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The relation between optical bleaching and sedimentological features of fluvial deposits in the Toruń Basin (Poland)

Piotr WECKWERTH[1, *], Krzysztof R. PRZEGIĘTKA[2], Alicja CHRUŚCIŃSKA[2] and Małgorzata PISARSKA-JAMROŻY[3]

[1] Faculty of Earth Sciences, Nicolaus Copernicus University, Lwowska 1, 87-100 Toruń, Poland

[2] Institute of Physics, Nicolaus Copernicus University, Grudziądzka 5/7, 87-100 Toruń, Poland

[3] Institute of Geology, Adam Mickiewicz University, Maków Polnych 16, 61-606 Poznań, Poland

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Distributions of equivalent doses (D_E) obtained by the Single Aliquot Regenerative-dose (SAR) OSL method applied for large aliquots of coarse quartz grains extracted from fluvial sediments are presented and analysed with respect to a fluvial palaeoenvironment. The Nowe Dąbie and Łochowo fluvial succession from the western part of Toruń Basin (eastern part of Noteć–Warta streamway, Toruń-Eberswalde ice-marginal valley) was analysed. The fluvial depositional conditions controlling the extent of daylight bleaching are reconstructed by sedimentological studies. The relation between the amount of bleaching and sedimentological properties of fluvial deposits indicate that ripple cross-laminated sands that accumulated on the floodplain and horizontally-bedded sands deposited in shallow channels are more appropriate for OSL dating than sands derived from the deep channel. Along with luminescence results obtained for the river deposits, data measured from an ancient pottery sample, ensuring complete reset of the OSL signal, are presented, compared to and discussed. On this base the poorly bleached sediment samples are identified and an adjustment factor is introduced for correcting their OSL dating results in order to avoid age inversion. The application of the adjustment factor is found to minimize overestimation of OSL ages of sediments.

Key words: OSL age inversion, quartz, optical bleaching, sand-bed braided river, ice-marginal streamway/valley.

INTRODUCTION

The main problem in the luminescence dating of fluvial deposits is the assumption of well-bleached mineral grains, in which the OSL signal was totally reset at the time of sedimentation (Murray et al., 1995; Olley et al., 1998; Stokes et al., 2001; Murray and Olley, 2002; Singarayer et al., 2005; Rittenour, 2008). The effectiveness of optical bleaching is determined by many conditions which strongly depend on the fluvial depositional environment, transport mode and sedimentation rate. This problem especially concerns luminescence dating of fluvial deposits younger than 1 kyr (Jain et al., 2004). Partial bleaching prior to the burial is related to the mode of transport (suspension, saltation or rolling and sliding), transport distance, water depth, type of fluvial system, flow regime variability and sediment sources and/or sinks in the proglacial area (Gemmell, 1988, 1994; Krbetschek et al., 2002; Schwamborn et al., 2002; Jain et al., 2004; Preusser et al., 2008; Rittenour, 2008). Adrielsson and Alexanderson (2005) as well as Alexanderson (2007) discuss the problem of assessing the bleaching rate when depositional setting and grain size vary. It might be expected that silt and very fine-grained sand will be well-bleached due to turbulent flow during transport in suspension; however, solar resetting is limited to increased suspended sediment concentrations (e.g., Berger and Luternauer, 1987; Berger, 1990). Many studies have shown that grains coarser than silt and very fine sand are more suitable for OSL dating, despite the fact that coarser grains are more likely to have been transported as bedload, and in this case solar resetting depend on water depth (e.g., Olley et al., 1998; Alexanderson, 2007; Vandenberghe et al., 2007; Rittenour, 2008). Meanwhile, bank or bed erosion of older sediments and input from urbanised catchment areas is responsible for the observed non-zero offset (Stokes et al., 2001; Rittenour, 2008). Additionally, other factors such as floods, storms and high-discharge events cause rapid redeposition or erosion of sediments, limiting solar exposure (Gemmell, 1994; Rittenour, 2008). Jain et al. (2004) suggest that the partial bleaching of fluvial deposits older than 1 kyr is not an impediment to obtaining their age, but the main limitation is connected with laboratory dosimetry and dose measurements.

The main aim of the paper is to establish a luminescence – based chronology for the Weichselian pro- and extraglacial fluvial deposits of the Toruń Basin. The fluvial sediments are dif-

* Corresponding author: pweck@umk.pl

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ferentiated by their structural and textural features, enabling distinction of particular sedimentary units. Each unit sampled for luminescence dating and incomplete bleaching was recognized by measuring the equivalent dose (D_E) distributions. It appears that a few samples were insufficiently bleached which requires special treatment for D_E assessment in order to avoid age overestimation. Such analysis of luminescence data was correlated with the architecture of depositional environments of sand-bed braided rivers and with mode of material transport and deposition. The reason for undertaking these studies was the OSL age inversion observed in a sequence of thick fluvial deposits exposed at the Nowe Dąbie and Łochowo sites (Fig. 1). Inversion of OSL ages caused by partial bleaching of sediments has been found in the Nowe Dąbie succession. Nowe Dąbie fine-grained sandy samples have similar grain-size distributions, although the sands derive from different types of sedimentary structures. Insufficient sediment bleaching related to processes of fluvial redeposition was analysed in the Łochowo succession. Łochowo sandy samples are characterized by large diversity in grain-size distributions and sedimentary structures.

STUDY AREA

The research sites are located in the western part of the Toruń Basin (Fig. 1) which is situated in the eastern part of the Noteć–Warta ice-marginal streamway in Poland. The lower sections of both the proglacial and extraglacial river valleys converge in the Noteć–Warta ice-marginal streamway. Because of this, the Toruń Basin formed by processes of fluvial erosion and

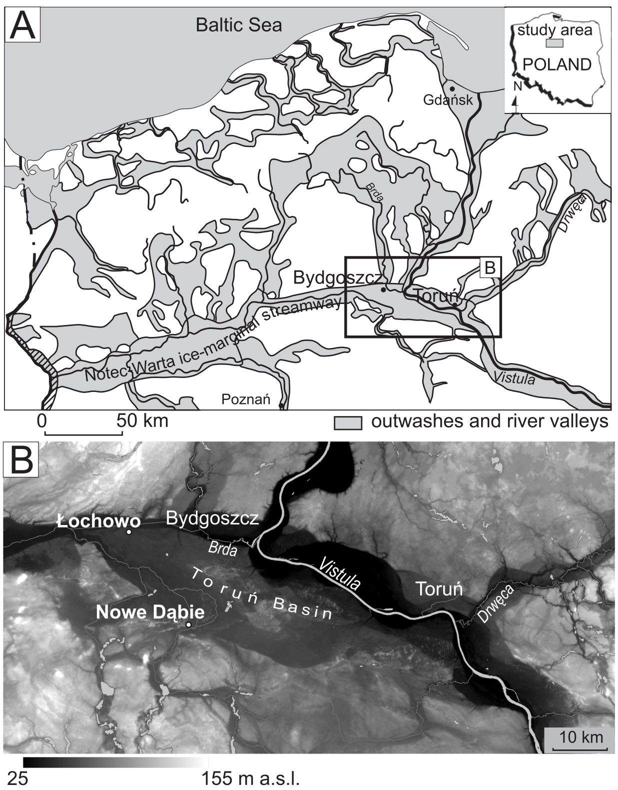

Fig. 1. Location of study area (A) and sites analysed in the Toruń Basin (B)

accumulation (Weckwerth, 2010). At the base of the river terraces older fluvial deposits are recorded. This fluvial succession, which predominates in the geological structure of the Toruń Basin, filled buried valleys until the end of the Weichselian glaciation (Weckwerth, 2010). The deposition of the younger fluvial succession took place during the Middle Weichselian, i.e. approx. 29 kyr ago (Weckwerth et al., 2011). After the first advance of the Scandinavian Ice Sheet (SIS) into the Toruń Basin during the Weichselian glaciation (approx. 28 ± 4 kyr ago) the youngest fluvial succession – the Zielonczyn Formation – (Weckwerth et al., 2011) was deposited (between 27 and 21 kyr ago). At many sites these two fluvial successions from the Middle Weichselian and the beginning of the Late Weichselian are often found to underlie much younger river deposits which form the river terraces developed after SIS recession.

