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THE EFFECT OF FLUVIAL ENVIRONMENTS ON SEDIMENT BLEACHING AND HOLOCENE LUMINESCENCE AGES – A CASE STUDY FROM THE GERMAN ALPINE FORELAND

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Abstract: This study investigates the potential of luminescence to date deposits from different fluvial sedimentary environments; namely point bar deposits, sandy and silty channel fills and floodplain sediments. Samples were taken from Holocene (<5 ka) terraces of the Lech and Danube rivers, for which independent age constraint is available through ^{14}C ages, archaeological data and historical maps. OSL-ages were obtained using small aliquots of coarse grain quartz for the majority of samples. Two further samples were dated by the IRSL-signals of polymineral fine grain extracts, as no sufficient number of coarse grains could be extracted from these sediments. In order to detect and account for incomplete bleaching, we used the decision process suggested by Bailey and Arnold [Statistical modelling of single grain quartz D_e distributions and an assessment of procedures for estimating burial dose. Quaternary Science Reviews 25, 2475-2502, 2006]. Although their model was designed for single grains of quartz, our study shows that it is also applicable to multiple grains of quartz, provided that a low number of luminescent grains is present on one aliquot. Luminescence ages of point bar deposits and a sandy channel fill correspond most closely to the independent age control. In the floodplain, sand-striped floodplain channel deposits were incompletely bleached to a moderate degree, yielding ages with acceptable overestimations, while fine-grained floodplain deposits were worst bleached. One crevasse splay deposit was so severely incompletely bleached that none of the age models was able to yield accurate ages.

Keywords: luminescence dating, quartz multi-grain, independent age control, fluvial sedimentary environments, incomplete bleaching, Northern Alpine Foreland.

1. INTRODUCTION

The timing of fluvial deposition can be determined by means of luminescence dating, (for recent reviews, see Rittenour, 2008; Fuchs and Owen, 2008; Thrasher *et al.*, 2009a). However there are different reasons why dating of these deposits may be problematic. Resetting of the luminescence signal may be incomplete due to the waterlain nature of these sediments, causing age overestimation if not accounted for. This problem has shown to be particularly relevant for young sediments (e.g. Jain *et al.*, 2004; Rodnight *et al.*, 2006; Fiebig *et al.*, 2009). Incomplete bleaching results in scattered and positively skewed equivalent dose (D_e) distributions (e.g. Olley *et al.*,

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1998). Further, low quartz signal intensities have been reported from many mountainous areas (e.g. Rhodes and Pownall, 1994; Preusser *et al.*, 2006; Klasen *et al.*, 2006; Lukas *et al.*, 2007; Steffen *et al.*, 2009). Most likely this problem is linked to the low number of sedimentation cycles experienced from source to depositional area (Lukas *et al.*, 2007; Pietsch *et al.*, 2008).

The aim of this study is to test quartz luminescence dating on known age Holocene fluvial deposits of the Lech and Danube rivers. Independent age control in the current study is available through ^{14}C ages, archaeological data and stratigraphical classifications (Schielein, 2012). The samples were taken from different fluvial sedimentary environments, namely bar deposits, channel fills and floodplain deposits. The luminescence ages are based on small single aliquot dating of quartz and will be used to test whether sedimentological properties affect the accuracy and precision of luminescence dating results. The mode of D_e calculation follows the decision process of Bailey and Arnold (2006). The decision process was originally designed to be used for single grains, and so the applicability of this process to multiple grain replicas of quartz was also tested. Further two samples were dated by their polymineral fine grain fraction using IR-stimulation, as there was not enough material for quartz coarse grain extraction. This aliquot size does not allow D_e distribution analyses, thus the accuracy of IRSL ages of these two samples is based only on the comparison with the independent age control.

2. STUDY AREA

Geological Setting

The study area is located at the lower reaches of the river Lech and at the confluence of the Lech and Danube (**Fig. 1**). The Lech valley is characterised by several Pleistocene and Holocene terraces. The focus of this study are Holocene sediments which were deposited by the meandering Danube and the partly meandering, partly anabranching Lech river (Schielein, 2012).

Fluvial environments in the study area

Fluvial deposits in general can be classified according to their sedimentary environments. Reineck and Singh (1980) describe three groups of fluvial deposits: channel deposits, bank deposits and flood basin deposits. The latter two are often quite similar and can be subsumed as flood plain deposits. Within these fluvial sedimentary environments Reineck and Singh (1980) classify several types of sediments:

- channel deposits: channel lag, point bar, channel bar, channel fill
- floodplain deposits: natural levee, crevasse splay, flood basin, marsh.

In meandering rivers such as the Holocene Danube and in meandering channels of an anabranching river such as the Holocene Lech, deposition on point bars is the major sedimentation process. Sand layers are frequently deposited in swales and on the surface of point bars during bankfull discharge and are often buried under further layers of gravel, if a successive river bed sedimentation reaches the surface of the point bar. In river systems with

