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### ► **To cite this version:**

Frank Preusser, Laurent Schmitt, Hugo Delile, Loïc Grosprêtre. Optically Stimulated Luminescence (OSL) dating of the sedimentation history of the Yzeron Basin (Chaudanne sub-catchment), Rhône Valley, France. *Quaternaire*, 2011, 22 (1), pp.73 - 83. <10.4000/quaternaire.5877>. <halshs-01099914>

**HAL Id: halshs-01099914**

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Submitted on 7 Jan 2015

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# OPTICALLY STIMULATED LUMINESCENCE (OSL) DATING OF THE SEDIMENTATION HISTORY OF THE YZERON BASIN (CHAUDANNE SUB-CATCHMENT), RHÔNE VALLEY, FRANCE



Frank PREUSSER <sup>1</sup>, Laurent SCHMITT <sup>2</sup>, Hugo DELILE <sup>2</sup> & Loïc GROSPRÊTRE <sup>2</sup>

## RÉSUMÉ

Optically stimulated luminescence (OSL) dating is used to determine the (robust) chronology of the phases of sediment deposition and incision in a headwater sub-basin of the Yzeron Basin, France. Different statistical approaches to extract the mean equivalent dose from dose distributions are compared to estimate the effect of differential bleaching of the OSL signal prior to deposition. Two approaches result in OSL ages that are internally consistent and in excellent agreement with radiocarbon dating, indicating that all investigated sediments are younger than AD 1500. From this data a complex deposition and incision history is constructed for the last 500 years. It is concluded that sediment deposition was mainly forced by sediment supply from ploughing areas. Two short-lived phases of incision during the first half of the 19<sup>th</sup> century were probably caused by a decrease of sediment supply due to a decline in the frequency of heavy precipitation events. The channel incised during this period was later partly filled with sediment. The decline of agricultural land use from about 1915 onwards decreased sediment supply, while the increase of urbanisation from about 1950 amplified the flow energy of flooding by pluvial waters and overflows from storm basins, causing the presently ongoing incision in the area that began about AD 1975.

**Keywords:** luminescence, dating, headwater sediment deposits, partial bleaching, early modern and modern periods.

## ABSTRACT

DATATION PAR LUMINESCENCE STIMULÉE OPTIQUEMENT (OSL) DE L'HISTOIRE SÉDIMENTAIRE DU BASSIN DE L'YZERON (SOUS-BASSIN DE LA CHAUDANNE), VALLÉE DU RHÔNE, FRANCE

Des datations par OSL (Optically Stimulated Luminescence) sont utilisées pour reconstituer la chronologie de phases d'aggradation et d'incision dans un sous-bassin élémentaire du bassin de l'Yzeron (France). Différents traitements statistiques visant à extraire les doses équivalentes moyennes des distributions des doses sont comparés pour estimer l'effet de la variété du blanchiment du signal OSL antérieur au dépôt. Deux approches conduisent à des âges OSL cohérents entre eux et bien corrélés à des dates radiocarbones. Elles indiquent que tous les sédiments étudiés sont plus jeunes que 1500 ans ap. J.-C. A partir de ces données une histoire complexe de phases de dépôt et d'incision est reconstituée sur les 500 dernières années. Il apparaît que l'aggradation est principalement liée à la forte fourniture sédimentaire issue des labours. Deux brèves phases d'incision durant la première moitié du 19<sup>e</sup> siècle semblent liées à une baisse de la fourniture sédimentaire due à une diminution de la fréquence de précipitations intenses. L'incision de cette période fut par la suite partiellement comblée par des sédiments. Le déclin des labours à partir des années 1915 diminua la fourniture sédimentaire alors que le développement de l'urbanisation après 1950 augmenta l'énergie des crues (rejets d'eaux pluviales et de déversoirs d'orages), causant l'incision actuelle qui débuta vers 1975.

**Mots-clés :** luminescence, datation, dépôts de tête de bassin, blanchiment partiel, époques moderne et contemporaine.

## 1 - INTRODUCTION

Erosion and deposition of sediments in drainage basins in the headwaters of small rivers are mainly triggered by the impact of climate change and human activity (e.g., Hanson *et al.*, 2004; Leopold & Völkel, 2007; Fuchs & Buerkert, 2008). The major controlling factors behind whether a system is erosional or depositional are (i) the density and nature of vegetation cover (e.g., grassland versus forest), (ii) the amount and in particular the intensity of precipitation

(i.e. the occurrence of extreme events such as heavy thunderstorms), and (iii) whether humans are using land for either agriculture (i.e. disturbing the land surface by ploughing) or settlements (i.e. sealing of the land surface). When a drainage system changes from stable conditions to either an erosional or depositional mode, this is often of major importance for local communities (e.g., due to the loss of fertile soil). It is therefore necessary to understand why systems change their behaviour and one approach is to investigate its response to changes in the past.

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In this context, an important issue regards the dating of hillslope and alluvial headwater deposits to allow the geological evidence to be placed into the regional evolution of climate and the history of human occupation. 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 will rely on the dating of reworked material (e.g., wood). As a consequence, such dating approaches may overestimate the true time of sediment accumulation (e.g., Lang & Hönseid, 1999). Luminescence methods are now frequently used for the dating of colluvial sediments, as originally suggested by Wintle & Catt (1985) and recently reviewed by Fuchs & Lang (2009).

This article presents a case study on optically stimulated luminescence (OSL) dating of hillslope and alluvial headwater deposits from the Yzeron Basin, located at the western margin of the Rhône Valley in France. Establishing a robust chronology in this region is required to answer the question regarding the forcing factors behind sediment deposition and incision on hillslopes. In contrast to most previous studies, the sediments under consideration are very young (< 500 years) and a substantial data set (50 aliquots per sample) of luminescence measurements is available. In this light and with an upper age given by two radiocarbon samples, we will investigate the performance of different statistical approaches to extract mean  $D_e$  values from the dose distributions.