METHODS

SEDIMENTOLOGICAL ANALYSES

Reconstruction of the fluvial processes includes the genetic classification of the deposits by distinguishing sedimentary units (N1, L1 and L2; Figs. 2 and 3) which are characteristic of particular environments of fluvial deposition and flow regime (Miall, 1978; Zieliński, 1992, 1993). The grain-size distribution of gravelly sand was determined at intervals of 1 phi by sieving and for sandy clay was measured with laser particle size analyser (*Analysette 22*) at intervals of 0.25 phi. The sediment transport of the fluvial environment was analysed on the basis of grain-size compositional parameters i.e. median grain diameter d_{50}, mean grain size Mz (defined as the arithmetic mean of 3 percentiles: d_{16}, d_{50} and d_{84}) sorting σ, skewness Sk_I and kurtosis K_G (Table 1). The transport mode was evaluated from the grain-size parameters by the use of CM diagrams (C – the one-percentile and M the median of the grain-size distribution; Passega, 1964; Passega and Byramjee, 1969; Mycielska-Dowgiałło and Ludwikowska-Kędzia, 2011). Palaeohydraulic parameters such as flow depth H (m), mean velocity of palaeocurrent V (m/s), and Froude number were estimated (Table 1; Weckwerth, 2009, 2011).

LUMINESCENCE DATING

Sample preparation. The coarse grains were extracted by wet sieving (100–200 μm) and treated with H_2O_2 (38%) and HCl (10%) to clean and remove organic matter and calcite. To separate quartz from other minerals, heavy liquids were used and the grains were collected from suspension within the density window from 2.61 to 2.70 g/cm^3. Finally, quartz grains were etched with HF (40%) for 40 min.

Gamma measurements. The annual dose rate values (D_R), comprised of beta and gamma radiation, were calculated on the basis of gamma spectra measured with the help of a Canberra spectrometer (Oczkowski and Przegiętka, 1998; Oczkowski et al., 2000).

Equivalent dose measurements. The OSL measurements were carried out on an automated *Riso TL/OSL DA 12* reader (Bøtter-Jensen and Duller, 1992) equipped with a xenon lamp and excitation filter pack (*GG-420* and interference filter) for stimulation (410–580 μm), and PM with a *Hoya U 340* filter (7.5 mm) for detection (290–370 μm). A beta source ^{90}Sr/^{90}Y

Table 1

Sediment transport and palaeohydraulic parameters of an ancient river (Nowe Dąbie site) reconstructed from the thickness of cross-bedded units and grain-size distribution

Sedimentary unit (lithofacies)	Lab number	Sample depth [m]	d_{50} [µm]	Mz [Φ]	σ	Sk_I	K_G	H [m]	V [m/s]	Bed and channel forms	Fr	Flow regime
N1 (Sh)	KO1	10.05	152	2.71	0.49 (w)	0.11 (p)	0.94 (m)	0.1–0.2	up to 0.6	upper plane bed	0.4–0.6	transition stage
N1 (Sr)	KO2	6.90	171	2.40	1.007 (p)	–0.19 (n)	1.56 (vl)	ca. 0.3	0.3	ripples	0.2	lower field of lower regime
N1 (Sl/Sh)	KO3	3.70	198	2.27	0.71 (m)	–0.11 (n)	0.78 (p)	0.9–1	up to 1.2	diminished dunes, upper plane bed	0.4–0.6	transition stage
N1 (Sr)	KO4	2.15	180	2.41	0.67 (mw)	–0.18 (n)	0.94 (m)	ca. 0.3	up to 0.2	ripples	0.1	lower field of lower regime

d_{50} (µm) – median grain size; textural parameters (after Folk and Word, 1957): Mz – mean grain size; σ – sorting (w – well-sorted, p – poorly sorted, m – moderately sorted, mw – moderately well-sorted), Sk_I – skewness (p – positive, n – negative), K_G – kurtosis (vl – very leptokurtic distributions, m – mesokurtic distributions, p – platykurtic distributions); H – flow depth; V – flow velocity; Fr – Froude number

delivering 42 mGy/s was applied for irradiation. The samples were put on stainless steel discs in quantities of 5 mg per aliquot.

The D_E values were estimated by using the single aliquot regenerative dose method (SAR-protocol). For every sample 24 aliquots were measured by 100 s of green stimulation at 125°C, after a preheat of 10 s at 240°C (Murray et al., 1997; Murray and Wintle, 2000). The test doses applied (for calibration compensating), in order to correct for OSL sensitivity changes, were fixed at 10% of expected D_E values for the fluvial samples and 100% of D_E in the case of the brick sample, used here as reference material only for comparison purposes in the analysis of D_E distributions.

For all calculations, only the beginning part of the OSL decay curve (0–1.2 s) was used. The applied regenerative doses Di (i = 1, 2, …7) covered a close range around the D_E value. The growth curve was constructed by linear fitting using the most appropriate data points (typically four, which are the best approaches to D_E). The recovery tests were included in the regeneration measurements and their results were found to be in good accordance (in the range of 4%) with values of a given laboratory dose. Beside recovery tests, the reliability of the results obtained was checked with the help of the recycling ratio monitored during routine SAR measurements for repeated regenerative dose value (usually $D1$ and $D5$), and aliquots exhibiting incorrect recycling ratio values (typically no more than 4 aliquots out of the series of 24) were not taken into account for the analysis. The purity of samples (absence of feldspar contamination) was checked for each aliquot by routine infra-red (IR) OSL tests at the end of the OSL measurements.

RESULTS

NOWE DĄBIE FLUVIAL SUCCESSION

Description. The >10-metre-thick fluvial deposits (unit N1, OSL samples KO1–KO4) from Nowe Dąbie underlie glacial till (Fig. 2). The fluvial succession is dominated by medium- and large-scale sets of planar and low-angle cross-bedded sands (Sp and Sl) and ripple cross-laminated or horizontally-bedded sands (Sr, Sh). The median grain size d_{50} of the deposits is 0.138–0.317 mm (unit N1, Fig. 2). The quartz grains in the unit N1 are characterized by good rounding, and aeolian grains occur very seldom. The sands within the N1 unit are homogeneous in grain size (Fig. 2). Unit N1 contains three lithofacies associations: (1) Sp (Sh, Sr, St), (2) Sr, Src, SFh, and (3) Sp (Sl, Sr, St).

The lithofacies association of (1) planar cross-bedded, horizontally laminated, ripple cross-laminated and trough cross-bedded sands Sp (Sh, Sr, St), is built by moderately sorted fine- and medium-grained sands. It lies in the lowermost position in the Nowe Dąbie profile. The median grain diameter d_{50} of lithofacies Sh (OSL sample KO1) is 152 µm, while for lithofacies Sp and St it ranges from 150 to 250 µm and for Sr from 140 to 170 µm. Lithofacies association (2), lying above, consists of ripple cross-laminated and, horizontally laminated fine-grained sands and silty sands Sr, Src, SFh. The median grain diameter d_{50} of ripple cross-laminated sands (OSL sample KO2) is 171 µm. Lithofacies Sr is poorly sorted, and the skewness of grain-size distribution is negative and very leptokurtic. The uppermost lithofacies association (3) Sp (Sl, Sr, St) consists of planar and low-angle cross-bedded sands which are overlain by ripple cross-laminated and trough cross-bedded sands (Fig. 2). The median grain diameter d_{50} of sample KO3 (lithofacies Sl) is 198 µm and for sample KO4 (lithofacies Sr) – 180 µm. The deposits of both samples KO3 and KO4 are moderately and moderately to well-sorted. The skewness of their grain-size distributions is negative.

Interpretation. Nowe Dąbie fluvial succession was deposited in a low-gradient (0.0003–0.0007 m/m), sand-bed braided river, where aggradational forms developed (sandflat braided river; Cant, 1978; Cant and Walker, 1978; Zieliński 1992, 1993; Sambrook Smith et al., 2006; Ashworth et al., 2011; Weckwerth et al., 2011). The sandy fluvial succession (unit N1) represents two fluvial subenvironments: channel deposits [lithofacies associations Sp (Sh, Sr, St) and Sp (Sl, Sr, St); OSL samples KO1, KO3 and KO4] and floodplain deposits [lithofacies association Sr, Src, SFh; OSL sample KO2; Fig. 2].

