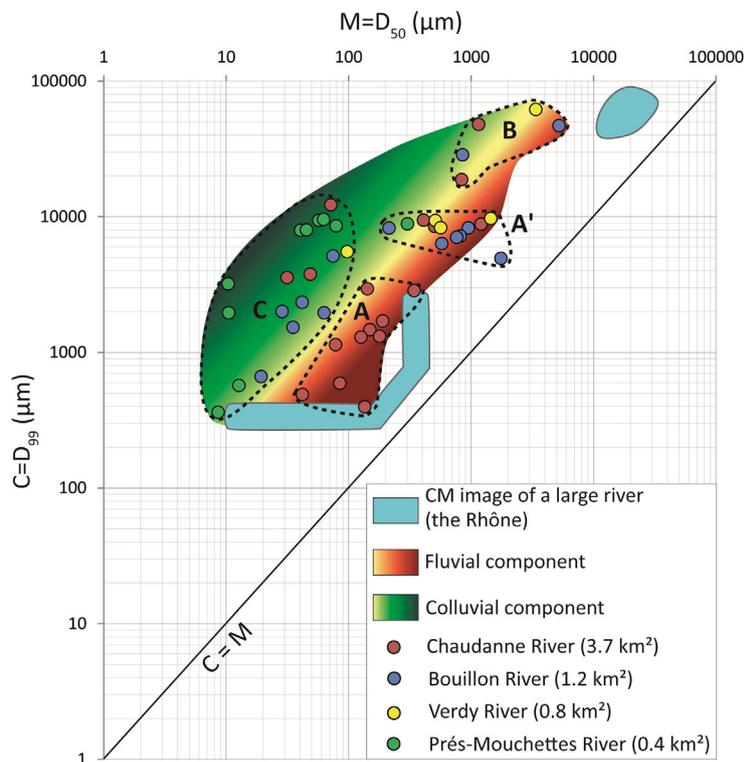
twentieth centuries according to historical studies (Lorcin, 1974; Lorcin and Housset, 2008; Rubellin, 2009), radiocarbon age frequency (Fig. 4B), and reconstitution of land use evolution (see land use maps of A.D. 1820 in Fig. 3). These particles, mobilized by sheet runoff over plowed fields, could generate a kind of mud flow toward the valley bottoms (Bertran and Texier, 1997). Typically, these colluviums produced by runoff over croplands take the appearance of sheets within the footslopes (Bertran and Texier, 1997).

The red field (fluvial component) contains the A, A' groups and a part of the B group (Fig. 7). These deposits correspond to well-sorted bars (graded suspension and rolled granules, A group), and well to poorly sorted gravel bars or lens. The major difference between the two groups is the level of sorting, which is more developed for the A group (Fig. S2). This group is exclusively composed of sediments from the Chaudanne River, whose valley bottom is wider and more flared (20 to 60 m). The lateral inputs of colluvium are thus relatively restricted (Notebaert et al., 2013). Conversely, the Verdy and Bouillon streams (A' group, Fig. 7) flow through relatively narrow valley bottoms (< 20 m), where lateral inputs of coarse material are relatively higher (Notebaert et al., 2013). With this in mind, these sand and gravel lenses cause a much faster aggradation of the alluvial floor of the Chaudanne, Bouillon, and Verdy rivers than the previously discussed C group

(Près-Mouchettes River) because the diffuse flows are able to form stratified sedimentary structures (Bertran and Texier, 1997; Bertran et al., 1998).

6.3. Proposal of a sedimentary cascade model

The available age constraints and knowledge of land use allow us to establish a scheme of hydrosedimentary evolution over time in the four catchments. According to the excavated stumps of the Chaudanne river, before the sixteenth century, valley bottoms are more than 3.5 m below their current level (Figs. 5 and 6), and are covered by a riparian forest of genus *Populus*, *Salix* and *Alnus glutinosa/incana* (Preusser et al., 2011). At this time, the relatively mild hydroclimatic conditions of the Medieval Climatic Optimum (MCO)-LIA transition period should restrict sediment inputs into the fluvial system. This low sedimentary supply was probably due to relatively small proportion of ploughlands in the watershed (Fig. 4B) so that no or only weak aggradation occurred. This limited land use seems to be strengthened by the absence of colluvial deposits in the basal part of the stratigraphies except for that of the Près-Mouchettes, which is entirely composed of colluvium (Figs. 2 and 7). Consequently, water could have flowed into a single channel (or little anastomosing channels) presenting low lateral dynamics (notably