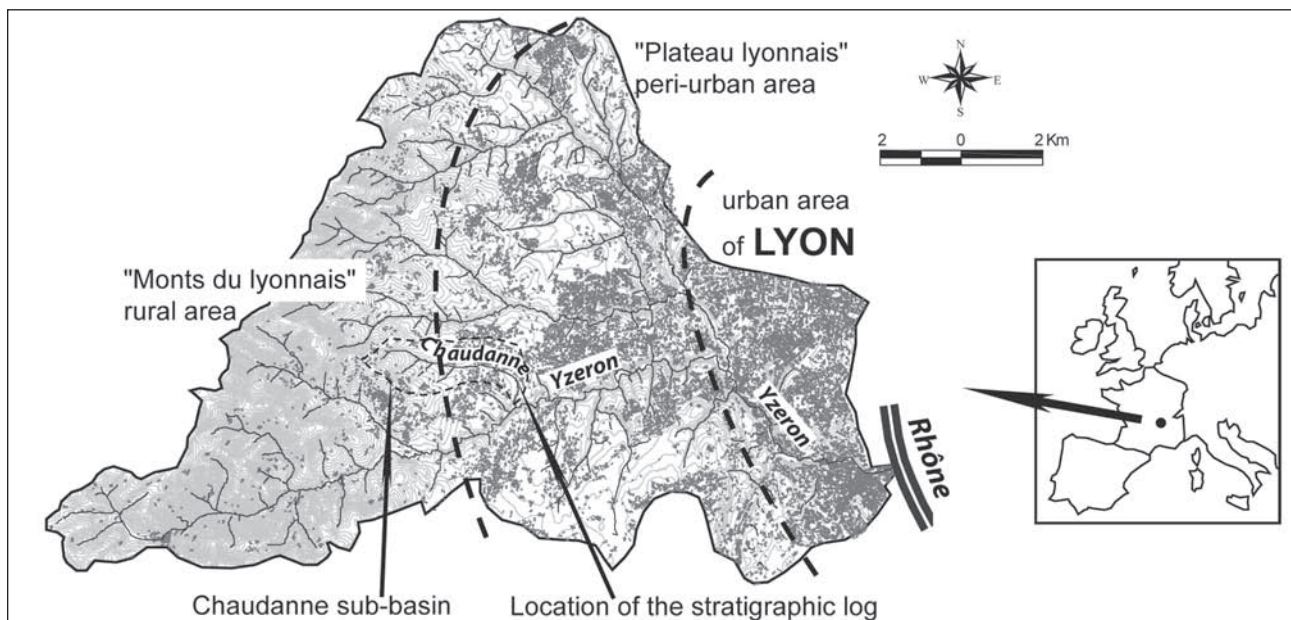
Palaeoenvironmental research in the Yzeron Basin was initiated by problems with managing the morphological dynamics of headwater streams in this region. Important channel incision is observed for one third of the streams and is characterised by an average lowering of bed channels by 2 m, with a maximum incision of 4 m. It is known from public records that these morphological

disturbances began mostly between 1973 and 1990 (Cordier, 2006; Grosprêtre & Schmitt, 2008). The most important incision is observed in the peri-urban sub-basins where urban inflow (UI) and/or combined sewer overflow (CSO) increase peak flow and consequently the energy level during floods. This also leads to an increase in flood frequency. However, incision also occurs in the upland rural area where CSO is absent and UI is much less common. This raises the question of the origin of channel degradation in the rural area. Our hypothesis is that the current incision in the rural area could be the result of a decline in sediment supply from hillslopes and the watershed, due to reduced agricultural activity (i.e. ploughing). Conversely, the hillslope deposits in which incision occurs could have been deposited during times of higher agricultural activity. This hypothesis could also explain why incision is so important in the peri-urban area, as it is enhanced by UI and CSO. More generally, it seems crucial to place the current channel adjustments in a large temporal trajectory of the morpho-sedimentary dynamics of the valley bottoms. This hypothesis is similar to the model developed for larger basins in the French pre-Alps and the Jura Mountains, where bed material is coarser (Bravard, 2002; Liébault & Piégay, 2002). Testing our hypothesis requires the establishment of a high-resolution deposition chronology and to compare this with the historical evolution of hillslope land cover.

## 2 - REGIONAL SETTING

### 2.1 - SITE DESCRIPTION

The Yzeron River Basin (147 km<sup>2</sup>) is a right-side tributary of the Rhône River located near the city of Lyon (fig. 1). From west to east, in the downstream direction,



**Fig. 1: Location of the Chaudanne sub-basin and river in the Yzeron basin.**

*Fig. 1: Localisation du sous-bassin et du cours de la Chaudanne dans le bassin de l'Yzeron.*

the basin drains a subdued degraded granitic and gneissic mountain (Monts du Lyonnais, a mostly rural area), a gneissic and partly granitic plateau (Plateau Lyonnais, a mostly peri-urban area in the Lyon neighbourhoods), and some inherited, mostly alpine, fluvial and glacial features (part of the urban area of Lyon). In the last area streamflows are rare because of the high permeability of the subsurface. Some discontinuous loess covers exist in the eastern part of the basin. Valley bottoms are relatively large and encased in the plateau (Schmitt *et al.*, 2004). The Chaudanne River, the focus of the present study, is a first order tributary of the Yzeron River (fig. 1). It drains a watershed of 3.7 km<sup>2</sup>, constituted from downstream of the Monts du Lyonnais and a gneissic part of the Plateau Lyonnais. In the Monts du Lyonnais and the Plateau Lyonnais, the variation in runoff is relatively large due to the weak permeability of the subsurface (Chocat, 1997). Hillslopes are generally covered by sandy regolith with a depth of up to more than 1 m (Mandier, 1984), which is highly sensitive to soil erosion in the absence of permanent vegetation. Mean seasonal discharge corresponds to an oceanic pluvial regime with a Mediterranean influence (high hydrological extremes).

Land use in the Chaudanne basin remained the same during the 19<sup>th</sup> century but significantly changed during the 20<sup>th</sup> century (Cottet, 2005; Privolt, 2009). For example,

the proportion of urbanised area increased dramatically (1 % in 1914, 37 % in 2008) at the expense of land used for agriculture (drop from 97 % to 60 %) (Privolt, 2009). It appears that surfaces that potentially provide sediment supply, i.e. ploughing areas, decreased by more than 35 %. This could possibly explain a sediment deficit in the headwater water system, and thus incision.