In the first fluvial subenvironment, of braided channels – associations: Sp (Sh, Sr, St) and Sp (Sl, Sr, St), there are compound bars formed in lower flow regime conditions. The upper parts of bars were washed out when the flow changed from lower to upper regime (lithofacies Sl and Sh). The grain-size distribution of OSL sample KO1 (horizontally-bedded sands Sh)

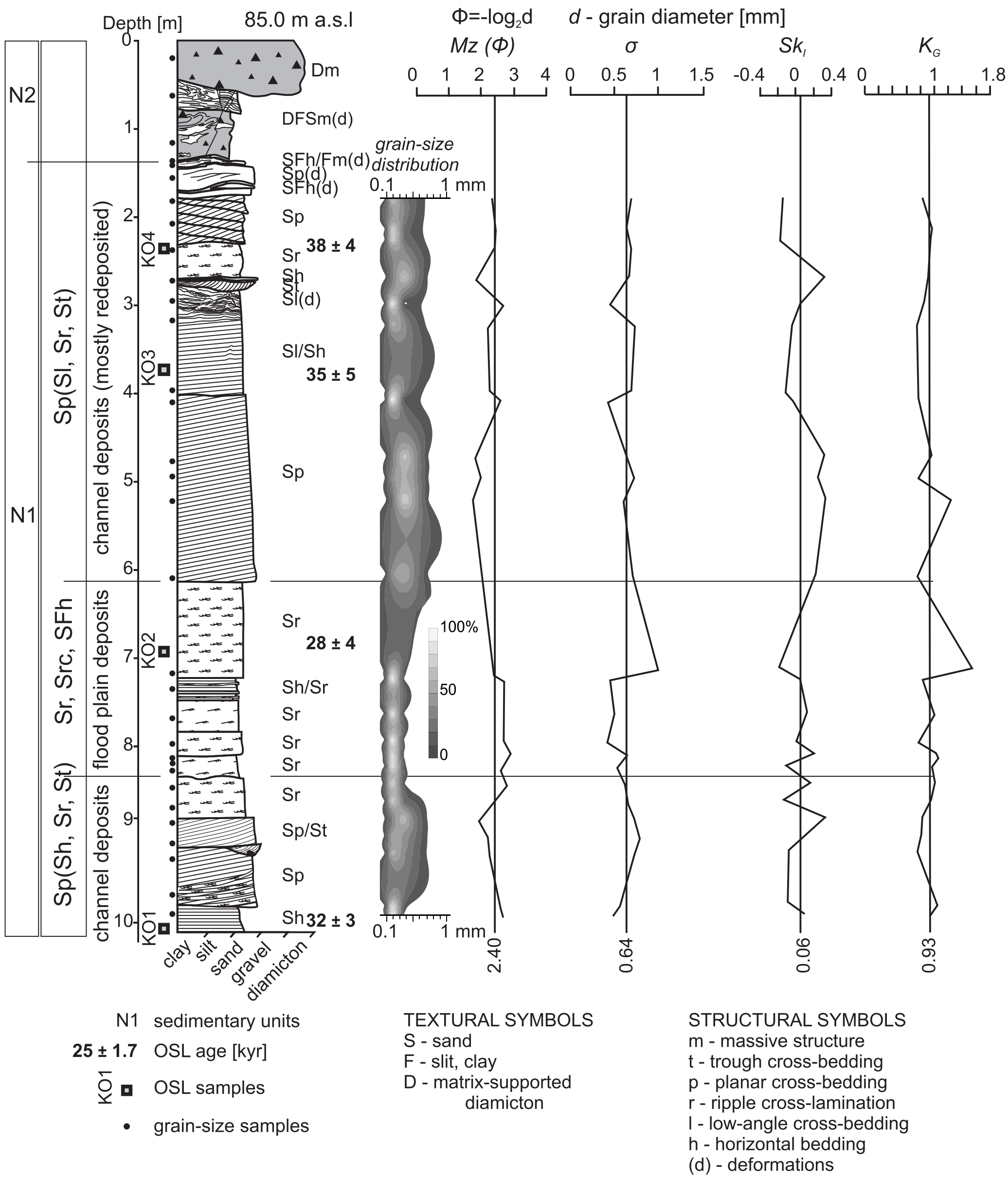

Fig. 2. Sedimentary log of the fluvial succession at the Nowe Dąbie site

Statistical parameters of the grain-size composition of the deposits: Mz – mean grain size, σ – sorting, Sk_I – skewness, K_G – kurtosis (after Folk and Ward, 1957)

indicates the best sorting of all samples (Figs. 2 and 4A). Moreover, the positive skewness value for this sample suggests that the sands were deposited due to decreasing water flow velocity. In the Passega CM diagram, OSL sample KO1 is located in the lower part of segment Q/R (Fig. 4C) indicating transport by suspension and saltation.

The sands of OSL sample KO3 from low-angle planar cross-bedded sands (Sl) can be related to transitional water flow conditions (Fr 0.4–0.6, see Allen, 1965; Julien and Raslan, 1998; Prent and Hickin, 2001; flow depth 0.9–1.0 m; mean flow velocity 1.0–1.2 ms^{-1}; Table 1). The washed-out dunes were covered by three-dimensional dunes (lithofacies St) and by ripples (lithofacies Sr) during waning flow of flood water. The sands of OSL sample KO4 from lithofacies Sr were deposited during low-energy flow (Table 1). Sediments from both samples KO3 and KO4 were transported by rolling and saltation (graded suspension – segment O/P in the Passega CM diagram; Fig. 4C).

The silty sands and fine-grained sands (sample KO2) of the second fluvial subenvironment, the floodplain (overbank) subenvironment, were deposited as a result of suspension fallout (lithofacies SFh) and ripple migration (lithofacies Sr). In sample KO2 (lithofacies Sr) fine grains prevail, as shown by negative skewness of the grain-size distribution. During flooding this sediment was transported in suspension (Fig. 4C) and by traction currents.

ŁOCHOWO FLUVIAL SUCCESSION

Description. The Łochowo site is located on the ice-marginal valley terrace at the height of 67.7 m a.s.l. (Fig. 3). This ter-

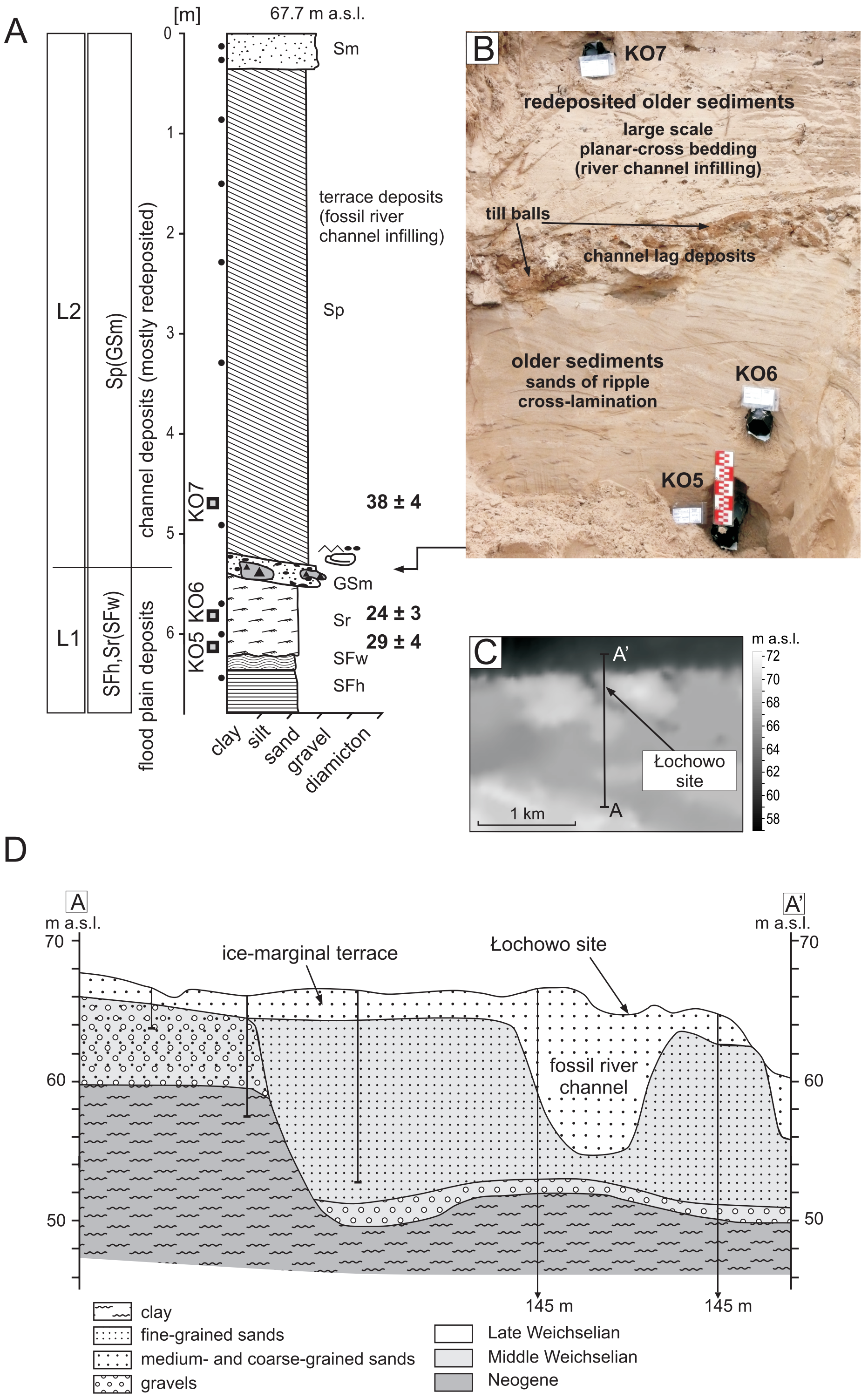

Fig. 3. A – Łochowo sedimentological log; B – KO5-KO7 sample positions within Middle and Late Weichselian sands interbedded with by channel lag deposits; C – location of geological cross-section and Łochowo site on the surface of an ice-marginal terrace; D – geological cross-section through the fossil river channel