- A: Well-sorted sand bars (graded suspension and rolled granules)
 A': Well to poor-sorted gravel bars or lens, according to the proportion of sandy matrix in deposits
 B: Angular blocks forming part of the bedload or at the limit to the transport capacity of the watercourse
 C: Deposits coming from silty colluvium with granules mainly from diffuse runoff on ploughed lands

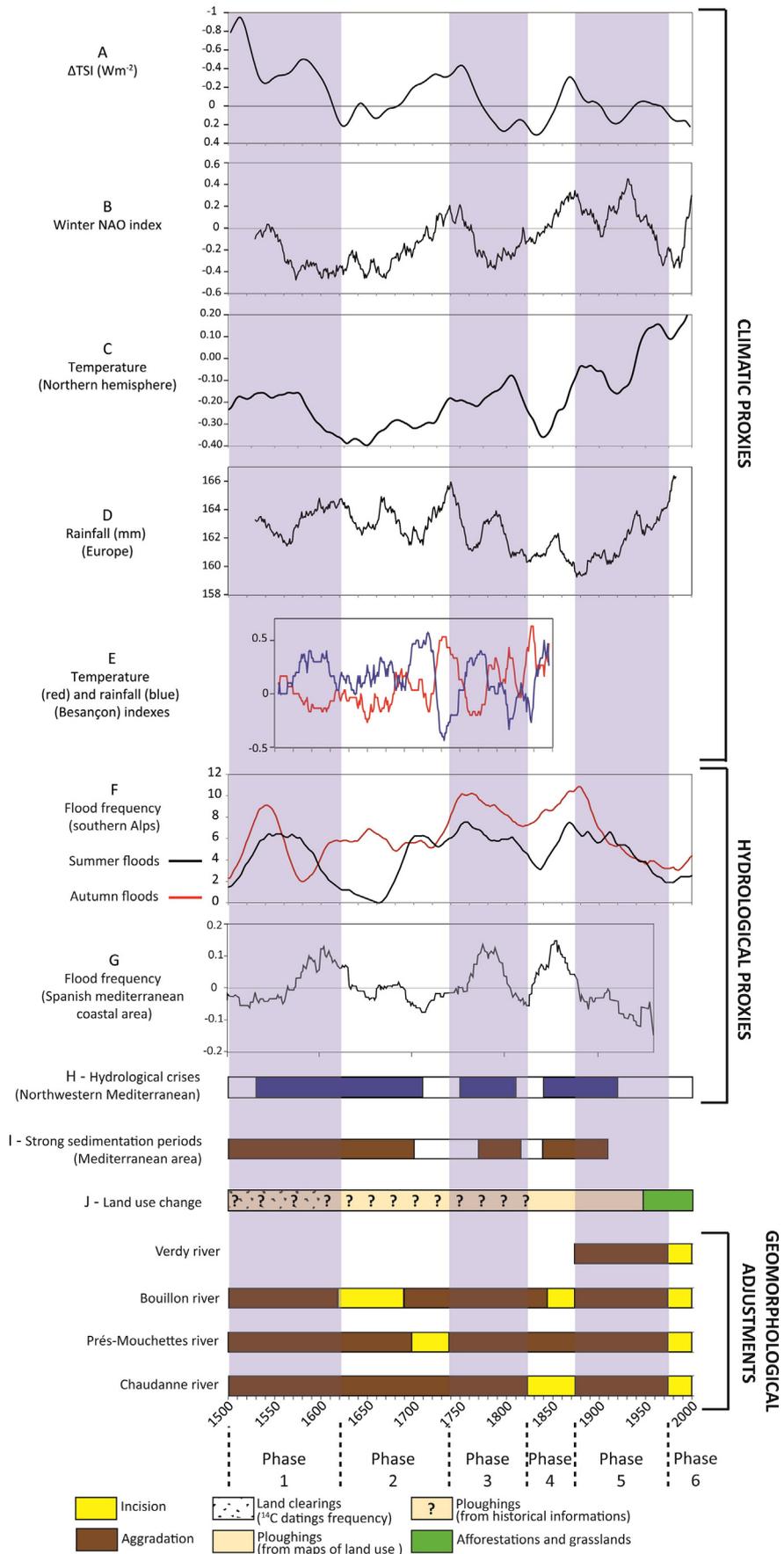
Fig. 7. Plot of grain size 99 percentile (D_{99}) versus median grain size (D_{50}) for the different samples analyzed. The different color groups correspond to different rivers assigned to either fluvial (red field) or colluvial (green field) components. Sediment sorting increases together with the size of subcatchments (surface in km^2). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