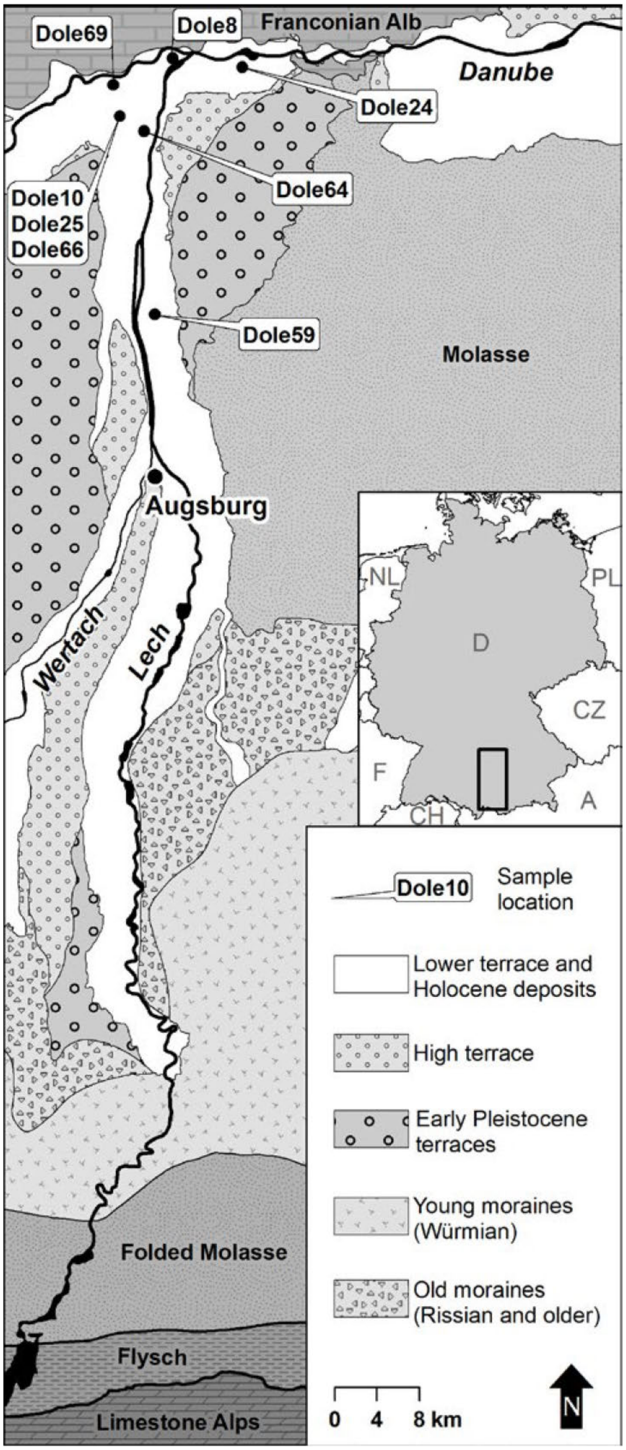


Fig. 1. *Geological map of the study area and all sampling locations.*

braided or anabranching channels, gravel bars build up along the flow direction in channels.

Channel fill deposits of the Holocene Lech and Danube river form when channels have been abandoned due to avulsion of a stream channel or due to cut-off processes in meander loops. Moreover, channels can be cut into floodplain deposits and the underlying gravel deposits of a river terrace when branches of an anabraching river diverge from the main stream during flood events. If the river does not migrate in such a channel, it will be abandoned sooner or later. After abandonment all types of channels get filled with fine grained sediments, but in high energetic discharge during flood events, sands and even gravels can be deposited in a palaeo-channel.

During overbank flows, coarse sediments – mostly sand but also gravels – are deposited near the river channel on natural levees. Crevasse splays form in the floodplain behind levees when the latter are breached by an extreme flood event. Fine-grained suspended sediments are deposited with increasing distance from the river bed on the floodplain. These floodplain deposits are composed of horizontally bedded layers of fine sand, silt and clay, reaching several metres in thickness. In their lowest part, sand striped floodplain channel deposits *sensu* Schirmer (1995) can be identified, mainly in floodplains of meandering rivers. These deposits are accumulated during flood events on inactive point bars and represent the beginning of floodplain sedimentation. All fluvial environments in the study area are shown in a schematic illustration (**Fig. 2**).

Independent chronostratigraphy of sampled deposits

Bar deposits

The Lechauseen section was exposed in a gravel bar deposits from a Holocene Lech terrace ca. 25 km upstream of the Danube-Lech-confluence (**Fig. 1**). The gravels contain a sand lens at a depth of 1-1.5 m (**Fig. 2a**). Finds of rounded brick fragments in the gravel formation, which are present in fluvial accumulations solely since Roman times, allow assigning this terrace to the Subatlantic period (~0-2500 a BP, Mangerud *et al.*, 1974). From the sand lens, a sample for OSL dating (Dole59) and a charcoal sample for radiocarbon dating were taken. The charcoal was dated to 1565-1395 cal BP (Schielein, 2012).

Another sample for OSL dating (Dole64) from a point bar deposit (**Fig. 2a**) was taken ca. 7 km upstream from the confluence in the Lech valley (**Fig. 1**). Here, a palaeomeander of the Lech river undercuts the subboreal (2500-5000 a BP, Mangerud *et al.*, 1974) terrace and eroded parts of a Roman *villa rustica* at the outside bank. Archaeological data indicate the occupancy of the estate between the 1st and the 4th century AD (Czysz, 1990). It is likely that the *villa rustica* was abandoned because of the approaching Lech river. The point bar deposits at the sampling location, 300 m inbound from the inner bank of the palaeomeander, are expected to have been accumulated during Roman times, most likely around 1.6 ka or slightly older, as the sampling location lies a few hundred meters inside of the meander bend and a point bar build up over some centuries can be assumed. (Schielein *et al.*, 2011; Schielein, 2012).