n – w - wavy lamination; for other explanation see Figure 2

race is built by two fluvial units (L1 and L2), incised into Neogene clay and reaches over 14 m thick.

Unit L1 contains one lithofacies association of ripple cross-laminated, wavy- and horizontally laminated fine-grained sands and silty sands (Sr, SFw, SFh) which lie in the lowermost position in the Łochowo profile. Ripple cross-laminated sands (Sr) overlie wavy- and horizontally laminated silty sands (SFw and SFh). The median grain diameter d_{50} of fine-grained sands in unit L1 is 134 μm (lithofacies SFh), 154 μm (lithofacies Sr; OSL sample KO5) and 138 μm (lithofacies Sr; OSL sample

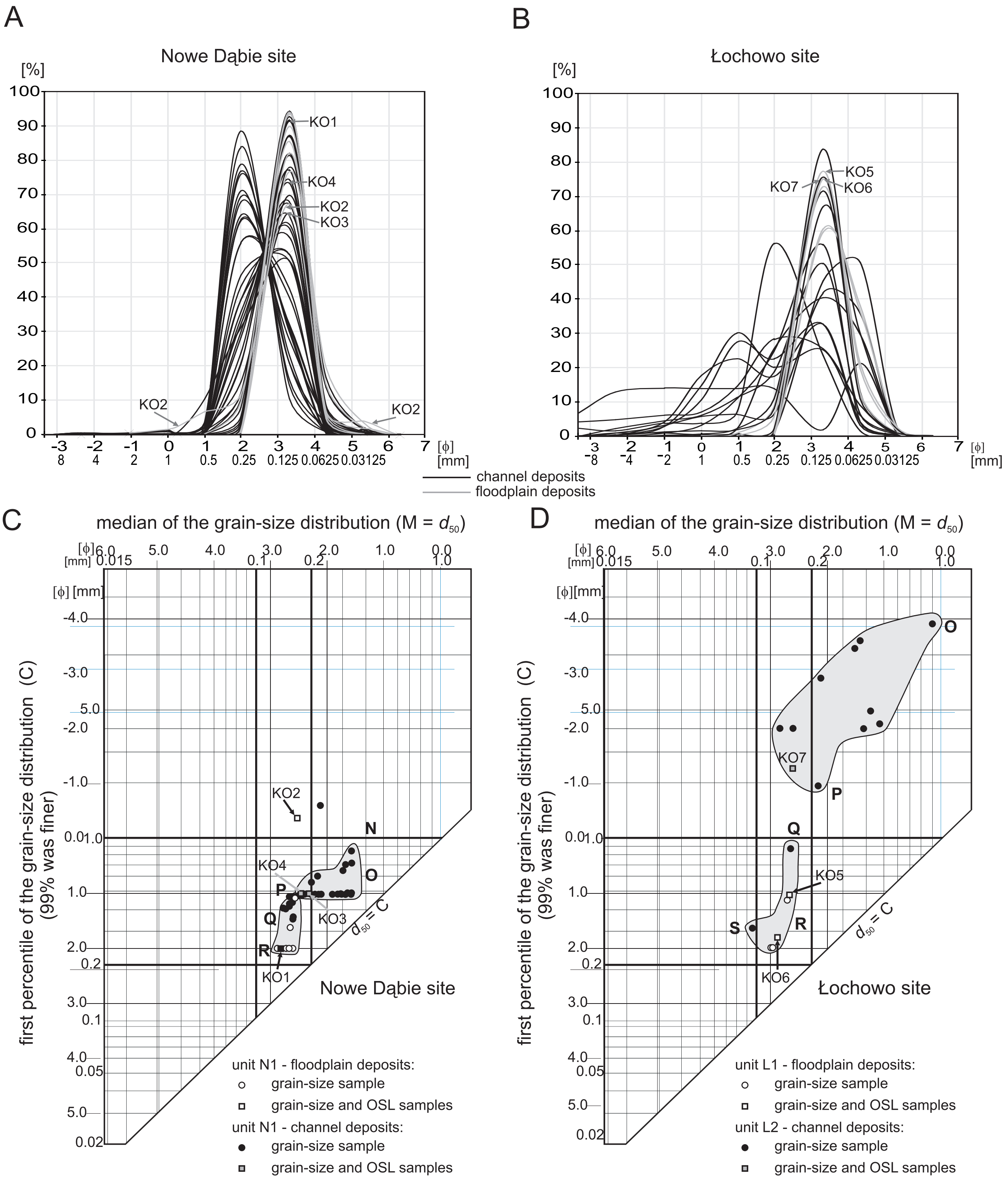

Fig. 4. Grain-size distribution of channel and floodplain deposits

A, B – frequency curves of the grain-size composition in the Nowe Dąbie and Łochowo pits; **C**, **D** – C/M patterns of sands from the Nowe Dąbie and Łochowo sites: N/O – rolling sediments, O/P – rolling sediments with some suspension sediments, P/Q – graded suspension (saltation) with some rolled sediments, Q/R – graded suspension (saltation) deposits, R/S – uniform suspension (after Passega, 1964; Passega and Byramjee, 1969)

KO6). Sediments of association Sr, SFw, SFh are moderately and well-sorted and the grain-size distribution curves are symmetrical (OSL sample KO5) and have positive values (OSL sample KO6; Fig. 4B). The values of the kurtosis (or peakedness) parameter indicate lepto- and mesokurtic grain-size distributions for OSL samples KO5 and KO6, respectively.

Unit L2 contains one lithofacies association of planar cross-bedded and massive sandy gravel Sp, (GSm) which infills a palaeochannel 5.2 m deep. Its concave base is overlain by lithofacies SGm with till clasts up to 60 cm in diameter (Fig. 3A, B). Large-scale lithofacies Sp reaches a maximum thickness of 4.7 m along the axis of the palaeochannel and consists of coarse- to fine-grained sand of median grain-diameter d_{50} from 159 μm in the lower part up to 412 μm in the upper part of lithofacies Sp (OSL sample KO7). Fine-grained sand of backflow ripple lamination forms intercalations within the Sp lithofacies. Sand in the lower part of lithofacies Sp is moderately sorted (OSL sample KO7) and in the middle and upper part is poorly sorted (Fig. 4B). The average grain-size distribution for the whole Sp lithofacies is symmetrical, while in the lower part of Sp the grain-size distribution is leptokurtic and in the upper part of Sp is platykurtic.

Interpretation.The fluvial succession in the Łochowo site accumulated in two depositional phases of a sand-bed braided river. The sands of the first phase (unit L1) were deposited on an overbank subenvironment, at first from graded suspension (OSL sample KO5, segment Q/R in the Passega CM diagram; Fig. 4D) and then from uniform suspension (OSL sample KO6, segment R/S in the Passega CM diagram; Fig. 4D). At the beginning of the second phase of deposition (unit L2), a deep channel was eroded and then filled by steeply inclined sandy layers (large-scale lithofacies Sp). The till clasts forming the channel-lag (lithofacies SGm) were derived from erosion of a till layer lying between units L1 and L2. The petrographic composition of gravels within the till clasts (Weckwerth et al., 2011) shows that the till layer accumulated before the L2 unit, during the Weichselian glaciation. Fluvial erosion of older sediments (unit L1) increased the sediment flux. The diverse grain-size distribution of fossil channel sediments was caused by diverse flow competence (channel deposits in Fig. 4D). Most coarser particles were transported by rolling, saltation and sliding on the steeply inclined sandy layers (segment O/P in the Passega CM diagram; Fig. 4D). Backflow ripples occurring at the toe of inclined layers were deposited from graded and uniform suspension in backflow eddy currents (unit L2 – channel deposits in segment Q/R/S in the Passega CM diagram; Fig. 4D).