from the vegetation) and moderate hydrodynamics. In such conditions, some events could have reworked and transported as bedload the coarsest particles, which probably were provided from remnants of periglacial alluvial sheets or local rocky outcrops, even if minor indirect injections from reworking of colluvial deposits of footslopes should not be underestimated.

The depth of excavated stumps found in the current river bed of the Chaudanne allows us to estimate the thickness of sediments deposited between the sixteenth and nineteenth centuries and thus indicates the level of floodplains before that period (Figs. 5 and 6). This aggradation of the valley floor was logically associated with its lateral enlargement, wherein the channel pattern may have evolved toward an anastomosed style (probably not continuous) with abundant sandy bars. This evolution has concerned flat bottom valleys of the Plateau Lyonnais like those of the Chaudanne River. In the field, we detected evidence for ancient stream beds, probably not continuous over time, throughout the current lateral depressions lining each side of the Chaudanne River floodplain. These were not observed in the Monts du Lyonnais. In general, the aggradation is composed of coarse and relatively well-sorted fluvial deposits (groups A, A' and B) in which there are occasional colluvial intrusions (group C) (Figs. 2 and 7). The major source of the coarsest material has shifted toward the reworking of the colluvial footslope deposits, which contain small blocks. Such angular blocks have been detected in a stratigraphic section of a colluvial fan at Vaise (suburb of Lyon; Bertran et al., 1998). The aggradation and the lateral expansion of the floodplains (exclusively for the Plateau Lyonnais area) favored the coupling of hillslopes and stream channels during this period. This process conducted individual channels and the

anastomosed bed to improve their erosion efficiency on (i) footslope deposits and (ii) colluvial fans incorporating angular blocks.

The major change occurred during the 1950–1960s when watercourses probably began to contract into a single channel. Indeed, for the Chaudanne River, interviews with riverine property owners indicate that a small stream channel (about 1 m width and 50 cm depth) still existed at this time and that frequent overflows arose. This might explain the rounded shape of riverbanks developed with mostly sandy deposits trapped by grassland. This first stage of channel contraction could have been caused by the end of the LIA and a decrease of croplands and ploughlands (Fig. 3) that reduced hillslope erosion and thus sediment inputs to rivers. This trend accelerated during the second half of the twentieth century owing to the continuous decrease in cropland on the one hand and the increase of afforestation and urban areas on the other hand (Fig. 3). This tendency is confirmed by the disappearance of colluvial deposits since the second half of the twentieth century in the upper part of the stratigraphies except for that of the Prés-Mouchettes, which is entirely composed of colluvium (Fig. 2). By the classical effect of retroaction, these new conditions weakened the lateral dynamics of stream beds that rendered rarer the reworking and the transport of colluvial deposits stored on floodplains or on footslopes. This trend is confirmed because at that time the stream channel was marked by a deep entrenchment and a great lateral enlargement (Grosprêtre, 2011; Preusser et al., 2011) making the frequency of overflows decrease along many reaches. Thus, supply of the coarsest sediments is now dominated by indirect inputs from bed and bank erosion of layers previously deposited from the sixteenth to nineteenth century (Fig. S2).



In this sedimentary cascade model, characterized by alternating phases of storage and removal (Figs. 5 and 6), the simultaneous or alternating combination of the multiple sedimentary sources arise under anthropogenic control. Climatic variations should not be underestimated though.