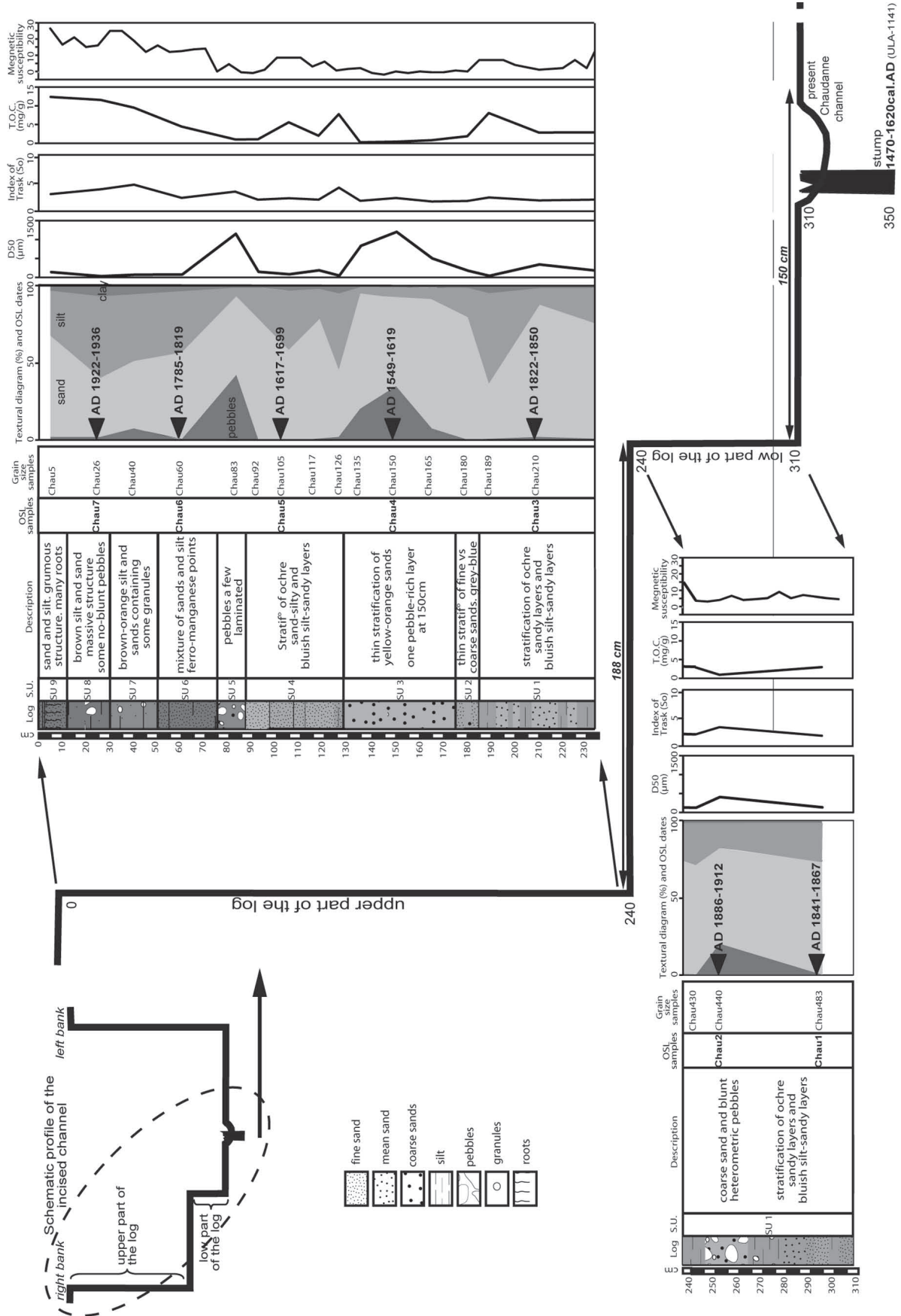
The investigated section (fig. 2) is located on the right bank of a deeply incised (3 m) reach of the Chaudanne River. Dendrochronology indicates that this incision began around 1975, following the establishment of UI and CSO due to peri-urbanisation (Cordier, 2006). From the investigated outcrop, the following data was collected: a general description of the different stratigraphic units (SU) (colour, structure) (tab. 1), median grain size and sediment sorting (18 samples), content of Total Organic Carbon (TOC) (18 samples) and magnetic susceptibility (measured each 5 cm). Figure 2 also indicates also the shape of the bank, which presents a bench at a depth of 240 cm, and the position of OSL samples. While OSL samples CHAU1-2 have been taken from a lower bank in the channel, samples CHAU3-7 are from the main exposure.

The sediments are mostly sands but contain some pebbles (3-4 layers) or silt. Clay is rare and does not exceed 5 %, the higher values being related to higher silt content.

Depth (cm)	Stratigraphic Unit	Description
12-0	SU9	Sand and silt (30-40%); grumous structure; many roots.
30-12	SU8	Brown silt (ca. 50%) and sand layer with massive structure; contains layer of no-blunt pebbles.
50-30	SU7	Brown-orange silt (ca. 50%) and sands, with granules; polyedric structure.
75-50	SU6	Sands and silt (max. 45%) with ferro-manganese spots.
87-75	SU5	Sand/silt with high pebble content (45%); partly laminated structure.
128-87	SU4	Stratification of ochre sand-silty layers and bluish silt-sandy layers, silt-clay content varies between 10 and 50%.
175-128	SU3	Thin stratification of yellow-orange sands; pebble-rich layer at 150cm; silt represents less than 10%.
185-175	SU2	Thin stratification of grey-blue fine and coarse sands; silt is about 20%.
308-185	SU1	Stratification of ochre sandy layers and bluish silt-sandy layers; layer of coarser particles (coarse sand and blunt heterometric pebbles) a 264-246cm; silt is about 20-25%.

**Table 1: Sedimentological description of the investigated section.**

*Table 1 : Description sédimentologique de la coupe étudiée.*



**Fig. 2: Stratigraphic log of the investigated section with a sketch showing the outcrop topography (after Delile (2009) modified).** OSL samples CHAU1-2 were taken from a lower part of the bank. Sample CHAU3 was originally interpreted to be stratigraphically older than CHAU4. According to the results of OSL dating, however, we suggest it represents a filled-up underbank excavation during the end of the early 19<sup>th</sup> century incision phase.

*Fig. 2: Log stratigraphique de la coupe étudiée et profil topographique schématisé de la berge (d'après Delile (2009) modifié). Les échantillons OSL CHAU1-2 ont été prélevés sur une banquette inférieure de la berge. L'échantillon CHAU3 a été initialement interprété comme stratigraphiquement plus ancien que CHAU4. Cependant, compte tenu de la date OSL obtenue, il est suggéré qu'il s'agit d'un dépôt consécutif à une excavation sous la berge pendant la fin de la phase d'incision du 19<sup>e</sup> siècle.*

The sediments are generally stratified and are moderately sorted according to the Trask index. The studied sediments are interpreted mostly as alluvial deposits but some hillslope deposits are apparently also present (SU8 and SU9). The occurrence of alluvial processes is confirmed by the flat valley bottom topography over a width of approximately 10-20 m. The content of organic matter (TOC) is higher in the silt-rich layers (SU1 highest layer, SU4), and the increase of TOC in the upper part of the stratigraphic log (SU6 to SU9) is possibly explained by present pedogenic processes. The latter also explains the increase of magnetic susceptibility in the upper four SUs. Colours of the whole log indicate a relatively high hydromorphy, with alternative permanent saturated phases (blue-grey colours; conditions of reduction) and phases of temporary saturated conditions (ochre-yellow-orange colours; conditions of oxidation) (Delile, 2009).

The age of sediment deposition is constrained by an *in situ* trunk of a tree found one metre beside the outcrop. Another trunk was found in a similar position about 20 m up-valley. These and ten other tree trunks found along the presently incising channel of the Chaudanne stream are of the genus *Populus*, *Salix* and *Alnus glutinosa/incana*, indicating a humid, riverine environment (Sarah Ivorra, personal communication). From this evidence, it is concluded that the trees were growing on a previously lower level of the valley bottom, and were later covered by the sediments exposed in the section. Radiocarbon dating of the two trees located close to the investigated section gave ages of AD 1470-1620 (ULA-1141;  $355 \pm 20$   $^{14}\text{C}$  yr BP; depth 350 cm) and AD 1520-1650 (ULA-1140;  $285 \pm 20$   $^{14}\text{C}$  yr BP; depth 220 cm) (calibration by OxCal v3.10; Bronk Ramsey 1995, 2001). This indicates that deposition of the sediment sequence took place after about AD 1500.