D_E DISTRIBUTION AND LUMINESCENCE AGES

The data used in age calculations are summarized in the Tables 2 and 3. Dose rate (*DR*) and equivalent dose (D_E) values are given with their standard errors. The OSL age uncertainty is calculated according to the law of error propagation for independent variables. However, the uncertainty of equivalent dose is a major factor limiting the accuracy of the OSL age. Furthermore, it will be demonstrated later that the precision of OSL dat-

Table 2

The OSL results obtained for fluvial samples collected from Nowe Dąbie

Samples (lithofacies)	Sample depth [m]	*DR* [mGy/a]	OSL results				
			Uncorrected		*R* adjust. D_E factor	Corrected	
			D_E [Gy]	Age [kyr]		D_E [Gy]	Age [kyr]
KO1 (Sh)	10.05	1.12094 ± 0.00535	40 ± 3	36 ± 3	0.90	36 ± 3	32 ± 3
KO2 (Sr)	6.90	1.11638 ± 0.00571	34 ± 5	31 ± 4	0.90	31 ± 5	28 ± 4
KO3 (Sl/Sh)	3.70	0.83477 ± 0.00373	45 ± 7	54 ± 8	0.65	29 ± 5	35 ± 5
KO4 (Sr)	2.15	0.85430 ± 0.00355	47 ± 5	55 ± 6	0.70	33 ± 4	38 ± 4

As received D_E values and OSL ages are given in the column; for the Nowe Dąbie succession a correction was applied in order to compensate for insufficient bleaching and recalculated values are shown in the column; the meaning of the *R* factor is explained in the discussion section

Table 3

The OSL results obtained for fluvial samples collected from Łochowo site

Samples (lithofacies)	Sample depth [m]	*DR* [mGy/a]	OSL results	
			Uncorrected	
			D_E [Gy]	Age [kyr]
KO5 (Sr)	6.2	1.26057 ± 0.00775	36 ± 4	29 ± 4
KO6 (Sr)	5.8	1.39459 ± 0.00664	34 ± 4	24 ±3
KO7 (Sp)	4.7	1.13754 ± 0.00487	43 ± 3	38 ± 4

As received D_E values and OSL ages are given in the column

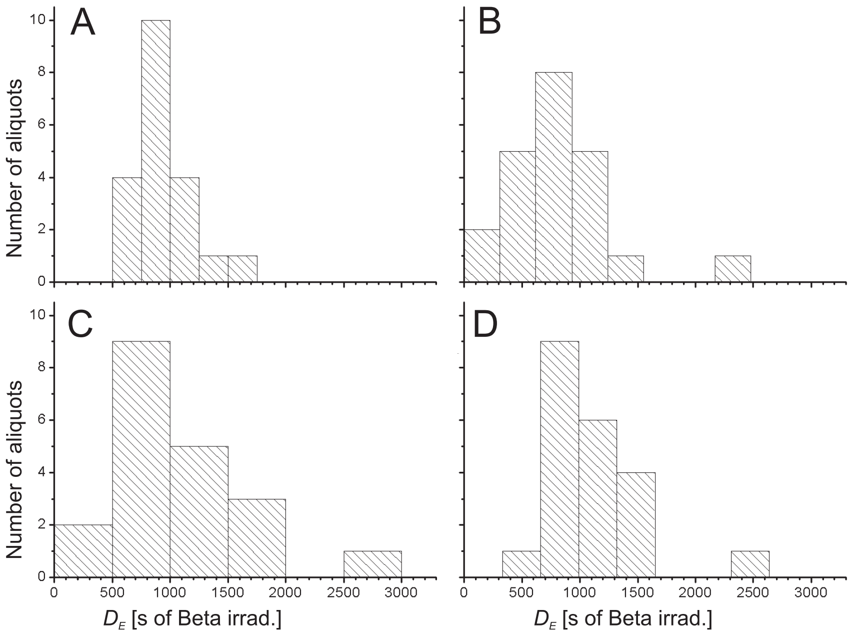

Fig. 5. Distributions of D_E values for fluvial sediments exposed at the Nowe Dabie site

A – KO1: mean = 950s, SD = 250s (27%), SE = 60s (6%), n = 20; **B** – KO2: mean = 800s, SD = 440s (55%), SE = 95s (12%), n = 22; **C** – KO3: mean = 1060s, SD = 600s (57%), SE = 130s (13%), n = 20; **D** – KO4: mean =1100s, SD = 410s (37%), SE = 90s (8%), n = 21; SD denotes the standard deviation, SE – standard deviation of the mean, n – number of accepted aliquots

ing of fluvial sediments is also limited mainly by uncertainties in equivalent dose estimation.

The histograms presenting distributions of D_E values obtained from SAR OSL measurements for the Nowe Dąbie samples are given in Figure 5. The D_E values are expressed as beta source irradiation time (in seconds) in order to avoid taking into account the systematic uncertainty of the beta dose rate calibration. It can be seen that the D_E histograms of sediment samples differ from Gaussian distributions. Nevertheless, in the first attempt to date the deposits, the raw mean D_E values were used in age calculations. Here, OSL ages of the Nowe Dąbie series (Table 2, uncorrected) resulted in evident age inversion. By contrast with the disparity between samples KO1 and KO2, samples KO3 and KO4 are located in the same area in the Passega CM diagram (Fig. 4C).

The OSL ages obtained for the Łochowo succession (samples KO5, KO6 and KO7) also show age inversion (Table 3, uncorrected). However, this effect is not so distinct as in the case of the Nowe Dąbie succession and at the present stage of study the authors were satisfied with the results of standard analysis of the Łochowo succession. On the other hand, for OSL results measured from the Nowe Dąbie samples, a new treatment of data is proposed (Table 2, corrected).

We suspect that the asymmetry and overdispersion seen in the D_E distributions are connected with the origin of the deposits. In order to test this assumption we compared the distributions of Natural OSL signals I_0 (Fig. 6) and regenerated OSL signals I_1, measured after irradiation by laboratory dose $D1$, which was adjacent to the D_E value (Fig. 7). The comparison is presented for two sediment samples: KO3 – showing the broadest and most asymmetrical D_E distribution,

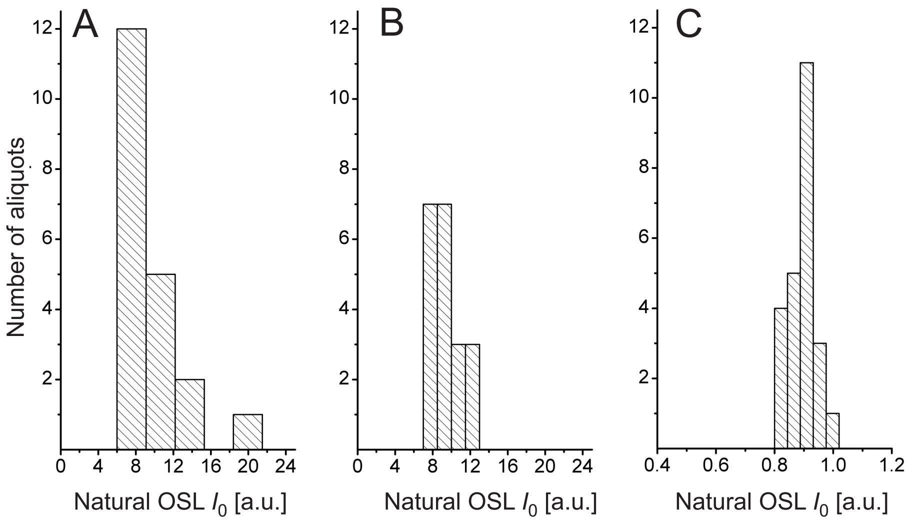

Fig. 6. Distributions of calibrated natural OSL signal I_0 (corrected for aliquot to aliquot variations of OSL sensitivity) measured for fluvial sediments

A – KO3: mean = 9.7, SD = 3.1 (32%), SE = 0.7 (7%), n = 20; **B** – KO1: mean = 9.35, SD = 1.65 (18%), SE = 0.4 (4%), n = 20; **C** – medieval brick sample Mal2: mean = 0.898, SD = 0.044 (5%), SE = 0.009 (1%), n = 24; SD – denotes the standard deviation, SE – standard deviation of the mean, n – number of accepted aliquots