6.4. Hydrogeomorphological adjustments to climate variability and land use changes

Despite high sediment supply from hillslopes, the rhythm of aggradation appears discontinuous through time. Two incision phases occur between the sixteenth and nineteenth centuries (A.D. 1620–1740 and 1820–1870; Fig. 8), suggesting an internal secular rhythmicity within the LIA. We hypothesize that these incision phases might have been triggered by variations in the rainfall regime and, more precisely, by a decrease in the frequency of heavy rainfall events leading to a relative lowering of sediment supply from hillslopes. This hypothesis is supported by previous studies made in regional environments (Gob et al., 2008; Astrade et al., 2011). Fig. 8 compares the evolution (A.D. 1500–2000) of climatic and hydrologic proxies with geomorphic adjustments (aggradation vs. incision) of the four streams considered here and in other well-studied fluvial systems of the Mediterranean region. This figure shows that the LIA was marked by three periods of high fluvial activity and two periods of relative calm (Gob, 2005; Gob et al., 2008).

From A.D. 1500 to 1620 (first gray band, Fig. 8), the Bouillon, Chaudanne, and Près-Mouchettes valley bottoms recorded high sedimentation rates, as did several rivers of the Mediterranean area (Fig. 8I). Such sedimentation increase was also recorded in rivers of the southern Massif Central (Jacob, 2003; Gob et al., 2008), as well as of the western side of the Monts du Lyonnais. In this area, small alluvial plains of the Forez basin were filled with <2–3 m of sandy-gravel sediments, in which are found fossilized wood pipes dating from the mid-fifteenth century (Cubizolle, 2009). Municipal archives of Lyon report that the second half of the sixteenth century was marked by a sharp intensive cooling and major flooding of the Rhône River (Municipal archives of Lyon, 2012). Similarly, historical studies of rivers flooding in the lower Rhône valley described a broad flood phase over the sixteenth century (Pichard, 1995; Pichard and Roucaute, 2014). Further and at a larger scale, this first period corresponds closely to a peak in flood frequency in the southern Alps (Fig. 8F) and Spanish Mediterranean coast (Fig. 8G) and to the first torrential crisis in the northwestern Mediterranean area (Fig. 8H). These were generated by a decrease of the total solar irradiation (Δ TSI, Fig. 8A) and the increasingly negative values of the winter NAO index (Fig. 8B), which led to a decrease of temperature and an increase of rainfall (Figs. 8C–E). This causal relationship between climatic evolution (cool and wetter conditions) and hydrological adjustments (more frequent floods) has been recently emphasized for the northwestern Mediterranean region during the Holocene (Benito et al., 2015a, b). Even though there is evidence for climatic deterioration at this time, it is important to emphasize that this first phase relating to the aggradation of the valley bottom was caused also by the intensive land use suggested by the greatest frequency of radiocarbon ages during this period (Figs. 4B and 8).

Bouillon and Près-Mouchette valley bottoms lowered between A.D. 1620 and 1740 (first white band, Fig. 8). This incision phase is slightly early compared to the sedimentation and hydrological decrease in the Mediterranean area of A.D. 1700–1770 or 1710–1750, respectively (Figs. 8H, I). The Rhône River is not exempt from this general trend as it manifested a slowdown in activity during the first half of the

seventeenth century and A.D. 1712–1740 (Pichard 1995; Pichard and Roucaute, 2014). This decline in fluvial activity seems to be related to the first multidecadal phase of droughts during the second half of the seventeenth and early eighteenth centuries that occurred in most of the Mediterranean's western basins (Carozza et al., 2014). Climatic fluctuations seem to be the main control factor influencing the decrease in flood frequency along the Spanish Mediterranean coast and southern Alps (at least for summer floods), the timing of which is rather well centered on our recorded incision phase (A.D. 1620–1740; Figs. 8F and G). In the same way, hemispheric-scale parameters of the temperature and the winter NAO started to increase continuously early in phase two. However, both values remained slightly below their phase one averages until the end of phase two. During the first part of phase two, TSI values are positive; whereas during the second part they shift toward negative values (Fig. 8A). It is relatively difficult to assess precisely the impact of land use on the vertical dynamics of the valley bottoms during phase two because only historical textual information is available (De Farcy, 1950; Lorcin and Housnel, 2008). According to it, plowing activities would have been intense during this period, consequently ensuring a good connectivity between slopes and riverbeds. Aggradation did not occur, however. Instead, incision took place, probably because of the insufficient runoff related to the decrease in flood frequency required to ensure the transport of sediments toward the valley bottoms (Bravard, 2002).