### 3 - METHODOLOGY

#### 3.1 - BASICS OF LUMINESCENCE DATING

Luminescence dating uses a light-sensitive signal in quartz and feldspar minerals that is depleted (bleached) during sediment transport, when the grains are exposed to daylight. During burial, when the grains are sealed from daylight, the latent signal in the minerals rises, being induced by ionising radiation from the surrounding environment. For dating, two values have to be determined, firstly, the amount of radiation absorbed by the minerals and stored as the latent luminescence signal, and, secondly, the amount of radioactivity in the sediment (dose rate). The first value is achieved by comparing the natural luminescence output to that of known given doses, and is termed equivalent dose ( $D_e$ ). A comprehensive review of luminescence methodology has been provided by, for example, Preusser *et al.* (2008, 2009).

The major limitation in luminescence dating of young hillslope and fluvial deposits is incomplete resetting of the signal prior to deposition. If any signal was present in the mineral grains at the time of deposition, it will be

added to the signal accumulated during burial and give an apparently higher luminescence age. This is why Optically Stimulated Luminescence (OSL) is preferred over thermoluminescence (TL) for the dating of sediments, as the OSL signal is several orders of magnitude more light-sensitive (i.e. it is more rapidly set to zero). For the detection of partial bleaching, it is important to keep in mind that individual grains within sediments have different depositional histories, i.e. have been exposed to daylight for different periods of time. Hence, sediments often consist of a mixture of completely and incompletely bleached grains (Duller, 1994). The most common approach to detect this differential bleaching in sediments is measuring a substantial number of single grains or small aliquots (cf. Wallinga, 2002). In this context, it is important to note that only a very small percentage (down to 1-2 %) of all quartz grains exhibit most of the OSL signal (Duller *et al.*, 2000). Many grains do not even emit any OSL signal. Hence, in small aliquots containing less than 100 grains, the OSL signal will originate from a few or even a single grain. The distribution of a suite of  $D_e$  values determined for a sample is statistically analysed and different methods have been suggested on how to extract the population of aliquots that represents the dose accumulated since deposition (cf. Bailey & Arnold, 2006). The statistical approaches used here are explained below.

#### 3.2 - SAMPLE PREPARATION, MEASUREMENT AND AGE CALCULATION

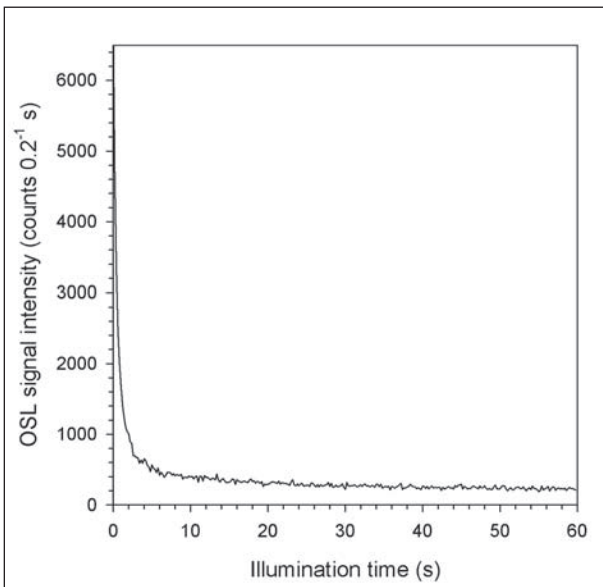
Samples were taken by forcing steel tubes into the freshly cleaned sediment exposure and sealing both ends of the tubes for transport. An additional kilogram of sample material was taken for the determination of the concentration of dose-rate relevant elements (K, Th, U). The steel tubes were opened in the red-light preparation laboratory and material from both ends was discarded as it may have been exposed to daylight during sampling. The rest of the material was dried and sieved (see table 2 for used grain size). Subsequently, samples were treated with HCl,  $\text{H}_2\text{O}_2$  and Na-Oxalate to remove carbonates, organic matter and disperse clay particles. The quartz fraction was isolated using heavy liquids (LST fast flow with densities of 2.70 and 2.58  $\text{g}\cdot\text{cm}^{-3}$ ) (Mejdahl, 1985) and etched with 40 % HF for 1 h, followed by treatment with HCl to dissolve fluoride precipitates.

All OSL measurements were done using a Risø DA20 TL/OSL reader. Quartz samples were exposed to IR diodes prior to all measurements and aliquots delivering any substantial signal response to this stimulation were discarded from further analyses as they probably contain feldspar contamination. OSL was recorded during a 60 s stimulation by blue diodes at 125 C using a Hoya U340 detection filter. The OSL signal from most aliquots is rather bright and dominated by the fast component (fig. 3). The first 0.2 s of the signal have been used for analyses. A modified single aliquot regenerative dose (SAR) (Murray & Wintle, 2000, 2003) was used for  $D_e$  determination (fig. 4). A series of standard performance

Depth (cm)	Grain size ( $\mu\text{m}$ )	n	K (%)	Th (ppm)	U (ppm)	Mois. (%)	W (%)	D ( $\text{mGy a}^{-1}$ )
26	100-150	51	$3.24 \pm 0.03$	$11.94 \pm 0.29$	$3.47 \pm 0.12$	19.4	$20 \pm 5$	$4.06 \pm 0.44$
60	150-200	50	$3.76 \pm 0.04$	$10.69 \pm 0.42$	$3.13 \pm 0.02$	20.1	$20 \pm 5$	$4.37 \pm 0.33$
105	150-200	40	$3.82 \pm 0.03$	$14.07 \pm 0.31$	$4.09 \pm 0.06$	22.9	$20 \pm 5$	$4.78 \pm 0.24$
150	150-200	45	$4.15 \pm 0.03$	$5.59 \pm 0.09$	$1.76 \pm 0.02$	5.9	$10 \pm 5$	$4.52 \pm 0.33$
210	150-200	44	$3.84 \pm 0.03$	$11.67 \pm 0.26$	$3.32 \pm 0.09$	16.8	$20 \pm 5$	$4.43 \pm 0.33$
252	150-200	43	$3.78 \pm 0.03$	$11.24 \pm 0.26$	$3.42 \pm 0.05$	14.3	$20 \pm 5$	$4.43 \pm 0.42$
295	150-200	43	$3.90 \pm 0.03$	$12.23 \pm 0.53$	$3.61 \pm 0.07$	-	$20 \pm 5$	$4.86 \pm 0.43$