Channel fill deposits

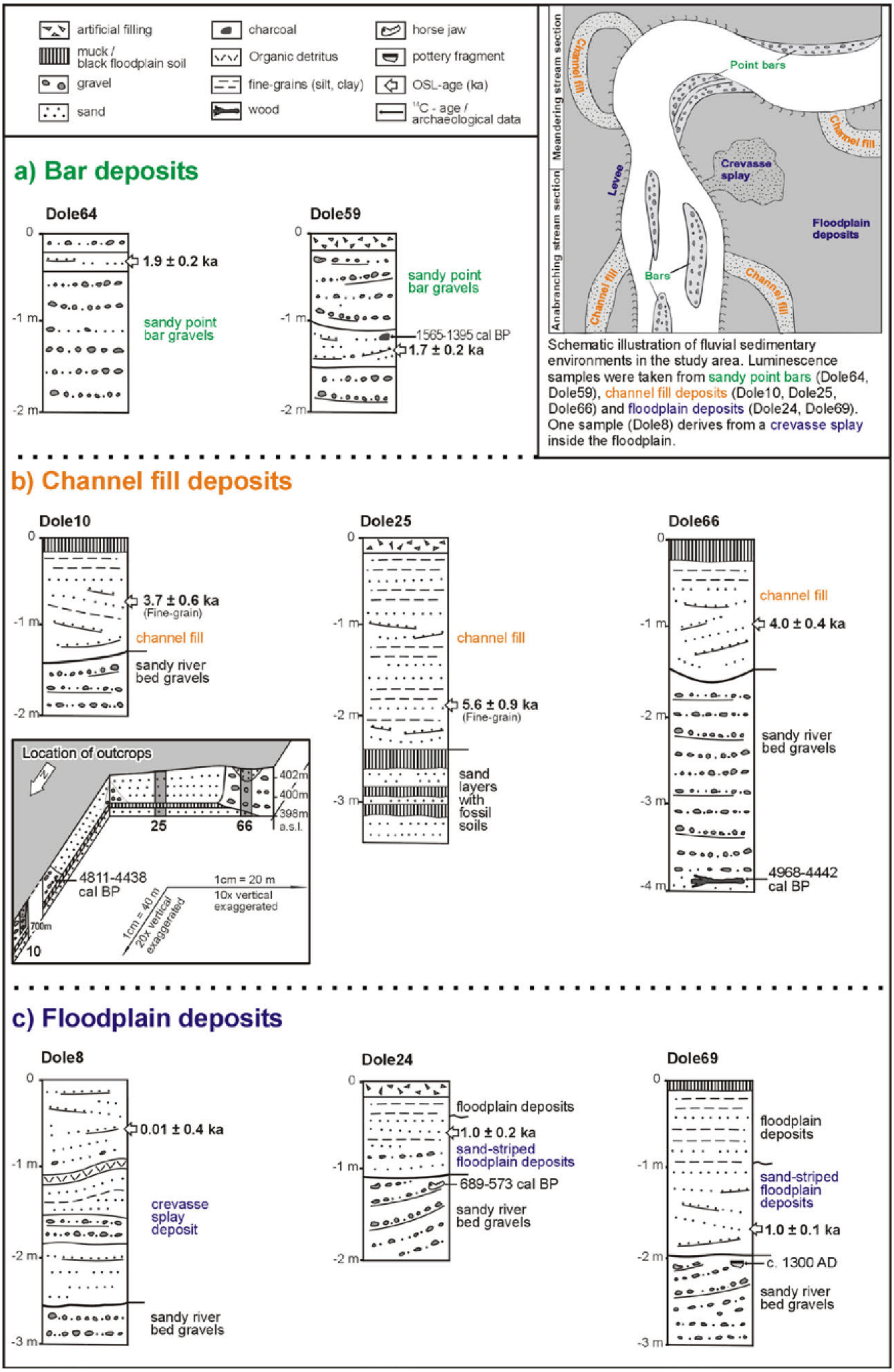
Samples Dole10, 25 and 66 were taken from channel fills in the same Lech terrace which is well exposed in the gravel pit of Eggelstetten (**Fig. 1**, **Fig. 2b**). The channels yielding samples 10 and 66 are cut ca. 1.5 m into the gravel body and are filled with loamy sands. Sample Dole25 was taken from a 2.3 m thick channel fill deposit consisting of well layered sand, silt, and clay, which was identified as floodplain deposit inside the channel. The correlation of the terrace level to the Subboreal was proposed by Schreiber (1985) and Roman streets and settlements on its surface confirm an age of at least 1.5 ka (Schielein, 2012). In the Eggelstetten pit, at the base of the gravel body 2-4 m below the surface level, wood and plant remains yielded radiocarbon ages of 4968-4438 cal BP (for details and further age evidence for the Subboreal deposition of this terrace see Schielein, 2012). The age of the channel fills should fall between the deposition of the terrace gravels and the roman settlement. Most likely, channel filling followed shortly after terrace aggradation.

Floodplain deposits

The Burgheim outcrop is situated at the inner bank of a palaeomeander in the Danube valley about 6 km downstream of the Lech-Danube confluence (**Fig. 1**). OSL sample Dole24 was taken from sand-striped floodplain channel deposits at a depth of 0.6 m below the surface level (**Fig. 2c**). The accumulation of the river terrace is assigned to the Subatlantic, based on its stratigraphical position, the weak soil formation and rounded brick fragments in the gravel body. A ^{14}C age of 689-573 cal BP was obtained from a horse jaw embedded in the gravel (Schielein, 2012).

Another sample (Dole69) was taken from floodplain deposits covering a Danube terrace 7 km upstream of the confluence (**Fig. 1**). The Reichertswert outcrop shows floodplain deposits formed of silty to clayey overbank fines in the higher part and a sand-striped floodplain channel deposit as lower part, from which the OSL-dated sands originate (**Fig. 2c**). The underlying gravel body contains rounded brick fragments and a pottery sherd at its top. The latter was archaeologically assigned to an age of about 1300 AD by H. Losert (University of Bamberg, pers. comm.). The medieval terrace implies a younger age (<0.7 ka) for the superimposed floodplain deposits.

One further samples (Dole8) was collected from a crevasse splay deposit lying on the recent Lech terrace about 1 km upstream from the confluence (**Fig. 1**). The crevasse splay stretches out from the natural levee of the



Schematic illustration of fluvial sedimentary environments in the study area. Luminescence samples were taken from sandy point bars (Dole64, Dole59), channel fill deposits (Dole10, Dole25, Dole66) and floodplain deposits (Dole24, Dole69). One sample (Dole8) derives from a crevasse splay inside the floodplain.

