

ROTHERWAS, HEREFORDSHIRE OPTICALLY STIMULATED LUMINESCENCE (OSL) DATING OF SEDIMENT SAMPLES

SCIENTIFIC DATING REPORT

Jean-Luc Schwenninger, Ian Bapty and David Peat



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ROTHERWAS
HEREFORDSHIRE

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Jean-Luc Schwenninger, Ian Baptý, and David Peat

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SUMMARY

A series of twenty-five OSL samples were collected from prehistoric deposits exposed in the construction corridor of a new access road, linking the A49 and the Holme Lacy Road in the Rotherwas Industrial Estate south-east of Hereford (see Fig 1). The samples relate to a c 50m wide linear paved feature discovered in 2007 and which runs along the full 3.3km length of the access route. The site includes a dispersed scatter of middle Neolithic and mid-to-late Bronze Age pits and postholes. Initial dating evidence was limited to a small number of features and generally remained tentative due to the absence of firmly diagnostic cultural material with only a single pit containing late Neolithic flint and Grooved Ware pottery. A nearby Roman ditch cut through a series of colluvial deposits sealing a compact sandy horizon containing probable Iron Age pottery and overlying a surface which appears to have been constructed using cobbles and pebbles, a feature which was later to become known as the 'Rotherwas Ribbon'.

CONTRIBUTORS

Jean-Luc Schwenninger, Ian Bapty, and David Peat

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1.0 INTRODUCTION

1.1 General

Difficulties in dating the 'Ribbon' through cultural remains or stratigraphic evidence, prompted a scientific dating programme supported by English Heritage. Radiocarbon samples were taken from pits containing fire-cracked stones and from a charcoal-rich spread present across part of the 'Ribbon' surface. These dated consistently to the period spanning the end of the 3rd through to the early part of the 2nd millennium cal BC, thereby confirming the dating of the final phases of use of the 'Ribbon' by the limited material assemblages. The presence of a later Neolithic (Grooved Ware) pit in the area immediately to the west and the reasonable conjecture that the ditch truncated by the 'Ribbon' was also likely to be of Neolithic date, strongly suggest that the feature may have originally been laid out and constructed during the late Neolithic or earlier. In order to help clarify the dating, additional OSL samples were taken from sediments overlying and underlying the 'Ribbon' with the aim to further constrain the dating of the monument. Six samples were selected for analyses and the results provide an independent age control and additional support for a late Neolithic construction date.