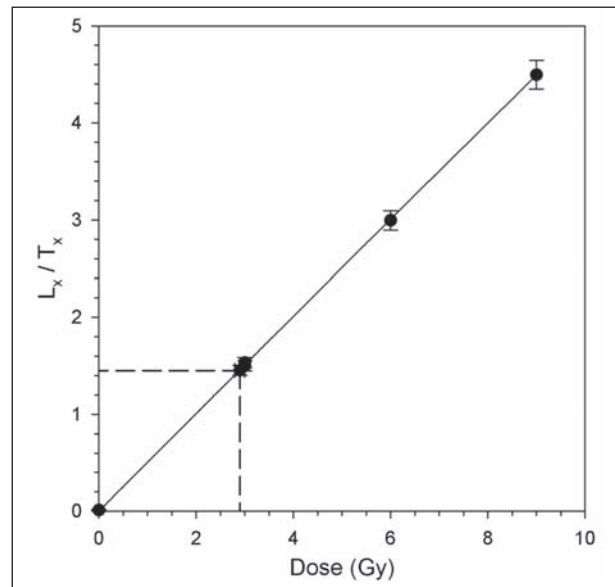
**Table 2: Dosimetric data used for OSL dating.**

Table 2: Données dosimétriques utilisées pour la datation OSL.



**Fig. 3: Typical OSL decay curve of an aliquot of sample CHAU1.**

Fig. 3: Courbe de décroissance OSL typique d'une aliquote de l'échantillon CHAU1.



**Fig. 4: Typical dose response curve of an aliquot of sample CHAU1.**

Fig. 4: Courbe de réponse de dose typique d'une aliquote de l'échantillon CHAU1.

tests was carried out (Wintle & Murray, 2006) and accordingly samples were preheated at 230 C for 10 s prior to all OSL measurements. For this procedure, the dose recovery ratio for a given dose (1.06 Gy) is 1.05 with a relative standard deviation (RSD) of 14.5 %. Following Rodnight (2008), more than 50 aliquots have been measured for each sample, the vast majority of which passed through the usual rejection criteria of the SAR protocol.

Samples for dose rate determination were dried, placed in Marinelli beakers containing ca. 500 g, stored for at least four weeks and measured for up to five days using a low-level high-resolution gamma spectrometer (cf. Preusser & Kasper, 2001). The weighted mean and its uncertainty calculated for different gamma lines (Th: 338.3, 583.2, 727.2, 911.2, 968.9, 2614.5 keV; U: 295.2, 351.9, 609.3, 1120.3, 1764.5 keV) was used to calculate the specific activities of radionuclides, which were transferred into

dose rates using the conversion factors of Adamiec & Aitken (1998). Following the approach described by Zander *et al.* (2007) and Preusser & 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 hydrological situation. The contribution from cosmic dose rate followed Prescott & Hutton (1994). All age calculations were performed using ADELE software (Kulig, 2005) and dosimetric data is summarised in table 2. The uncertainty calculations do not account for systematic calibration errors (gamma spectrometry, beta source) as these are not quantifiable. However, it is expected that the major uncertainty of the OSL ages comes from the estimation of average moisture content during burial, and a substantial uncertainty has been used in the age calculation to account for this.

### 3.3 - ANALYSES OF $D_e$ DISTRIBUTIONS

None of the various statistical approaches for extracting mean  $D_e$  from differentially bleached sediments has proven to universally give the correct results (Bailey & Arnold, 2006). For assessing the reliability of mean  $D_e$  calculation, we compare four different approaches here. The *Central Age Model* (CAM, Galbraith *et al.* 1999) is designed to identify the central tendency in a dose distribution (similar to the arithmetic mean) and will overestimate the  $D_e$  accumulated during burial in differential bleached sediments. However, this approach provides an important statistical value, the overdispersion that is discussed below, and  $D_e$  values calculated for this approach are given here for comparison. The *Finite Mixture Model* (FMM, Galbraith & Green, 1990) discriminates between discrete populations within a dose distribution. For differentially bleached sediments, the lowest population of  $D_e$  values is considered to represent the grains in which the OSL signal was set to zero at deposition (Rodnight *et al.*, 2006). The *Minimum Age Model* of Galbraith & Laslett (1993) (MAM) fits a truncated normal distribution to the logarithms of the individual  $D_e$  values, with the truncation point giving the mean. The potential weakness of this approach is that it is very sensitive to outliers at the lower edge of the dose distribution. In contrast, the FMM allows the identification of outlying low values as a separate population that can be removed from data analyses. The *Minimum Age Model* of Preusser *et al.* (2007) (MAP) is based on the approach introduced by Fuchs & Lang (2001) that uses the relative standard deviation (RSD) of mean  $D_e$  observed in dose recovery tests as a threshold (i.e. the reproducibility of the OSL measurement for a known given laboratory dose). Starting with the lowest  $D_e$  value, and including one additional  $D_e$  value at a time, the mean and standard deviation are calculated until the RSD reaches the threshold. However, this approach is also very sensitive to outliers at the lower edge of the distribution. Furthermore, it does not consider other sources of variability in the dose distribution, i.e. the effect of microdosimetry. Actually, Mayya *et al.* (2006) have demonstrated by Monte Carlo simulations that the latter effect is substantial, and Rufer & Preusser (2009) have visualised this using autoradiography. In their approach, Preusser *et al.* (2007) calculate the combined effects of laboratory reproducibility and microdosimetry, and also integrate an automatic 5 % outlier probability in their procedure.

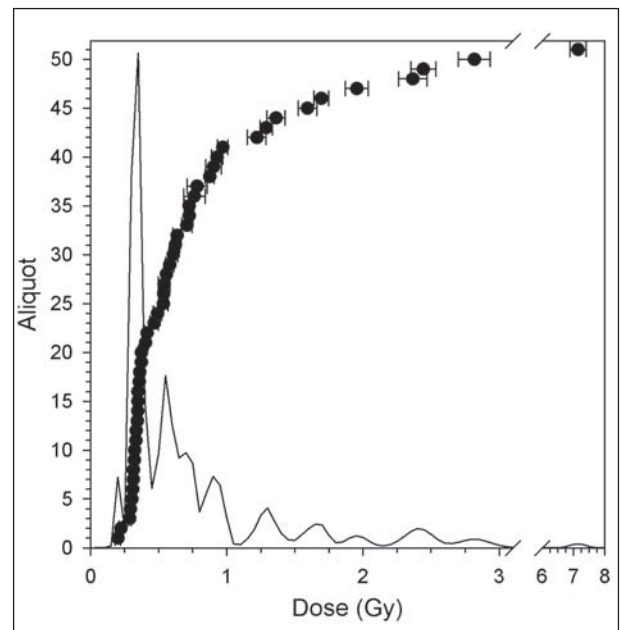
FMM and MAM rely on the overdispersion as an input parameter, which defines the spread of data additional to the spread expected from the errors on each  $D_e$  value (Galbraith *et al.*, 1999). This value has to be estimated empirically and we use an overdispersion of 0.19 as observed in two apparently well bleached samples from the area (Preusser, unpublished data). For MAP, the threshold parameter is calculated by combining the 14.5 % RSD observed in the dose recovery tests for our samples with an expected effect from microdosimetry of 15 %, as a typical value derived from literature (cf. Preusser *et al.*, 2007). This leads to an expected RSD of

21 %. Interestingly, RSD values of 20 % and 22 % have been found for the two well bleached samples mentioned above, giving us good confidence that this threshold parameter has been adequately assessed.