Fig. 2. *Profiles of sampled deposits and their fluvial sedimentary environments (inset). Obtained luminescence ages are given in bold numbers.*

recent Lech river over an area of ca. 240×400 m. The outcrop consists of a layer of medium to coarse sands up to 1.5 m thick with bands of organic detritus, fine clastic sediments and gravels (**Fig. 2c**). The sands contain a high proportion of mica flakes, indicating that they are derived from nearby Tertiary Molasse sands building up the underlying stratum of the Quaternary river terraces and are exposed directly downriver from a Lech dam, situated only several tens of meters away from the outcrop. Therefore the sampled sands most likely experienced only a short transport and were deposited after the construction of the dam in the 1950s. Historical maps confirm that the outcrop is located in a 19th century main stream of the anabranching Lech river (Schielein, 2010).

3. METHODS

A chronostratigraphy for the fluvial deposits in the study area was established using morphostratigraphic classifications, radiocarbon dating, archaeological data and historical maps. Radiocarbon dating of organic material was carried out by Beta Analytic Inc. (Miami) and Poznań Radiocarbon Laboratory. The ^{14}C ages (2σ errors) were calibrated with OxCal software (Bronk-Ramsey, 1995) using the INTCAL 04 curve (Reimer *et al.*, 2004). All ^{14}C ages are given as calibrated years BP (before 1950).

The luminescence samples derive from gravel or sand quarries. For the determination of the equivalent dose, the coarse grain fraction (150-200 µm) of quartz was extracted from the bulk sediment by physical and chemical laboratory treatment (e.g. Lomax *et al.* 2007). The quartz grains were mounted on stainless steel discs, using a 2 mm mask, which approximates 100 to 150 grains per aliquot. For the two polymineral fine grain samples (Dole10 and Dole25), the 4-11 µm fraction was enriched by settling using Stokes law. A suspension of the fine grain material (40 mg) and acetone (20 ml) was produced and 1 ml of suspension each pipetted onto stainless steel discs, covering the entire 9 mm diameter disc. All preparation steps were undertaken under subdued red-light.

The standard measurements were carried out using the single-aliquot regenerative-dose (SAR) protocol of Murray and Wintle (2003). For stimulation, blue LEDs (125°C for 40 s) were used and OSL emission was filtered through a U340 filter (7.5 mm). Signals were integrated over the first 0.6 s, and with the subtraction of a background calculated using the last 10 s of the signal. Measurements were rejected if recycling ratios exceeded 10% from unity, recuperation exceeded 15% of natural signals and test dose errors exceeded 20%. For the best bleached sample (Dole66), a preheat plateau test (**Fig. 3a**) was carried out to check the signal stability over a temperature range (180 to 280°C). Based on this test, the preheat and cutheat temperatures in most samples were set to 230 (10 s) and 200°C (0 s), respectively. Two samples (Dole24 and Dole8) where dated in an earlier measurement cycle using different conditions, i.e. preheat and cutheat temperatures of 180 (10 s) and 160°C (0 s), respectively. This is based on another preheat plateau test of sample Dole24 (**Fig. 3b**).

The applicability of the protocol was tested on three samples (Dole63, 64 and 69) through dose recovery tests. The natural signals were bleached in the luminescence reader using blue LEDs, and a known dose of 2 Gy was administered. Tests were performed on three 8 mm aliquots each and the same preheat-cutheat conditions as in the standard measurements were used. Dose recovery ratios of these three samples were 1.02, 1.00 and 0.99 (arithmetic mean), supporting the validity of the chosen

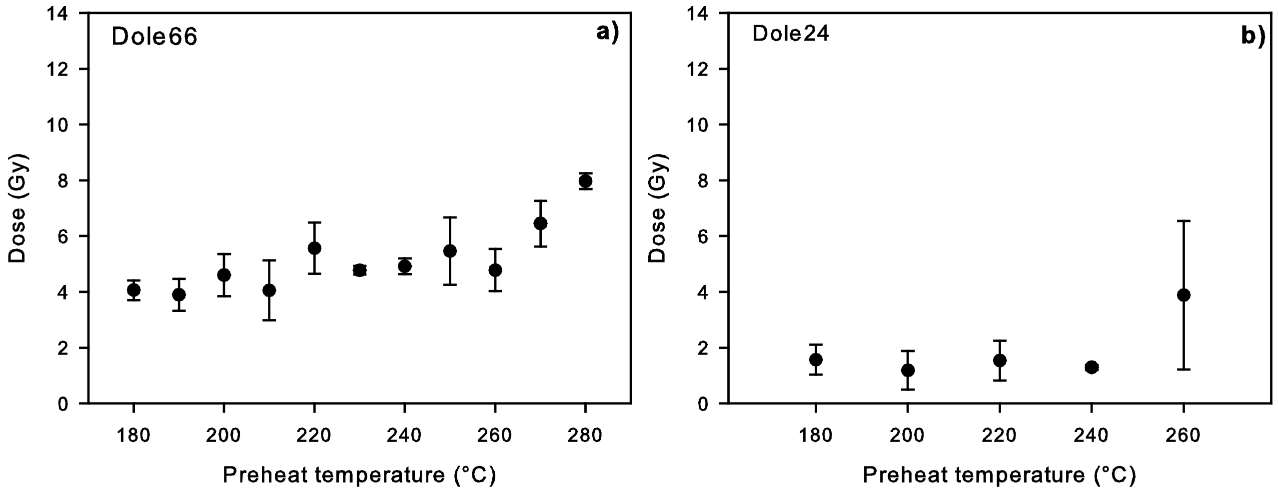


Fig. 3. *Preheat plateau tests of sample a) Dole66 and b) Dole24. Each temperature was measured on three large (8 mm) aliquots and the cut-heat temperature was set to 200°C (for temperatures below 220°C, to 20°C below the preheat temperature). D_e values represent the arithmetic mean and the test was performed on naturally dosed samples.*

protocol. No feldspar contamination was present, which was tested at the end of each measurement sequence with an IR depletion test. Representative signal decay and dose response curves of the samples are shown in **Fig. 4**.