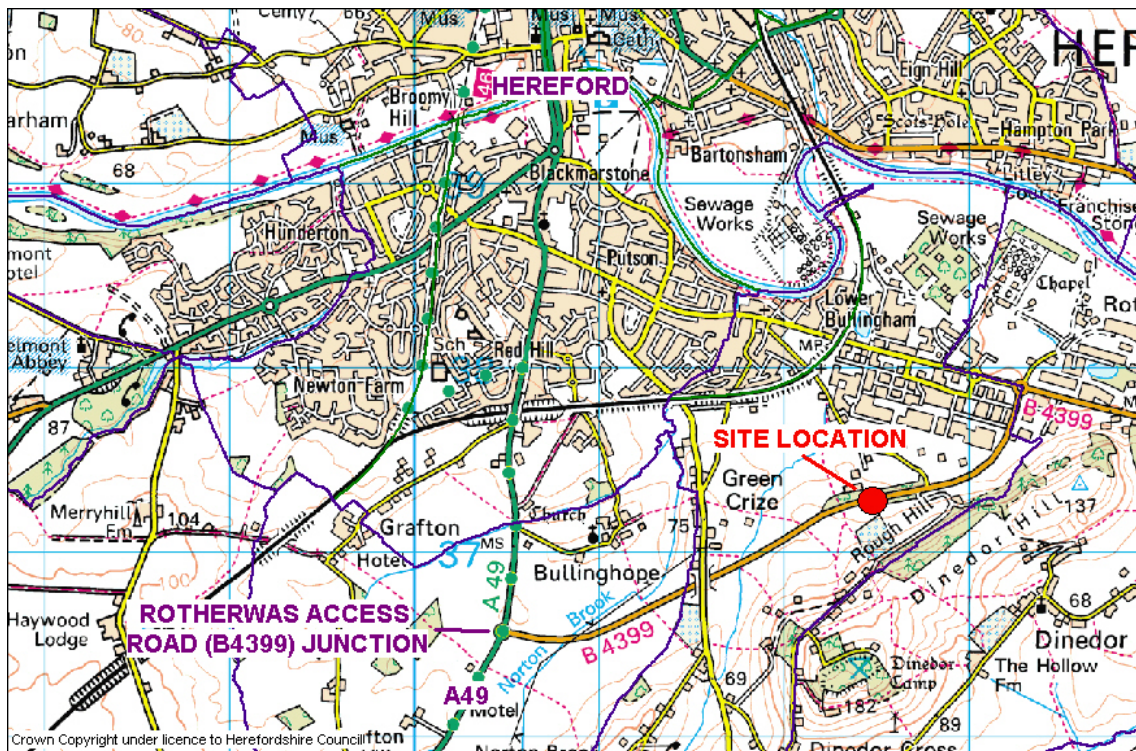


Figure 1: Location of the Rotherwas 'Ribbon' site near Hereford, Herefordshire

1.2 Site location and sample collection

A total of twenty-five OSL tube samples were collected by David Peat from the Research Laboratory for Archaeology, University of Oxford on three separate visits to the site in February and March 2010. The samples were taken from freshly cleaned faces exposed in eight different trenches. Following consultation with English Heritage, six samples were chosen for dating and further details including their laboratory codes and trench locations are provided in Table 1. Precise sampling locations are featured in Figures 2, 3, and 4.

During sampling, *in situ* NaI γ -ray spectrometry measurements were made using a portable field spectrometer (EG&G Ortec micro nomad) at all the sampling locations and the instrument was calibrated against the Oxford blocks (Rhodes and Schwenninger 2007). Further details regarding individual samples are presented in Table 1.

Table 1: Sample details

Field code	Laboratory code	Trench and context	<i>in situ</i> NaI γ -ray spectrometry
RWR10-02; OSL 2	X3899	T2; 3017 (Stone surface)	Yes
RWR10-10; OSL 10	X3916	T3; 3552 (Natural gravels)	Yes
RWR10-11; OSL 11	X3917	T3;3545 (Sand over the Ribbon)	Yes
RWR10-12; OSL 12	X3918	T3; 3513 (Colluvium)	Yes
RWR10-23; OSL 23	X3929	T5; 4532 (Soil sealing lower stone surface)	Yes
RWR10-24; OSL 24	X3930	T5; 4507 (Buried soil sealing the middle stone surface)	Yes



Figure 2: Location of sample OSL 2 (photo by D. Peat)



Figure 3: Location of OSL samples 10, 11, and 12 (photo by D. Peat)