## 4 - RESULTS AND DISCUSSION

### 4.1 - OSL DATING

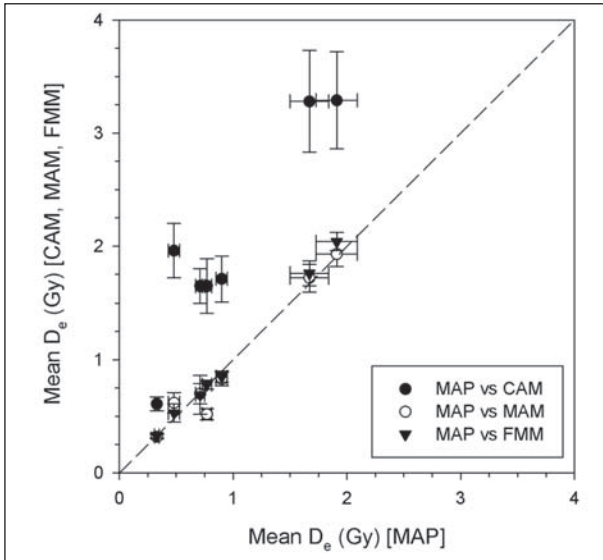
An example of the spread of  $D_e$  values is given in figure 5, representing the youngest sample of our data set (CHAU7). This plot reveals the skewed nature of  $D_e$  distributions, but with a distinct peak at its lower edge. Figure 6 and table 3 compare mean  $D_e$  extracted for the different methods, using MAP as a reference. This plot reveals that the CAM, as to be expected for differentially bleached sediments, results in significantly higher mean  $D_e$  estimates (average ratio CAM/MAP =  $2.28 \pm 0.82$ ). This clearly demonstrates that any kind of arithmetical averaging of the values from the  $D_e$  distributions is inappropriate; the CAM results in values up to four times higher than the other three methods. For MAM and MAP, five of the two values are consistent, but two values are off-set by some 30 % (ratio MAM/MAP =  $0.98 \pm 0.18$ ).



**Fig. 5: Dose distribution plot of sample CHAU7 revealing that the OSL signal of the individual grains of this sediment was differentially bleached prior to deposition.**

*Fig. 5: Distribution des doses de l'échantillon CHAU7 montrant que le signal OSL des grains individuels de ce sédiment a été blanchi différemment avant le dépôt.*

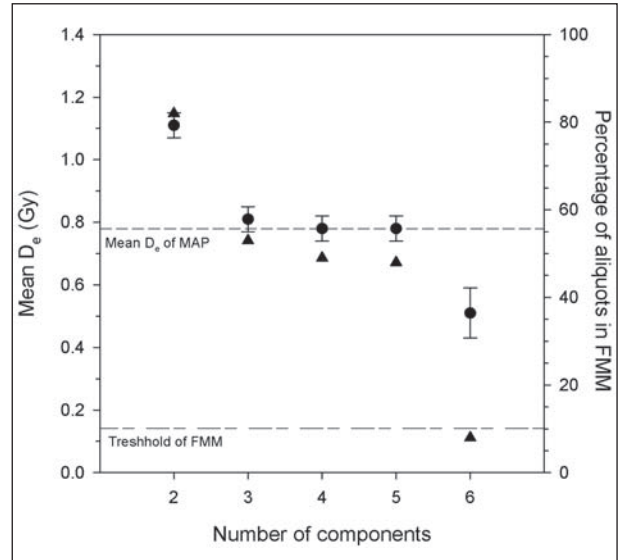
The FMM approach requires beside the overdispersion a second input value, the number of populations expected for a certain distribution, and we have carried out tests using between two and ten individual components. The example in figure 7 shows that constant mean  $D_e$  values are obtained when using three to five components. These



**Fig. 6:** Comparison of mean  $D_e$  values calculated for different statistical approaches using the Minimum Age approach of Preusser *et al.* (2007) as reference (MAP).

It is shown that (i) the Central Age Model (CAM) is significantly overestimating the MAP values, (ii) the Minimum Age Model (MAM) gives similar but more scattered results, and (iii) the Finite Mixture Model (FMM) gives almost identical values.

*Fig. 6 : Comparaison des valeurs de  $D_e$  moyenne calculées à partir de différentes méthodes statistiques prenant l'Approche de l'Âge Minimum (MAP) de Preusser et al. (2007) comme référence. Il apparaît que (i) le Modèle d'Âge Central (CAM) surestime significativement les valeurs MAP; (ii) que le Modèle d'Âge Minimum (MAM) donne des résultats similaires mais plus dispersés et (iii) que le Modèle de Mélange Fini (FMM) donne des résultats presque identiques.*



**Fig. 7:** Testing the performance of the FMM by varying the number of components used for fitting.

Plotted is mean  $D_e$  and the percentage of aliquots included in the model versus the number of components. Using six or more components (not shown) results in unstable results, i.e. less than 10 % of the values are included in the model.

*Fig. 7: Test de performance du FMM en faisant varier le nombre de composantes utilisées pour l'ajustement. La  $D_e$  moyenne et le pourcentage d'aliquotes inclus dans le modèle ont été tracés en fonction du nombre de composantes. L'utilisation de plus de six composantes (non figurée) produit des résultats instables ne prenant en compte que moins de 10 % des valeurs.*