The two polymineral fine grain samples were measured using a SAR protocol (Wallinga *et al.*, 2000; Blair *et al.*, 2005). Preheat temperatures were set to 190°C (10 s), which was also based on a preheat plateau test. IRSL signals of polymineral fine grain samples are assumed to be dominated by the feldspar fraction. No fading tests were carried out on these two samples, thus a certain age underestimation might be expected. All measurements were conducted on Risø TL-DA-20 luminescence readers. Signals were detected through a LOT Oriel interference filter centered on 410 nm.

As incomplete bleaching in fluvial environments is common due to attenuation of sunlight under water, such samples comprise grains that experienced different levels of signal resetting (Duller, 1994). The presence of incompletely bleached grains with various residual doses will cause a scatter and a positive skew of D_e distributions. Many methods to detect and account for incomplete bleaching rely on analyses of these distributions (e.g. Olley *et al.*, 1998; Lepper *et al.*, 2000; Bailey and Arnold, 2006; Rodnight *et al.*, 2006; Pietsch, 2009; Cunningham and Wallinga, 2012). In the current study, we apply the decision process of Bailey and Arnold (2006), to classify the degree of bleaching, and to decide on the statistical model for D_e calculation.

Originally, the model of Bailey and Arnold (2006) was designed for single grain analyses, and care must be taken when transferring it to multiple grain analyses due to signal averaging effects (Arnold and Roberts, 2009). However, a range of studies showed that in insensitive samples, only very few grains contribute to the overall OSL signal of a multiple grain disc and as a consequence, a multiple grain distribution can be very similar to that of single grains (e.g. Thrasher *et al.*, 2009b; Cunningham and Wallinga, 2012). Calculated D_e values are based on a minimum of 30 aliquots in case of coarse grain analysis and 5 aliquots for fine grain analysis. This is a relatively low number, compared to, e.g., the required 50 D_e values suggested by Rodnight (2008). In the current study, a higher number of accepted D_e values could not be obtained due to insufficient reader capacity. The comparison with the independent ages shows that this low number of D_e values might be sufficient; however, a higher number of accepted D_e values would have been desirable.

This decision process of Bailey and Arnold (2006) uses the statistical parameters of overdispersion, weighted skewness and kurtosis for a characterisation of the D_e distribution and based on these parameters, proposes the central age model (CAM, Galbraith *et al.*, 1999), or minimum age models (MAM) for D_e calculation. These minimum age models include the 3 and 4 parameter MAM-3 and MAM-4 (Galbraith *et al.*, 1999) and the approach by Olley *et al.* (1998) to use only the mean of the lowest x% of the D_e values (L-x% approach). We slightly simplified the decision process, by only using a MAM-3. Furthermore, we also calculated D_e values using the Finite Mixture Model (FMM) (Galbraith and Green, 1990) in order to test it against the MAM and the independent age control. The FMM model is normally used for mixed dose populations (e.g. Roberts *et al.*, 2000; Lomax *et al.* 2011), but can also be used for incompletely bleached samples, if the 'youngest' dose population is used for age calculation (Rodnight *et al.*, 2006, Fiebig *et al.*, 2009). While Rodnight *et al.* (2006) proposed to exclude the 'youngest' dose population where their proportion was <10%, this was not necessary for our samples; all

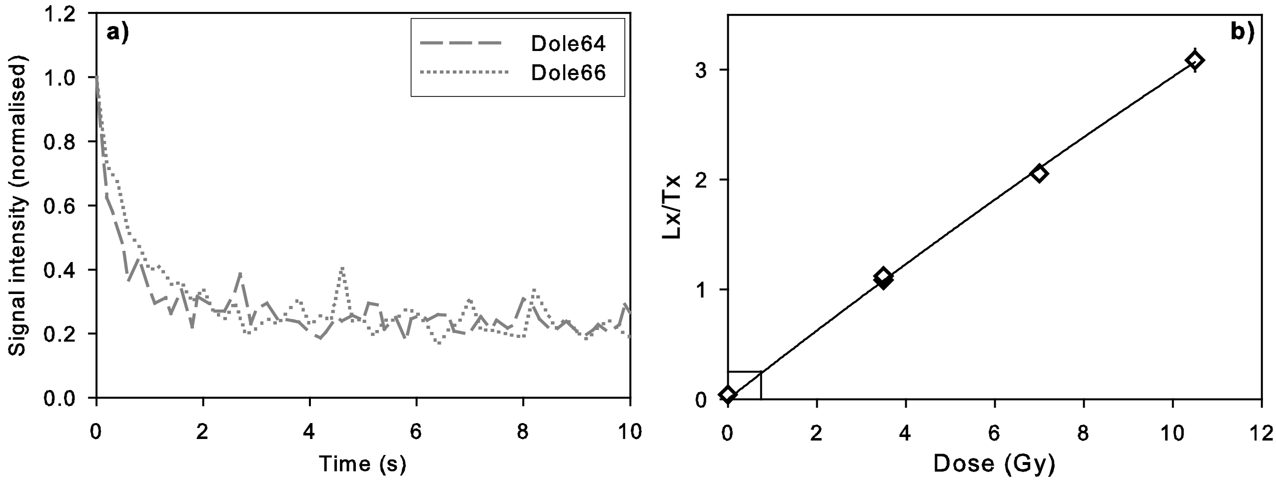


Fig. 4. *a) Representative, normalised decay curves of samples Dole64 and Dole66. Signals were recorded using 2 mm aliquots, and the decay curves represent natural signals (~1.5 Gy (Dole64) and ~4.8 Gy (Dole66)). b) Representative dose response curve of sample Dole24. Signals were recorded using 2 mm aliquots, black lines represent the natural signal (L_n/T_n) and equivalent dose of the respective aliquot.*

'youngest' dose populations had proportions of >10%. The MAM and the FMM require the input of a reference overdispersion value (the sigma value) which expresses variations caused by microdosimetry and differences in luminescence properties (e.g. recuperation). We used an estimated sigma-value of 20%, as this seems to be a relatively common spread in well bleached samples analysed on single grain level (Arnold and Roberts, 2009). In case of the L-x%-approach, we used a value of 5% (L-5%), as suggested in Olley *et al.* (1998).