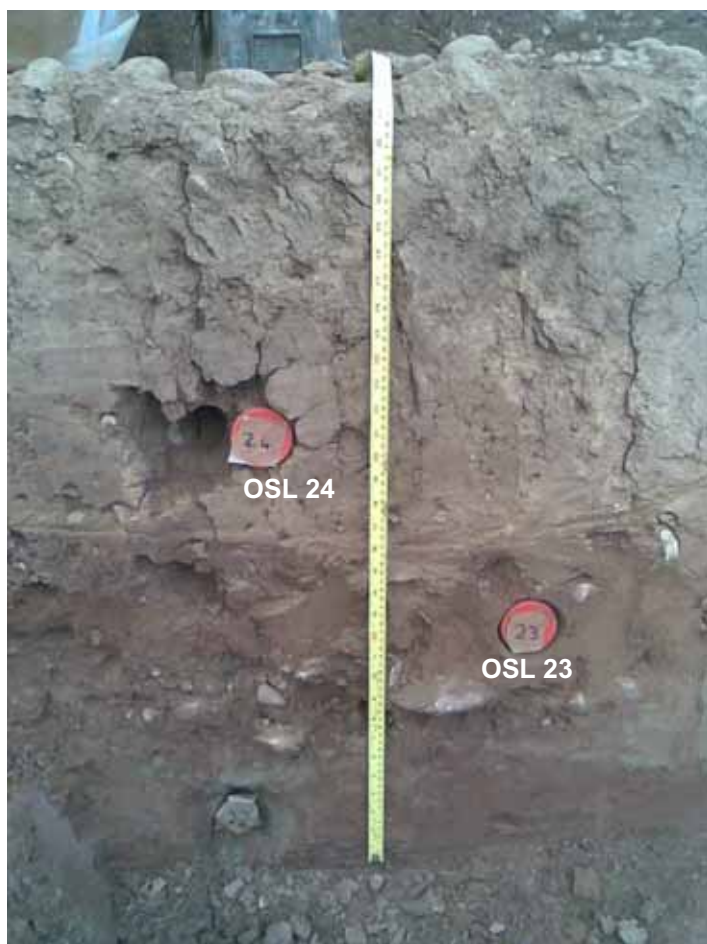


Figure 4: Location of OSL samples 23 and 24 (photo D. Peat)

2.0 METHODS

2.1 The physical basis of luminescence dating

When ionising radiation (predominantly alpha, beta, or gamma radiation) interacts with an insulating crystal lattice (such as quartz or feldspar), a net redistribution of electronic charge takes place. Electrons are stripped from the outer shells of atoms and though most return immediately, a proportion escape and become trapped at meta-stable sites within the lattice. This charge redistribution continues for the duration of the radiation exposure and the amount of trapped charge is therefore related to both the duration and the intensity of radiation exposure. Even though trapped at meta-stable sites, electrons become 'free' if the crystal is subjected to heat or exposed to light. Once liberated, a free electron may become trapped once again or may return to a vacant position caused by the absence of a previously displaced electron (a 'hole'). This latter occurrence is termed 'recombination' and the location of the hole is described as the 'recombination centre'. As

recombination occurs, a proportion of the energy of the electron is dissipated. Depending upon the nature of the centre where recombination occurs, this energy is expelled as heat and/or light. Therefore, when the crystal (mineral grain) is either heated or illuminated following natural or artificial laboratory irradiation (the 'dose') the total amount of light emitted (luminescence) is directly related to the number of liberated electrons and available recombination sites. This is the fundamental principle upon which luminescence dating is based. A more detailed account of the method may be found in Aitken (1998).

In cases where the duration of dosing is not known (as is the case for dating), estimates can be made from laboratory measurements. The response (the sensitivity) of the sample to radiation dose (ie the amount of light observed for a given amount of laboratory radiation, usually β -radiation) must be established. From this relationship the equivalent radiation exposure required to produce the same amount of light as that observed following the natural environmental dose can be determined, and is termed the palaeodose or 'equivalent dose' (D_e). The palaeodose (measured in Gy) is therefore an estimate of the total dose absorbed during the irradiation period (ie burial period). When the dose rate (the amount of radiation per unit time, measured in $\mu\text{Gy/a}$) is measured (or calculated from measured concentrations of radionuclides), the duration of the dosing period can be calculated using the equation

$$\text{Duration of dosing period} = \text{Palaeodose} \div \text{dose rate.}$$

The technique of optical dating was first applied to quartz by Huntley *et al* (1985), and methodological details were further developed by Smith *et al* (1986) and Rhodes (1988). The technique was demonstrated to work well for aeolian samples and has further proved to provide useful age estimates for a range of sedimentary contexts including fluvial and glacial contexts. Further developmental research has introduced palaeodose measurement protocols that use a 'single aliquot regenerative-dose' (SAR) protocol (Murray and Wintle 2000). These protocols generally have the potential to provide improved accuracy (eg through correction of sensitivity change, interpolation rather than extrapolation of D_e values) as well as increased precision. In some cases they may also provide an indication of incomplete zeroing of the luminescence signal at the time of deposition as detected by the relative scatter in individual palaeodose estimates or the asymmetry of dose distributions.