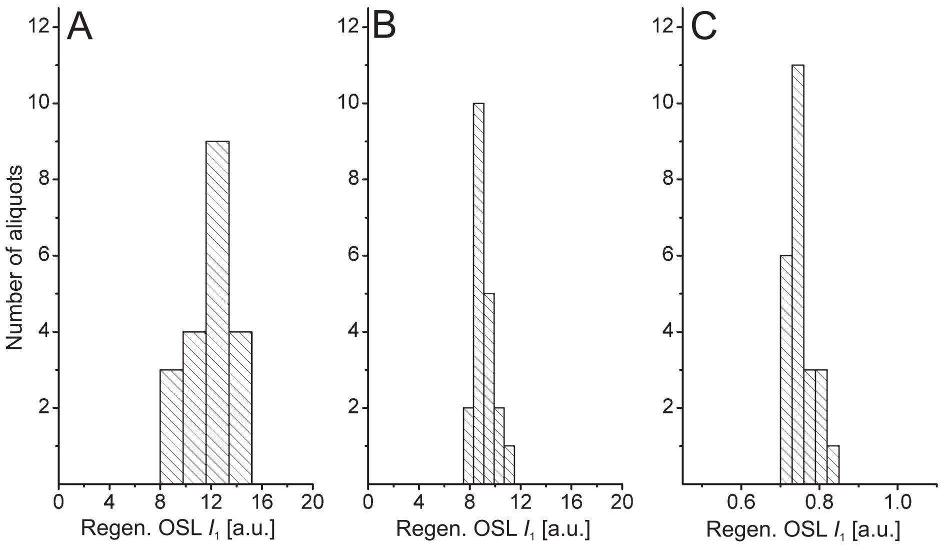

Fig. 7. Distributions of calibrated OSL signal I_1 (corrected for aliquot to aliquot variations of OSL sensitivity) measured after applying the first regenerative-dose for fluvial sediments

A – KO3: mean = 11.9, SD = 1.8 (15%), SE = 0.4 (3%), n = 20; **B** – KO1: mean = 9.1, SD = 0.8 (9%), SE = 0.2 (2%), n = 20; **C** – medieval brick sample Mal2: mean = 0.754, SD = 0.03 (4%), SE = 0.006 (<1%), n = 24

KO1 – for which a tighter histogram of D_E was obtained, and reference pottery sample Mal2, the meaning of which will be explained later.

From comparison of Figures 6 and 7 it can be noticed that for sediment samples (A) and (B) the odd asymmetrical shape of the I_0 histograms differs substantially from the regular outline of normal distributions of I_1. Furthermore, for both sediment samples, the percentage standard deviation values of natural OSL distributions (I_0) are twice that exhibited by artificially induced OSL – I_1. On this basis one can conclude that deformation and increased spreading of D_E histograms, characteristic of the river sand samples studied here, cannot be explained only by scatter of OSL sensitivity among individual grains and uncertainties due to measurement limitations. The characteristic D_E histogram shape can be found already imprinted in distributions of Natural OSL signals I_0 (Fig. 6). Hence one can conclude that asymmetry and overdispersion of D_E distribution are not significantly affected by SAR protocol, but may be rather related to phenomena connected to the nature of the sediment itself.

The sediment samples were collected from specific structural layers which can be distinguished inside thick and homogeneous sands. Due to this, it seems to be reasonable to assume that for the same grain-size fraction of quartz extracted from sand samples the effects of environmental radiation are alike. However, the variations in fluvial regime (which are imprinted in the texture of the sediment layers) could easily cause different extents of bleaching during transport and deposition of the grains. On this basis, one can expect that differences in the

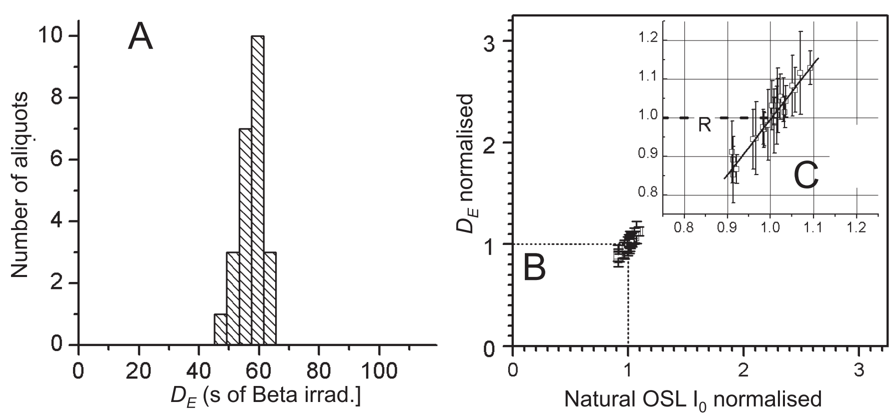

Fig. 8. OSL results for the medieval brick sample Mal2

A – compact and symmetrical distribution of D_E values is characteristic of totally zeroed material: mean = 57.1 s, SD = 4.1 (7%), SE = 0.85 (1.5%), n = 20; **B** – D_E values plotted against natural I_0 signal and inset (**C**) focusing on tight cramming of experimental data points on to the fitted line and estimation of the *R* factor – detailed explanation given in the text distributions of natural luminescence exhibited by the sediment samples should first and foremost reflect variations in the bleaching quality.

Although the large aliquot (in our case 5 mg) contains hundreds of grains, usually only a few of them give a significant luminescence signal. Therefore, the distribution of residual signal in grains can be reflected to a certain extent by the scatter of measured D_E values. On this basis we assume that asymmetry and overdispersion of D_E distributions are caused by uneven bleaching among the grains.

RELATION BETWEEN THE AMOUNT OF BLEACHING AND SEDIMENTOLOGY – DISCUSSION

The OSL ages of fluvial deposits may be overestimated and sometimes inverted due to sediment redeposition, bank erosion and limitation of solar resetting. In fluvial depositional environments, residual dose decreases with transport distance, but sediment flux input from the catchment area changes this pattern (Gemmell, 1988; Stokes et al., 2001; Alexanderson, 2007). The results of rounding and frosting analysis of quartz grains 0.5–0.8 mm indicate that at Nowe Dąbie grains from an aqueous environment predominate (Weckwerth et al., 2011). The significant participation of rounded grains in the Nowe Dąbie fluvial succession indicates that the deposits include material from older alluvial sediments (e.g., from the Eemian interglacial) due to erosion. In short transport and rapid redeposition their residual signal was not completely zeroed.

The results of our research show that the rate of bleaching depends on the fluvial depositional subenvironment (channel or overbank), transport mode (rolled, suspended or saltated) and type of bedforms i.e. type of lithofacies. The transport mode is reflected in grain-size distribution. Fuller et al. (1994) and Rhodes and Bailey (1997) suggest that finer grains (diameter up to 125 μm) are better bleached, but according to other reports (Olley et al.,1998; Murray and Olley, 2002; Wallinga, 2002; Alexanderson, 2007) coarser fractions (sand of grain diameter up to 250 μm) seem even to be more suitable for luminescence dating. In reality, sands of uniform grain sizes as in the Nowe Dąbie succesion (d_{50}; Table 1 and Fig. 4A, B) accumulated in various depositional conditions, e.g., in channel and overbank subenvironments. The transport and sedimentation of these sands occurred in shallow as well as in deep water.

In the case of sediments deposited in the channel subenvironment at Nowe Dąbie, the OSL samples KO3 and KO4 have mostly asymmetrical distributions of D_E (poorly bleached sediment) but for sample KO1 it is almost symmetrical (well-bleached sediment). However, sands of samples KO1 and KO3 represent similar flow conditions – the transition from lower to upper stage of the flow regime. The broadest and the most asymmetrical distribution of D_E values was observed in sample KO3 (Fig. 5). The platykurtic grain-size distribution of the sediments from sample KO3 indicates that the sediment flux was enriched in grains derived from channel erosion. The sands from sample KO3 (lithofacies Sl) derived from washed-out dunes developed on the surface of a compound bar (height 2.1–3.1 m), and were transported by rolling and saltation in conditions of moderate/high turbulence (segment O/P in the Passega CM diagram; Fig. 4C). The water flow accelerated on the bar margin and partly washed out the dunes. Sands derived from washed-out dunes were redeposited and would hinder daylight exposure. It seems probable that the channel bars may be built of non-bleached sediment. Our suspicion about bleaching quality is encouraged by analogous conclusions reported earlier for partially bleached sands of the Colorado River point-bar (Stokes et al., 2001) and Weichselian proglacial sediments transported and deposited due to high sediment load flow (Pisarska-Jamroży, 2006, 2008; Fiebig and Preusser, 2007; Preusser et al., 2007).