U-, Th-, and K-concentrations were determined using laboratory gamma spectrometry on ~800 g of sample material. None of the samples showed signs of radioactive disequilibria in the uranium decay chain. The radionuclide concentrations were converted to dose rates using conversion factors of Adamiec and Aitken (1998). Cosmic dose rates were calculated based on geographic position and sampling depth below surface (Prescott and Hutton, 1994). For the sandy samples, water contents of 10±7% were considered, whereas dose rates of silty samples were calculated with water contents of 17±7%, which is an average of actual water contents. Radionuclide concentrations, dose rates and sample properties are summarised in **Table 1**.

4. RESULTS

Only one sample (Dole66) yielded a D_e distribution which was not significantly skewed and we consider this sample well bleached (**Fig. 5**). For this sample, the decision process suggests the CAM. All other samples were significantly positively skewed, which led to the use of the minimum age models to calculate D_e values (**Fig. 5**). Measurements of four samples resulted in the MAM or FMM as the mode of D_e calculation. In three cases, FMM- and MAM-ages agreed with each other. In a fourth sample (Dole64), the MAM-age was significantly younger than the FMM-age, owing to two very precise D_e values in the low dose range (**Fig. 5**).

One sample (Dole8) was severely incompletely bleached and resulted in the L-5%-approach as mode of D_e calculation. It needs to be considered that in our case, the L-5% D_e is based on only two values, which is statistically unsound.

All D_e values, relevant statistical parameters of D_e distributions, resulting luminescence ages, and independent ages are summarised in **Table 2**.

Bar deposits

Both samples from bar deposits (Dole59 and 64) are incompletely bleached and the decision process of Bailey and Arnold (2006) resulted in the MAM. For Dole59, both the MAM and FMM resulted in agreeing ages of 1.7±0.2 ka, which is in accordance with the independent age control of 1565-1395 cal BP.

The luminescence ages of Dole64 (MAM: 1.3±0.2 ka, FMM: 1.9±0.2 ka) are in agreement with the morphological position of the terrace between the Subboreal and recent Lech terraces and the archaeological data. As the latter designate an Roman age of the luminescence sample, most likely around 1.6 ka or slightly older, the FMM-age is more appropriate. The low MAM-age is probably the result of very high precision D_e values in the low dose range, and a too low number of accepted D_e values.

Channel fill deposits

Samples Dole10, 25 and 66 were taken from channel fills, cut in the Subboreal Lech terrace and are expected to be slightly younger than c. 4.5 ka cal BP. Sample Dole66 appears completely bleached when applying the

Table 1. *Sample properties, radionuclide concentrations and dose rates. Dose rates include estimated water contents which represent averages of measured in-situ water contents.*

Sample	Grain size (µm)	Water content (%)	Depth (m)	Radionuclide concentrations K (%)	U (ppm)	Th (ppm)	Cosmic dose rate (Gy/ka)	Total dose rate (Gy/ka)
Dole 59	150-200	10±7	1.2	0.46±0.01	1.19±0.02	1.54±0.05	0.19±0.02	0.93±0.07
Dole 64	150-200	10±7	0.35	0.39±0.01	0.83±0.02	1.29±0.05	0.22±0.03	0.80±0.06
Dole 66	150-200	10±7	1.2	0.53±0.01	1.94±0.03	2.51±0.08	0.19±0.02	1.21±0.09
Dole 10 (polymin)	4-11	17±7	1.05	0.47±0.01	2.50±0.05	2.75±0.09	0.19±0.02	1.82±0.25
Dole 25 (polymin)	4-11	17±7	1.9	0.40±0.01	2.50±0.05	2.29±0.09	0.17±0.02	1.69±0.24
Dole 8	150-200	10±7	0.4	0.57±0.01	0.93±0.03	1.74±0.06	0.21±0.03	1.00±0.06
Dole 69	150-200	10±7	1.8	0.88±0.01	1.57±0.03	3.88±0.12	0.18±0.02	1.50±0.12
Dole 24	150-200	10±7	0.85	0.64±0.01	0.93±0.03	1.71±0.06	0.20±0.03	1.05±0.07

Table 2. *Luminescence measurement details, independent ages, statistical parameters (OD = overdispersion after Galbraith* et al. *(1999); weighted skewness after Bailey and Arnold (2006); age model and resulting age according to Bailey and Arnold (2006) and alternative age model, which substitutes the Minimum Age Model (MAM) by the Finite Mixture Model (FMM); n = number of aliquots used for D_e calculation).*