Sample	$D_e$ (CAM) (Gy)	$D_e$ (MAG) (Gy)	$D_e$ (FMM) (Gy)	$D_e$ (MAP) (Gy)	Age (CAM) (a)	Age (MAG) (a)	Age (FMM) (a)	Age (MAP) (a)	Age (MAP) AD
CHAU7	0.61 ± 0.06	0.32 ± 0.02	0.33 ± 0.02	0.33 ± 0.02	146 ± 17	77 ± 7	79 ± 7	79 ± 7	1922-1936
CHAU6	1.71 ± 0.20	0.83 ± 0.06	0.85 ± 0.05	0.90 ± 0.05	392 ± 52	191 ± 18	195 ± 16	206 ± 17	1785-1819
CHAU5	3.28 ± 0.45	1.72 ± 0.12	1.76 ± 0.11	1.67 ± 0.17	687 ± 103	360 ± 33	369 ± 32	350 ± 41	1617-1699
CHAU4	3.29 ± 0.43	1.93 ± 0.11	2.04 ± 0.08	1.91 ± 0.18	731 ± 105	429 ± 36	453 ± 33	424 ± 35	1549-1619
CHAU3	1.65 ± 0.24	0.52 ± 0.05	0.78 ± 0.04	0.77 ± 0.04	369 ± 58	116 ± 13	175 ± 14	172 ± 14	1822-1850
CHAU2	1.96 ± 0.24	0.62 ± 0.09	0.53 ± 0.08	0.48 ± 0.05	444 ± 60	141 ± 22	120 ± 19	109 ± 13	1886-1912
CHAU1	1.65 ± 0.15	0.70 ± 0.09	0.69 ± 0.17	0.71 ± 0.04	359 ± 39	153 ± 22	150 ± 38	154 ± 13	1841-1867

**Table 3:** Mean  $D_e$  calculated using different statistical approaches and resulting OSL ages.

*Table 3:  $D_e$  moyenne calculée d'après différents traitements statistiques et âges OSL obtenus.*

results are in agreement with the mean  $D_e$  calculated by the MAP. For six or more components, the results fall below the reference of MAP and include less than 10 % of all individual  $D_e$  values. According to Rodnight *et al.* (2006), components with less than 10 % of all values should not be considered as these may represent outliers. These authors also used a five component FMM and for our data, this approach generally gives almost the same results as the MAP (ratio FMM/MAP =  $1.02 \pm 0.06$ ; maximum offset 10 %). From this exercise we conclude that the FMM and MAP approaches can be considered as equivalent and likely providing reliable results for mean  $D_e$ . We will therefore only use the MAP ages in order to keep the discussion of the dating results straightforward. To allow direct comparison with radiocarbon dating, OSL ages are

transferred into years AD (*anno domini*; reference year 2008).

The uppermost sample (CHAU7) is dated to  $79 \pm 7$  a (AD 1922-1936), and the dating results increase consistently down the section with ages of  $206 \pm 17$  a (CHAU6, AD 1785-1819),  $350 \pm 41$  a (CHAU5, AD 1617-1699), and  $424 \pm 35$  a (CHAU4, AD 1549-1619). The latter sample is in excellent agreement with the radiocarbon ages of the two trunks, which indicate that the sediments must be younger than AD 1500. The two samples from the lower bank are dated to  $154 \pm 13$  a (CHAU1, AD 1841-1867) and  $109 \pm 13$  a (CHAU2, AD 1886-1912). These dating results indicate that the lower bank represents a later deposition event than the one found in the main section. Sample CHAU3 was according to field evidence interpreted to be older than

CHAU4, but the OSL age of  $172 \pm 14$  a (AD 1822-1850) is much younger than for CHAU4 ( $424 \pm 35$  a). Considering the apparent general reliability of OSL dating found at this site, we suggest that this sample was deposited in an area that has previously been laterally incised into underneath the bank (these processes have been observed in the present channel). A subsequent aggradational phase followed by a second incision, which reached a lower level than the first incision, led to the deposition of samples CHAU1 and CHAU2. Interestingly, all three samples belong to the same SU. Depending on the stability (cohesion) of the bank material, it is unlikely that sediment which fills the undercut bank will be preserved. As a consequence, we speculate that the age of sample CHAU3 (AD 1822-1850) just post-dates the time of the first incision.

#### 4.2 - IMPLICATIONS FOR SEDIMENTARY DYNAMICS

With the exception of SU8 and SU9, all other deposits are alluvial sediments as typical for headwater environments characterised by short transport distances between erosion and deposition areas (Cailleux & Tricart, 1959) and variations of transport energy during floods, reflecting lateral channel migration and/or variation of flood intensities. OSL dating, in concert with the radiocarbon dates and the absence of any soil formation within the sequence, indicate rapid aggradation at the valley bottom due to a substantial flux of sediment from the hillslopes and the watershed to the valley bottom.

Deposition began shortly after AD 1500 (radiocarbon and CHAU4) and continued until about AD 1800 (CHAU6). This finding is consistent with qualitative historical data showing intense ploughing in the area from the end of the Middle Age to the 18<sup>th</sup> century (de Farcy, 1950; Lorcin & Houssel, 2008). High sedimentation rates during this period were also found in southern, southwestern and central France (Allée, 2003; Bertran, 2004; Miras *et al.*, 2004).

The young OSL ages of samples CHAU 3, which is above the bank, and CHAU1-2, located below the bank and being very close to the channel, are interpreted as fluvial deposits following two important (about 2 to 3 m, respectively), rapid incision phases that occurred in short time after the end of the 18<sup>th</sup> century. The dating evidence suggests very rapid and alternating processes of incision and deposition: the first incision is directly followed by the deposition in an area of undercutting of the bank, while the second incision was characterised by a narrower channel and thus preservation of the previously incised and filled section. The rapidity of the incisions is suggested, for the first incision, by deposition in the underbank excavation, and for the second incision, by the narrowness of the incised section.

Historical data imply no significant change in land use during this period. As a consequence, incision may have been triggered by a variation in the rainfall regime. Interestingly, the period 1820-1840 is characterised by a decrease in the frequency of high rainfall events (Bravard, 2000; Jacob-Rousseau & Astrade, 2010). It therefore

appears likely that incision could have been triggered by phases of decreased sediment supply from the slopes into the fluvial system, at a time of intensive agriculture (i.e. ploughing). Such kind of evolution was also found for the prealpine Rhône basin (Bravard, 2000).