The following phase three extended from A.D. 1740 to 1820. It is a new period of aggradation of the valley bottoms in the western area of Lyon (second gray band, Fig. 8I). It is globally coeval with a strong sedimentation period in the Mediterranean area, a torrential crisis in the northwestern Mediterranean (Gob, 2005; Gob et al., 2008), and to higher flood frequencies in the southern Alps, Spanish Mediterranean coast, and more largely in the Mediterranean (Benito et al., 2015a, b). These hydrologic and geomorphological evolutions appear to result from climatic deterioration at a regional scale as evidenced by rainfall and temperature recorded in Besançon, some 200 km north-northeast of Lyon (Fig. 8E). But at the larger scale, most climatic proxies show a different trend: the overall decline of average European rainfall and the increase of Δ TSI and northern hemisphere temperature. Only the winter NAO index follows a trend consistent with climatic deterioration. Moreover, as we noted above, from the end of the Middle Ages to the nineteenth century, there was strong human pressure on land use, which would also explain this aggradation phase.

A new phase of incision occurred in the Chaudanne streambed in the mid-nineteenth century roughly between A.D. 1820 and 1870. More precisely, Preusser et al. (2011) argued the existence of two short-lived phases of incision during this period. These are separated by a subsequent aggradational phase (unknown age). The second incision reached a lower level (310 cm) than the first incision (240 cm). The first incision is directly followed by deposition in an undercut area of the bank, while the second incision was characterized by a narrower channel and thus preservation of the previously incised and filled section. As explained before, land use maps suggest no significant change during this period (Fig. 3), but a peak in agriculture occurred around 1860 in the Yzeron valley, followed by a decrease of vineyards and cropland (De Farcy, 1950). During this period, rainfall in Europe decreased to its lowest level since A.D. 1500 (Fig. 8D). According to several studies, the period A.D. 1820–1840 is also characterized by severe droughts and a low frequency of high rainfall events (Bravard, 2000; Jacob-Rousseau and Astrade, 2010, 2014; Astrade et al., 2011). Thus the incision of the Chaudanne streambed could have been triggered

Fig. 8. Evolution through time of the vertical dynamics of the four valley bottoms highlighting sedimentation (gray bands) and incision (white bands) phases. These latter are compared to the (A) total solar irradiance (Steinhilber et al., 2009a, b), (B) winter North Atlantic Oscillation (NAO) index (Luterbacher et al., 2002, 30-year moving average), (C) northern hemisphere temperature (Mann et al., 2009), (D) European rainfall (Pauling et al., 2006, 30-year moving average), (E) temperature and rainfall indexes at Besançon (Garnier et al., 2011; 15-year moving average), (F) flood frequency of the southern European Alps (30-year moving average) (Wirth et al., 2013), (G) flood frequency of the Spanish Mediterranean coastal area (Vallve and Martín-Vide, 1998; 30-year moving average), (H) hydrological crises of the northwestern Mediterranean area (Gob, 2005; Gob et al., 2008), (I) strong sedimentation periods in the Mediterranean area (Gob et al., 2008) and incision phases (yellow) identified in this studied according to the depth of OSL age inversions, (J) land use change (this study). All of these curves are produced from annual averages, excluding curves B and F. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