Sample	Fluvial environment	Over-dispersion (%)	Standardised weighted skew (significant?)	n	De (Gy) [Age model with proportion of aliquots used for D_e-calculation (FMM)]	Luminescence age [for FMM ages also MAM ages are mentioned]	Independent age (method)*
Dole 59	Point bar deposit	39	2.6 (yes)	30	1.61±0.12 [FMM, 85%]	FMM: 1.7±0.2 ka MAM: 1.7±0.2 ka	1.4-1.6 ka cal BP (^{14}C)
Dole 64	Point bar deposit	52	3.6 (yes)	42	1.49±0.09 [FMM, 76%]	FMM: 1.9±0.2 ka MAM: 1.3±0.2 ka	Slightly older than 1.6 ka (archaeological data)
Dole 66	Sandy channel fill	25	0.8 (no)	32	4.81±0.30 [CAM]	CAM: 4.0±0.4 ka	Slightly younger than ~4.5 ka cal BP (^{14}C)
Dole 10 (polymin)	Silty channel fill	3	0.3 (no)	5	6.69±0.36 [CAM]	CAM: 3.7±0.6 ka	Slightly younger than ~4.5 ka cal BP (^{14}C)
Dole 25 (polymin)	Silty channel fill	0	0.1 (no)	5	9.45±0.59 [CAM]	CAM: 5.6±0.9 ka	Slightly younger than ~4.5 ka cal BP (^{14}C)
Dole 8	Crevasse splay	116	7.5 (yes)	38	0.01±0.35 [L-5%]	L-5%: 0.01±0.4 ka	Younger than 50 years
Dole 69	Sand-striped flood plain	59	4.0 (yes)	38	1.43±0.10 [FMM, 65%]	FMM: 1.0±0.1 ka MAM: 0.9±0.1 ka	Slightly younger than 0.71 ka (archaeological data)
Dole 24	Sand-striped flood plain	65	2.5 (yes)	42	1.06±0.13 [FMM, 36%]	FMM : 1.0±0.2 ka MAM: 0.9±0.1 ka	Slightly younger than 0.69-0.57 ka cal BP (^{14}C)

**For details concerning ^{14}C dating see Table 3.*

Table 3. *Radiocarbon dating details. The ^{14}C ages (2σ errors) were calibrated with OxCal software (Bronk-Ramsey, 1995) using the INTCAL 04 curve (Reimer* et al.*, 2004).*

Laboratory code	Material	^{14}C age (^{14}C BP)	calibration results, 95.4% conf. intervals (cal BP)
Poz-32651	horse jaw	715±30	690-570
Beta-245225	wood	4130±60	4840-4440
Beta-256322	wood	4290±50	4970-4820
Beta-262203	plant remains	4080±40	4810-4440
Beta-265925	charcoal	1600±40	1570-1400

criteria of Bailey and Arnold (2006), resulting in the CAM as the mode of mean D_e calculation. The model gives an age of 4.1±0.4 ka and agrees with the independent age estimates. Samples Dole10 and 25 were dated using the feldspar-dominated signal of the polymineral fine grain fraction, as not enough sand sized material was available for coarse grain quartz dating. The technique does not allow analysis of D_e distributions to detect incomplete bleaching, as D_e variations on a grain to grain scale are masked by the large aliquot size. Therefore, the CAM was used for the D_e mean calculation. The IRSL age of 3.7±0.6 ka of sample Dole10 is in agreement with the ^{14}C age constraint and with the OSL-age of sample Dole66. Dole25 yields an IRSL age of 5.6±0.9 ka which overestimates the age of the terrace.

Floodplain deposits

Dole69 and 24 are derived from sand-striped floodplain channel deposits and overlie a terrace with an age of ~0.7 ka which represents the maximum age of the luminescence samples. It can be assumed that the deposition of these floodplain sediments took place shortly after terrace aggradation. Both samples are incompletely bleached and result in using the MAM or the FMM-model as mode of D_e calculation. The resulting quartz ages of 0.9±0.1 (Dole69) and 0.9±0.2 ka (Dole24) coincide with the independent ages on a 2σ error level. One further sample (Dole8) from a crevasse splay should have yielded a modern age of less than 50 years, most likely even a recent age. The sample was severely unbleached, containing doses corresponding to ages up to 90 ka. The decision process suggests a L-5% approach, resulting in an age of 0.01±0.35 ka. This age agrees with the inde-