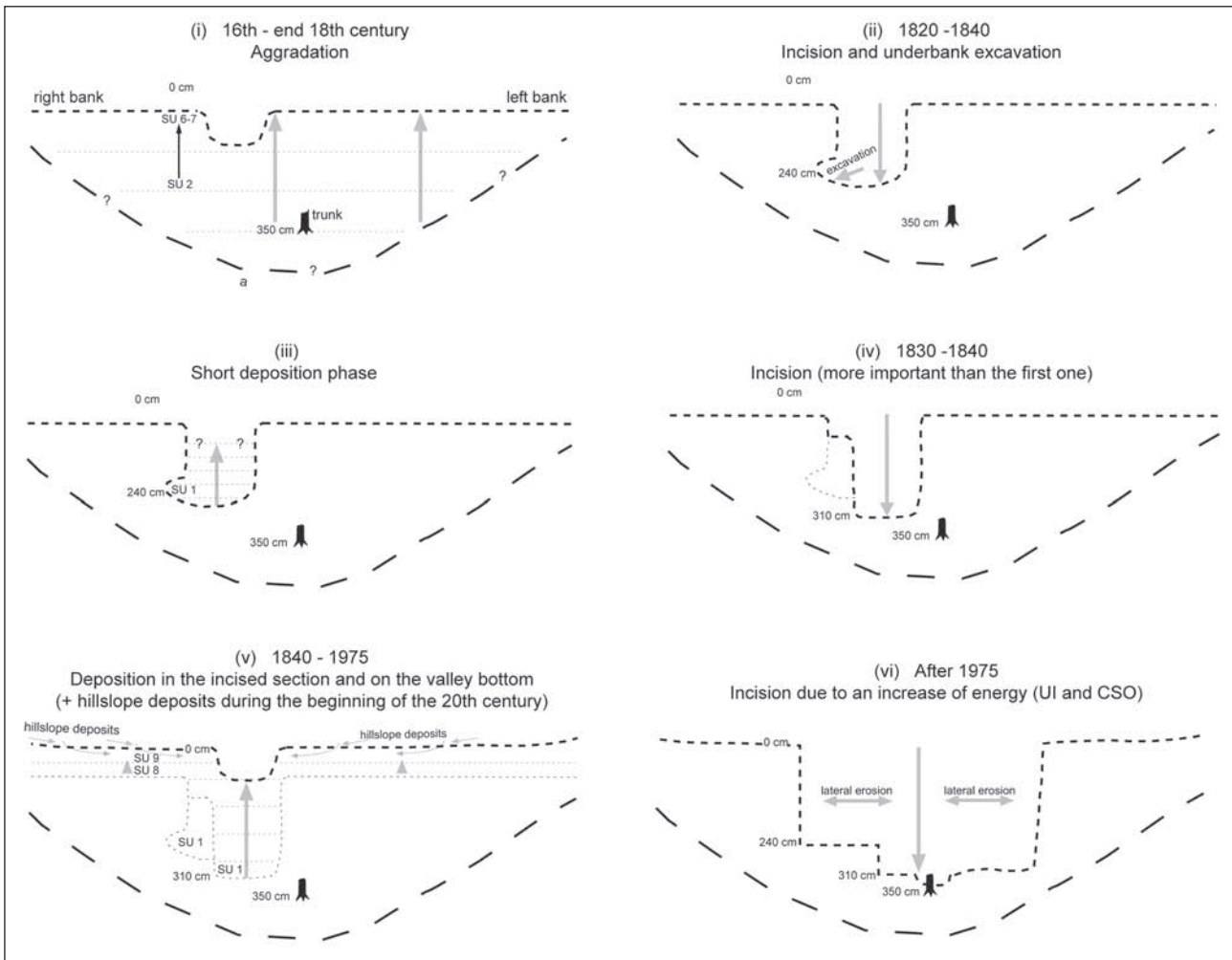
After the brief incision phases, aggradation continued until about AD 1975, when the present phase of incision started, following the urbanisation (and waterproofing) of an important part of the basin and the establishment of UI and CSO. This later (third) incision is more vertically and laterally developed than those of the 19<sup>th</sup> century due to the important increase of high flows induced by UI and CSO (Grosprêtre & Schmitt, 2008; Radojevic *et al.*, 2010). It is likely that this incision would have been inevitable in the future, even without UI and CSO, following the progressive decrease of ploughing and the increase of forest in the area since 1915 (Privolt, 2009; N. Jacob-Rousseau, personal communication). However in this case, incision would have probably been less developed (Grosprêtre & Schmitt, 2008). Alternative phases of aggradation and degradation are also suggested by the alternative layers of oxidation and reduction.

The most recent OSL date (CHAU7) concerns the poorly sorted SU8 containing some coarse particles that are not layered. It is considered as a hillslope deposit (colluvium) induced by intense rainfall events during the beginning of the 20<sup>th</sup> century. This deposit does not necessarily indicate total filling of the channel cut during the 19<sup>th</sup> century. It also appears possible that this deposit has been affected by human activities such as filling.

## 5 - CONCLUSION

OSL dating has shown a high potential to constrain the young sedimentation history in small drainage basin. Although all samples show clear evidence of differential bleaching of the OSL signal prior to deposition, the internal consistencies of OSL results and the excellent agreement with radiocarbon dating indicate that this problem is overcome by the statistical approaches used here. Overall, the chronology for the Chaudanne site appears to be very robust.

The sediment and morphological dynamics during the last five centuries can be summarised as follows (fig. 8): (i) aggradation since the 16<sup>th</sup> century to the end of the 18<sup>th</sup> century due to soil erosion in ploughing areas, (ii) rapid incision during the period 1820-1830 and undercutting of the right bank, (iii) short deposition phase that filled-up the excavation, (iv) second incision that was also fast but more important than the first one (1830-1840), (v) fluvial deposition in this incised section during the second half of the 19<sup>th</sup> century and the first three quarters of the 20<sup>th</sup> century; sedimentation of hillslope deposits at the valley bottom during the beginning of the 20<sup>th</sup> century, (vi) a last phase of incision that is much vertically and laterally developed (lateral erosion), starting at about AD 1975 due to an increase of energy during floods caused by UI and CSO; the decrease of sediment supply following the decline of ploughing after AD 1915



**Fig. 8: Scheme for the aggradation and erosion phases of the Chaudanne channel and valley bottom.**

The altitudes, in centimetres, are given in relative values, in order to be comparable to the altitudes in the figure 2.

Fig. 8 : Schémas des phases de sédimentation et d'érosion du chenal et du fond de vallée de la Chaudanne. Les altitudes, en centimètres, sont données en valeurs relatives de façon à être comparables avec celles de la figure 2.

probably increased sensitivity to channel degradation. This model is consistent with those proposed by Liébault & Piégay (2002) and Bravard (2000, 2002) for larger alluvial rivers, but it appears even more complex. This complexity is notably due to the high sensitivity of such small basins to climate variations and different kinds of land use changes and explains the incision during the beginning of the 19<sup>th</sup> century and that of today.

#### ACKNOWLEDGEMENTS

This study was funded by the Field Observatory for Urban Water Management (Observatoire de Terrain d'Hydrologie Urbaine, OTHU) and the ANR "AVuPUR" (Assessing the Vulnerability of Peri-Urban Rivers) project. Gamma spectrometry was carried out by Sönke Szidat, Departement für Chemie und Biochemie, Universität Bern. Sarah Ivorra (UMR 5059 CNRS, Centre de Bio-Archéologie et d'Ecologie, Montpellier, France) kindly identified the tree trunks. Grain size analysis was carried out thanks to the help of

Vincent Gaertner. Land use data were kindly provided by Marylise Cottet, Grégoire Privolt, Nicolas Jacob-Rousseau, Christine Jacqueminet, Kristell Michel, and Saïda Kermadi. We acknowledge Jean-Paul Bravard for helpful discussions concerning the palaeoenvironmental interpretation of the results, Sally Lowick for language corrections, and Sven Lukas for some helpful comments. Norbert Mercier and Gérard Nicoud are gratefully thanked for their constructive reviews.

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