by a decrease in sediment supply from hillslopes, favored by soil stability despite intensive agriculture (plowing). Such developmental processes are reported in some prealpine catchments of the Rhône's tributaries (Bravard, 2000). The low flood frequency in different parts of western Europe (Figs. 8F and G) is coeval with the shifting conditions recorded also in palaeoflood archives of Lake Blanc in the French Alps (Wilhelm et al., 2013). Finally, we believe that despite the sediment availability related to the significant ploughings at this period, runoff was not sufficient to ensure the transport of sediments toward the valley bottoms caused by the decrease in flood frequency, unlike the previous period (phase 3). Such inhibition of sediment inputs in river beds from the slopes, following a rainfall deficit, was observed in the eastern Diois (French Southern Alps) during the first part of the nineteenth century (Bravard, 2002). As explained above, climatic conditions seem to control this trend. Winter NAO increased throughout phase four, and Δ TSI reached its highest level early in this period then decreased rapidly after A.D. 1840 (Figs. 8A and B).

The OSL dating is not precise enough to determine exactly the timing of this phase four that ended earlier in the upper Ardèche (Jacob, 2003), southern Alps (Descroix and Gautier, 2002; Astrade et al., 2011), and in the Cévennes (Massif Central, France; Astrade et al., 2011). This was also the case for the Mediterranean area where many rivers recorded a decrease of their hydrological and sedimentary activity until A.D. 1840 (Fig. 8H and I).

The same time offset is observed in phase five with a return to high sedimentation rates about 30 years earlier in the Mediterranean area (around A.D. 1840) than in our studied watershed (around A.D. 1870). However, in the Cévennes, Jacob-Rousseau and Astrade (2014) reported high sediment delivery levels more synchronous with our chronology (since A.D. 1855–1870) that contributed to increased lateral mobility of riverbeds. In our basins, this new phase of sedimentary accumulation is not owing to climatic degradation because the end of the LIA is commonly dated to around the 1860s (Bravard, 1989; Labalette, 2009), and all indicators point toward a reversion to more clement climatic conditions (TSI, NAO, temperature, flood frequency). Consequently, land use could be a key to understanding this aggradation of valley floors. Figs. 3 and 8 clearly show that ploughlands and grasslands continued to be widespread up to A.D. 1914 in the four studied subcatchments. As discussed above, the major shift occurred between A.D. 1914 and 1970 when afforestation increased significantly (Figs. 3 and 8). While detailed land use evolution during this period is not known for the subcatchment scale, it seems that at the Yzeron's watershed scale, ploughlands and grasslands declined greatly from A.D. 1929 and 1970, respectively (Grosprêtre, 2011). Such aggradation of valley bottoms until the twentieth century is not an exception; for example, Jacob-Rousseau and Astrade (2014) listed detrital inputs to the valley bottoms up to the first half of the twentieth century in the Cévennes (France).

6.5. Seasonal variability of rainfall and geomorphological adjustments

There are no local meteorological series that would document the monthly evolution of rainfall before the end of the nineteenth century. However, from studies carried out in neighboring areas, we provide some assumptions about the role of rainfall seasonal variability on sediment transfer in the small studied watersheds. As mentioned above, the Lyon region is characterized by a semicontinental climate, with pronounced Mediterranean and oceanic influences. The average monthly rainfall is largest in autumn (September to November) and spring (April–May). Nevertheless, the most sustained rains occur more than 70% of the time in summer, from July to September (Comby, 1998; Lecourieux, 1999). Given the intensity of precipitation, storm events have the highest morphogenic efficiency on the slopes as well as in the valley bottoms. However, several studies conducted during the last 15 years on basins from the middle Rhône valley, the western Alps, and the eastern Massif Central have highlighted quite significant variations in annual rainfall distribution and intensity (Bravard, 2000;

Descroix and Gautier, 2002; Jacob-Rousseau and Astrade, 2010; Astrade et al., 2011; Jacob-Rousseau and Astrade, 2014).