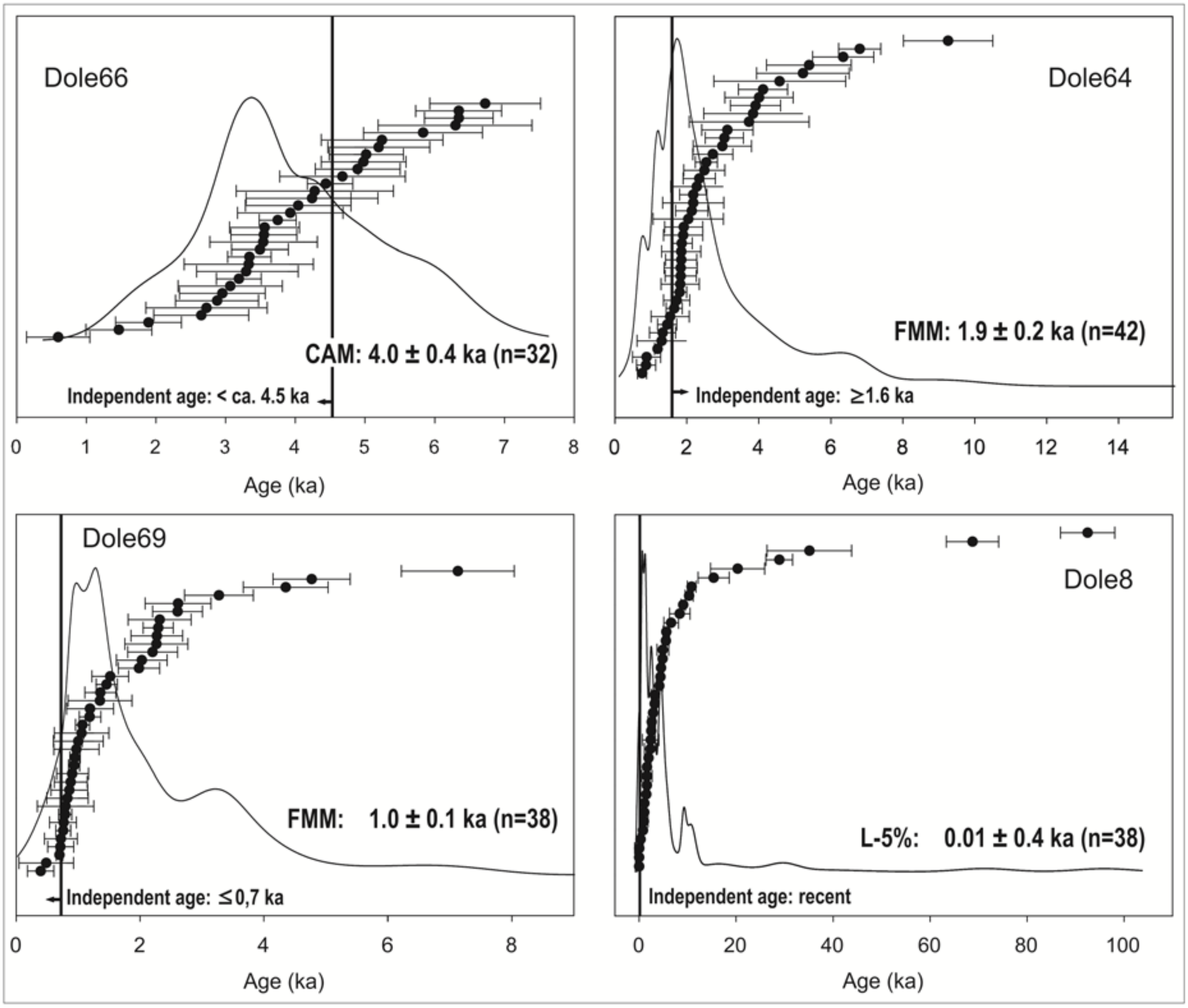


Fig. 5. *Frequency distributions and probability density functions of luminescence ages for one channel fill (Dole66), one point bar (Dole64), one floodplain (Dole69) and the crevasse splay (Dole8) deposit. Each individual age (circle with error range) was calculated by dividing the D_e value of one aliquot by the total dose rate. The bars and arrows indicate the independent age control.*

pendent age control, but exhibits a very large uncertainty. As mentioned before, this age is based on only two D_e values and thus needs to be considered as unreliable.

5. DISCUSSION

The OSL measurements of Holocene fluvial deposits from different sedimentary environments demonstrated varying degrees of bleaching. Most of the analysed fluvial samples are incompletely bleached but contain a high enough proportion of well bleached grains to yield accurate ages when minimum age models are used. Most likely the different degree of bleaching is a function of transport distance and mechanism, the previously accumulated dose and/or the duration of light exposure during sediment deposition.

A sandy channel fill deposit appeared as best bleached, yielding CAM ages in agreement with independent age control. Successful OSL dating of coarse grained Holocene channel fills was reported by Wallinga *et al.* (2001) for the Rhine-Meuse-Delta and by Fiebig *et al.* (2009) from the Austrian Danube and the Ebro. The bar deposits dated in our study were incompletely bleached, but yielded a high percentage of bleached grains, resulting in MAM and FMM ages agreeing with the independent ages. Porat *et al.* (2001) detected substantial residual doses of bar and active channels deposits in southern Israel, especially when the sediments experienced an adequate transport distance. The two sand striped floodplain deposits also yielded accurate MAM and FMM-ages within errors. A further sample from a crevasse splay, which obviously experienced only a very short transport and had accumulated a very high dose prior to this transport, was severely incompletely bleached, and resulted in a L-5% age with a very large uncertainty.

The degree of bleaching apparently depends on the transport distance and the degree of light exposure in different sub-environments. During high energetic discharge in active (bars) and abandoned channels (channel fills) the potential of bleaching the deposits is relatively high, as the water body does not contain much suspended sediment. In contrast, floodplain sediments typically show a low bleaching potential, due to the high amount of suspended fine-grained material in the water body and the resulting low amount of light exposure during transport.

The well bleached nature of the sandy channel fill sample (Dole66) in comparison with the age overestimation of a fine grained sample (Dole25) from the same environment may be indicative of faster bleaching of the quartz fraction compared to the feldspar fraction, as suggested by Godfrey-Smith *et al.* (1988). Another explanation is the larger degree of averaging on the large fine grain discs which contain many thousands of luminescent grains. In any case, fine grain dating should be avoided when dating fluvial samples, as this mineral fraction does not offer the required resolution for detecting incomplete bleaching. An alternative is to consider fine grain luminescence ages of fluvial samples only as maximum estimates. However, the sample Dole25 was taken from a channel filled with finer grains and is likely to be less bleached due to lower light exposure during floodplain sedimentation. In contrast, sample Dole10 is derived from a channel filled with loamy sands which were deposited under high energetic discharge in the channel and therefore are better bleached.

The decision process of Bailey and Arnold (2006) yields ages in agreement with independent age control in all cases where the quartz coarse grain fraction was measured. Hence, the decision process, originally designed for single grains of quartz can be applicable to multiple grain analyses under the premise that only a small percentage of luminescent grains are present in the samples. This finding supports the previous work of Thrasher *et al.* (2009b). Hence, for our samples, the decision process proved to be a powerful tool to detect incomplete bleaching and to decide on the mode of D_e calculation.

6. CONCLUSION

The study has shown that luminescence dating of young fluvial deposits can yield age estimates which are in agreement with independent age control. Measuring small aliquots of quartz in combination with the decision process of Bailey and Arnold (2006) appears the most suitable approach in the investigated environment, but care should be taken in the choice of fluvial environments. Fine-grained material which can only be dated using large aliquots should be avoided, as well as samples with a short transport distance and high previously acquired doses, such as re-deposited Tertiary Molasse. For our study area, albeit tested on a limited number of samples, bar deposits and sandy channel fills are likely to be better bleached than floodplain deposits. For future luminescence dating of fluvial deposits, we suggest a detailed survey of sedimentological properties of the samples including the identification of fluvial environments as well as the comparison with independent age control derived from other numerical dating methods and the morphostratigraphic situation.

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