The sand of presumably well-bleached sample KO1 was deposited in a channel subenvironment under a transitional stage of flow regime. Poorly bleached grains of sample KO3 were also deposited under a transitional stage of flow regime. However, in contrast to the sediments from sample KO3, horizontally-bedded sands (lithofacies Sh, sample KO1) were derived from sheet-like flow mostly in conditions of suspension with moderately turbulent water flow (lower part of segment Q/R in the Passega CM diagram; Fig. 4C). The water depth of sheet-like flow was shallow (about 0.2 m) and the average velocity was high, up to 0.6 ms^{-1} (Table 1). According to Best and Bridge (1992), during formation of planar-bedded sands, bedload transport is minor. Grains transported in suspension in shallow water (horizontally-bedded sands) shows that bleaching is more effective than during the development of washed-out dunes. Probably, sediments of sample KO1 were transported on the bar surface during waning flood and were more susceptible to bleaching than sediments of samples KO3 transported and redeposited in deeper water. Murray et al. (1995) suggested that bed-load grains are sufficiently bleached when the water level in river channel is low. If the water level is higher and bed-load grains are transported, then bleaching depends on the turbidity of the water. However, in the case of sample KO1 (horizontally-bedded sands) suspension in moderately turbulent flow was not the cause of partial bleaching of the sediments. This hypothesis is supported by the similar case of well-bleached fine-grained sands derived from the abandoned channel of a braided river reported by Thomas et al. (2007).

A similar transport mode to that of sample KO3 occurred also in the case of sample KO4 (lithofacies Sr). Ripple cross-laminated sands (Sr) were transported by rolling and saltation in conditions of moderate/high turbulence flow within the channel, but in lower flow regime conditions, unlike in lithofacies Sl, that was deposited in transitional conditions from lower to upper flow regime. This lithofacies (Sr) was deposited after washed-out dune development on a compound bar surface covered by shallow water. The grain-size distributions of both samples KO4 and KO3 are very similar. Ashley (1990) claimed that in the case of fine sands (grain size 180–200 mm as in samples KO3 and KO4), and when flow velocity decreases, washed-out dunes can suddenly turn into current ripples. In the Nowe Dąbie succession, deposition of ripple-cross laminated sands (lithofacies Sr – sample KO4) above sands of washed-out dunes (lithofacies Sl – sample KO3) was caused by decreasing flow velocity, without increase in bleaching rate (see Allen and Leeder, 1980).

Unlike in sample KO4, sediment of sample KO2 was deposited on the floodplain due to the development of a rippled bed configuration mostly by rolled grains (bedload). In this case the flow was shallow, rather slow and water was clean assuring favourable conditions for daylight bleaching (Murray et al., 1995; Gemmel, 1997; Olley et al., 1998; Murray and Olley, 2002). Sediments of sample KO2 (ripple cross-laminated sands deposited on a floodplain) are poorly sorted and relatively well-bleached. The OSL dating results of similar sands in the lower Mississippi Valley indicate minimal influence of partial bleaching despite suspended load from glacial meltwater discharge during Late Pleistocene (Rittenour, 2008).

In order to estimate the influence of the bleaching effect on the D_E distribution a reference sample with totally zeroed luminescence was measured. Since bleaching of geological deposits can always be questioned, the authors decided to use an ancient pottery sample, for which the previous OSL signal was undoubtedly erased due to prolonged high temperature treatment during its firing. Results obtained for the medieval brick sample (Chruścińska et al., 2008) – a representative one selected out of four different bricks investigated, are shown in Figure 8.

In addition to the histograms, D_E values are also plotted against recorded natural OSL values I_0 (Figs. 8B, C and 9). To make the results of different samples easy to compare at the same scale, both D_E and I_0 were normalised to their mean values. For equally bleached samples one can expect that all data points should be randomly distributed around mean values of D_E = 1 and I_0 = 1, and that D_E should be independent from I_0. However, instead of forming circles around point (1,1) the experimental results show linear dependence: $D_E = A\ I_0 + B$, where A and B are fitting parameters. Strong correlation between D_E and I_0 can indicate poor bleaching (Li, 1994). The geological deposit samples clearly demonstrate wide-range dependency $D_E(I_0)$ (Fig. 9) in contrast to the pottery sample, where such correlation is limited to a narrow range only (Fig. 8B, C).

However, the poor bleaching can not only skew the D_E histogram and make it wider, but also – which is even worse – incomplete resetting shifts the maximum of histogram to higher values making the calculated age of the sample older than it really is. Therefore, a tool is needed to detect insufficient bleaching and to test dating results.

The pottery results indicate that, for sediment samples, the flattest part of the $D_E(I_0)$ data plot should give the best estimate of D_E. This region can be defined by the postulated equation: $D_E = \text{const}(I_0) = R$, where R is the fitting parameter. The fitting procedure is started from the lowest I_0 value and is progressively repeated n–1 times (where n equals the number of data points). In every step, the next data point with successive I_0 value is included. As an outcome of such analysis we obtained a sequence of R results accompanied by χ^2 values, which characterizes the quality of the fit. By plotting R values against χ^2 we found that, in the case of KO3 (Fig. 10A) and KO4 samples, the data are focussed in the region of the minimum of χ^2 values. The corresponding R value was chosen as the adjustment factor – producing the best estimate of D_E, better than any average calculated from the whole set of D_E values. For the rest of the sediments and the pottery sample we obtained higher R values of adjustment factor; typical examples for KO1 and Mal2 samples are shown in Figure 10B, C.

In Figures 8C and 9 the final values of the adjustment factor R are indicated. This values correspond to the area where the most dense population of data give the best approximation to the hypothetical plateau region in the $D_E(I_0)$ plot. Since R values are termed as normalised values of D_E, it is postulated here that the as-received D_E averages (Gy) can be corrected by multiplying them by appropriate values of the adjustment factor R, producing as a result a better estimate of the deposit age (Table 2, corrected). After applying this correction the age inversion still remains; however, its effect becomes much weaker. Corrected OSL ages in most cases almost overlap with each other in the range of their uncertainty limits.

Beyond variations in bleaching quality, another factor, that can produce OSL age inversion, is a combination of the fluvial erosion and accumulation. These processes were active in turn at the Łochowo site. This resulted in deposition of older fluvial sediments (unit L1 in Fig. 3) after which streambed erosion and channel infilling by younger sediments (unit L2) took place. Older deposits, that lay below the unit with till balls (represented by moderately and well-sorted sands – samples KO5 and KO6) were transported and deposited in shallow and slow water flow onto the floodplain (lower flow regime). Sediments transported under conditions of uniform suspension and saltation assume favourable conditions for daylight bleaching (Berger, 1990; Gemmell, 1997). Similar fine-grained sands with silty intercalations derived from palaeofloods were described by Thomas et al. (2007). They noted that predepositional bleaching was good

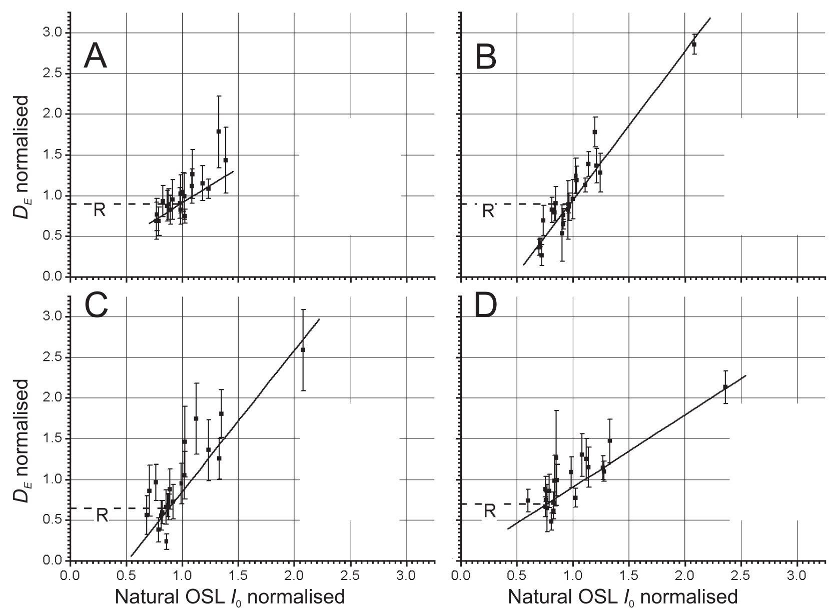

Fig. 9. Plots of D_E values versus natural OSL signal I_0 obtained for fluvial sediments