When comparing the vertical dynamics of the valley bottoms studied here (gray and white bands, Fig. 8) with the evolution of alpine floods (Fig. 8F), we observe that aggrading phases (phases one, three, five; Fig. 8) are perfectly centered on the maxima of the autumn floods, while the incision periods coincide with the minima of the summer floods (phases two, four, six; Fig. 8). The influence of intra-annual rainfall variability on hydrogeomorphological adjustments has also been demonstrated in the southern Alps and the Cévennes, where incision during the early nineteenth century occurred during a more pronounced rainfall deficit in September and October (the most important months for rainfall and river activity in this Mediterranean area) (Jacob-Rousseau and Astrade, 2010, 2014; Astrade et al., 2011). In addition, the same authors showed that during the 1850–1860s an important sediment discharge occurred during a period of unusually heavy rain in summer and autumn. These studies also suggest consideration of the role of the variability in atmospheric circulation. In the case of the Lyon area, the rainfall events can be classified into two main categories: firstly, the Atlantic disturbances related to the westerlies; and secondly, the Mediterranean rainfalls coming from the lower Rhône Valley (N–S exchanges). The latter produce more thunderstorms (Paturel, 1991). Bravard (2000), Descroix and Gautier (2002), and Astrade et al. (2011) also envisaged that one of the causes of the decrease in flood frequency could be the switch from a regime of Mediterranean summer storms to one of long and less intense rainfalls produced by westerly storm fronts coming from the Atlantic ocean during autumn and winter. This interpretation could be valid in the Lyon region given the origin of air masses.

Nevertheless, one should not underestimate the level of influence that the surface conditions of the basin have over the nature of geomorphic phenomena related to rainfall. Under the current conditions, with the absence of surfaces likely to provide a sediment load from the slopes, southern heavy rainfalls will promote river incision, as has been observed in November 2008. It was during this event that the trunks at the base of the Chaudanne section were excavated. This highlights the influence of Mediterranean climate on the Lyon region. The Mediterranean hydroclimatic events, whose intensity and frequency may vary over longer times, could be a very important driver of the vertical dynamics of the Lyon region's valley bottoms, particularly in the development of incision phases.

7. Conclusions

The OSL dating has shown a high potential to explain the recent sedimentation history of valley bottoms in small watersheds of the Yzeron basin (Rhône valley, France). These ages have revealed the complex history of the LIA's internal rhythms through several phases of aggradation-incision. Indeed, while the assemblage of radiocarbon dates is influenced significantly by ancient practices of land clearing by fires, thus confirming the limits of this method for dating developmental processes in such sedimentary environments, OSL ages reflect aggradation phases at valley bottoms and also, in some cases, incision phases of stream channels. This is an important issue in the case of small headwater streams, where underbank (and under-roots) scouring can play a relatively important role and explain OSL age-depth inversions.

Since A.D. 1500, these valley bottoms have undergone three cycles of aggradation-incision wherein two phases of low fluvial activity occurred (A.D. 1620–1740; 1820–1870). The impact of human activity was identified by the frequency of radiocarbon ages (first period) and the intense ploughings (third period). Nevertheless, the main controlling factor of the vertical dynamics of the valley bottoms seems to be the hydroclimatic variability of the LIA, exacerbated by land use conditions. This complexity is from the high sensitivity of such small basins to climate variations and different kinds of land use changes. Regarding

river management, it appears illusory to target the stability of the longitudinal profiles of Yzeron basin streams (in the present and/or the future) precisely in the measure that incision is likely to expand in the whole basin, even in subcatchments not affected by urbanization. Nevertheless, it seems important to mitigate UI and/or CSO induced by urbanization, because it increases significantly the volume of sediments removed by incisions in comparison with rural areas (Grosprêtre, 2011). River bed stabilization techniques should only be used in case local issues like destabilization risk houses or roads by incised channels.

The use of the CM technique allowed us to assess the main sediment sources (runoff over plowed lands, reworked materials from colluvial fans, hillslope foots, river banks and valley bottom deposits, and lateral erosion of the outcropping bedrock) in the Yzeron's subcatchments. Based on these interpretations, we proposed modeling long-term transport of the bedload as a sedimentary cascade, with alternating periods of storage (aggradation) and periods of incision.

The next step of our investigations in this area will be extensive field work, collecting cores along the transverse and longitudinal dimensions of the floodplains of the Yzeron catchment. By this, we hope to improve reconstruction of the fluvial architecture of the floodplain deposits as has been previously done in other basins (Walter and Merritts, 2008; Lespez et al., 2011).

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.geomorph.2016.01.010>.

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