A – KO1, **B** – KO2, **C** – KO3, **D** – KO4 and estimated values of the R factor

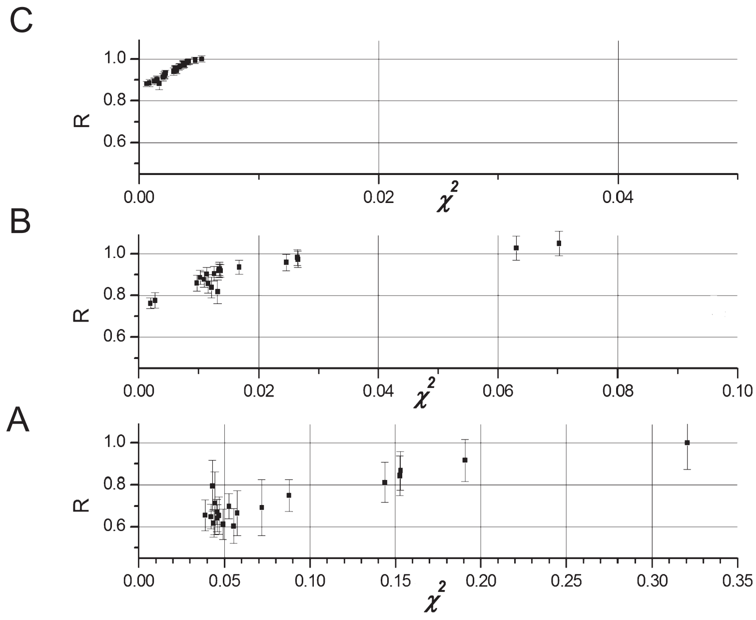

Fig. 10. The sequence of *R* values plotted against respective χ^2 values for fluvial sediments

A – KO3, **B** – KO1, **C** – medieval brick sample Mal2; note the difference in scale of χ^2 axis for different samples; see text for details of analytical procedure

for floodplain deposits. This is in contrast to the transport and depositional conditions of poorly bleached sediments accumulated within the palaeochannel of about 5 m depth filled by steeply inclined sandy layers. The redeposition of older sediments (unit L1) took place quickly in a deep and narrow channel due to strong flow (unit L2, sample KO7). This channel was infilled by sediments derived from erosion of the channel bottom and consequently the OSL age for sample KO7 is overestimated. This tends to support the suggestion by Gemmell (1994) and Jain et al. (2004) that source material derived from bed and bank erosion of older and non-bleached fluvial deposits affect sediment OSL age. These processes (occurring in a channel subenvironment) resulted in sediments that were not fully zeroed, composed of grains having different degrees of bleaching (Duller, 1994).

PHASES OF FLUVIAL ACTIVITY IN THE PROGLACIAL AREAS

Three phases of fluvial deposition occurred during the Middle and Late Weichselian in the western part of the Toruń Basin (Weckwerth et al., 2011). These phases of fluvial activity were interrupted by SIS advances. The first phase of fluvial system development took place during the end of the Middle Weichselian (before 28 ± 4 kyr ago). Fluvial deposits of similar age were identified in the northern part of the Toruń Basin (Wysota et al., 1996; Wysota, 2002). At that time compound bars, washed-out dunes and the proximal part of a floodplain (Nowe Dąbie site) were developed in a sand-bed braided river in the Toruń Basin. The lithofacies composition (planar cross-bedded and ripple cross-laminated sands) and grain-size distribution (unimodal, well and moderately sorted fine sands) indicate low-energy flow and long transport distance mainly as suspension and bedload. The high level of rounded grains in samples KO1–KO4 resulted from their long transport and repeated phases of redeposition (Weckwerth et al., 2011). The river system in the Toruń Basin might have been fed by older extraglacial deposits and from a melting ice sheet.

The second phase of fluvial activity in the Toruń Basin is recorded at the Łochowo site (unit L1). As earlier results (Weckwerth et al., 2011) indicate, during this phase about 27–21 kyr ago (between two SIS advances) fine-grained sands were deposited. Fluvial accumulation took place in a shallow braided river with tributaries of low sinuosity channels. At the Łochowo site, fluvial deposits of this age were transported and deposited on a floodplain in shallow flow conditions.

The third phase of fluvial system development took place in the Late Weichselian, after Toruń Basin deglaciation. The Noteć–Warta ice-marginal streamway was developed in the proglacial area due to meltwater flow from the north and extraglacial Vistula River flow from the south-east. Changes in the river base level were triggered by changes in the location of the Noteć ice-marginal streamway mouth (Galon, 1961; Weckwerth, 2010). These processes resulted in the development of ice-marginal valley terraces. The Łochowo site lies on the terrace of height 66–67 m a.s.l. which is narrower than the other higher terrace. The new narrower terrace developed due to river incision. This process was also responsible for the high rate of streambed erosion and redeposition of older fluvial sediments.

CONCLUSIONS

The range of bleaching in various subfacies of fluvial sediments were evaluated on the basis of sedimentological studies. D_E distributions can be explained as the result of bleaching effects. The *R* factor serves as a measure of D_E overestimation. Moreover, it seems that use of the R factor for correction of dating results almost eliminates the OSL age overestimation and inversion. For symmetrical distributions of D_E the *R* value is close to 1 and OSL age needs little or no adjustment. The deposits analysed at the Nowe Dąbie site accumulated in a low gradient sand-bed braided river. The very similar OSL dating results for the entire fluvial succession of the Nowe Dąbie profile (Table 2, corrected) suggest a high rate of deposition. Moreover, sediment redeposition within channels is supported by the results of the rounding and frosting analysis of the quartz grains.

The relation between the amount of bleaching and the sedimentological properties of fluvial deposits indicate that ripple cross-laminated sands accumulated on a floodplain (Sr) and horizontally-bedded fine-grained sands (Sh) deposited in shallow channels are more appropriate for OSL dating than sands deposited in deep channels. Incomplete bleaching can be expected for sands of compound bars, especially in the case of washed-out dunes and current ripples developed on the bar surface. All these bed bedforms (ripples, dunes, upper plane bed) are built of fine-grained sands of similar grain-size distributions, and in our opinion incomplete bleaching does not depend on particle size but on the type of bed or channel form and on flow conditions. The most appropriate water flow conditions for deposition of well-bleached sands are (1) the lower part of lower flow regime in an overbank subenvironment and (2) sheet-like flow with upper plane bed in a channel subenvironment. Both of these low and high energy water flows are shallow, up to 0.3 m in depth. Effective bleaching is also related to waning flood phase which occurs in an overbank subenvironment. In the case of cyclic sedimentation of fluvial deposits, the most appropriate samples for OSL dating should be taken from the upper parts of fining-up sedimentary cycles.

A useful tool for choosing the best sample for OSL dating is the Passega diagram, which indicates the type of sediment transport. More suitable for OSL dating are sediments transported in suspension. Shallow flow in a channel or in overbank subenvironment ensures good bleaching. A low aggradation rate can be regarded as an analogous factor in OSL dating analysis.

Sediment flux in a river channel may be fed by older sediments (glacigenic or fluvial) derived from bank and bed erosion of alluvial channels. In the case of redeposition over short distances, older sediments have incomplete bleaching. Incompletely zeroed residual luminescence signals can be expected also in the case of high aggradation rate of sediments. For this reason, erroneous OSL ages may occur in thick fluvial deposits that accumulated over a few depositional cycles.

Results of our research show that even small changes in water flow depth and velocity of sandy braided-rivers can cause diverse OSL data. For this reason OSL data from alluvial sediments should be used only as a last resort. However, the most reliable data may be expected for quartz grains transported in suspension in shallow water flow.

We are well aware of limitations of the proposed analysis, which does not take into account the entire complexity of the OSL response of quartz. Hence, this approach does not guarantee good results in each case. We sought to detect insufficient bleaching in samples and introduce a correction method that may overcome an observed age inversion. It was found that after applying this correction the age inversion was diminished to a level that is almost negligible in the range of uncertainty limits. The results obtained in any case suggest that low values of the *R* factor can indicate possible problems with daylight bleaching and a danger of D_E overestimation when the standard dating method is applied.

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