2.2 Sample preparation

The laboratory procedures adopted in this study were designed to yield pure sand sized quartz from the natural sediment samples. In order to obtain this material, samples were taken through a standard preparation procedure, as outlined below. All laboratory treatments were performed under low intensity laboratory safe-lighting, from purpose-built filtered sodium lamps (emitting at 588nm) and LED lightning (emitting at 578nm).

After removal of the exposed ends of the sampling containers, the unexposed central portion of the sample was wet-sieved and the 180-255 μ m grain size was used for dating. The chosen fraction was treated with hydrochloric acid (HCl) to remove carbonate and then treated in concentrated HF (67%) for 90 minutes. This treatment serves two purposes: (i) to dissolve feldspar grains, and (ii) to remove (etch) the outer surface of quartz grains (the only part of each quartz grain exposed during burial to natural alpha radiation). Any heavy minerals present were subsequently removed by gravity separation using a sodium polytungstate solution at 2.68g.cm⁻³. Finally, each sample was re-sieved to remove heavily etched grains. The order of the heavy liquid separation and second sieving are on occasion reversed for practical reasons, and for samples with extremely low yields, either or both of these treatments may be omitted after careful consideration. The prepared quartz samples were mounted on 10mm diameter aluminium discs for luminescence measurement using viscous silicone oil. The aliquot size was limited to 4-5mm in order to improve the detection of poorly bleached grains (from the spread and symmetry of individual D_e estimates) and to help reduce the effects on potential age overestimation.

Various tests for sample purity were made. Sub-samples of the prepared mineral fraction were exposed (within the Risø measurement system) to infrared (IR) light. Quartz generally does not produce measurable IR luminescence at room temperature whereas feldspar, which can suffer from anomalous fading of the infrared stimulated luminescence (IRSL) and OSL signals, or may be less rapidly bleached in some environments, produces an intense luminescence when stimulated with IR. The presence of a strong IRSL signal is therefore used as an indication for the presence of feldspar contaminants and is a criterion for rejection. In the rare cases where samples are rejected due to presence of high levels of IRSL, the prepared sediment sample is treated for ~2 weeks in concentrated H₂SiF₆ (silica-saturated HF) which effectively dissolves non-quartz material. If following this treatment, IRSL persists then the sample is subjected to a further two week H₂SiF₆ acid treatment before proceeding to the dating phase (luminescence measurement) and the results are interpreted with caution and the possible contamination of the sample discussed. In the case of the samples from Rotherwas, no prolonged etching in H₂SiF₆ was required as the majority of aliquots were found to have IRSL/OSL ratios well below 3%.

The measurement sequence adopted in this study included a post-IR blue OSL procedure (Banerjee *et al* 2001) designed to deplete any feldspar contribution to the OSL signal, by preceding each OSL measurement with an IRSL measurement. The IR exposure reduces the size of feldspar contributions, besides providing an alternative means to determine a palaeodose. In the context of this study sets of twelve individual aliquots were measured per sample. This included two aliquots used for additional dose recovery tests in order to establish whether a known laboratory dose could be recovered from the grain population following deliberate bleaching of the luminescence signal without any prior thermal treatment (contrary to the repeat dose step in which aliquots have undergone prior pre-heating).

In order to determine the attenuating effect of pore water on the environmental dose rate of the sediments, additional samples were collected in the field and hermetically sealed. The modern moisture content of the sample was determined in the laboratory by weighing the sample before and after oven drying at 50°C. These determinations formed the basis for the assessment of the mean water content of the samples throughout the burial period and were used in the dose rate calculations.

2.3 The single aliquot regenerative-dose (SAR) protocol

The SAR method is a regeneration procedure where the light level of the natural signal is converted into Gy via an interpolation between regenerated (ie known dose) points. The natural and regenerated signals are measured using the same aliquot. Sensitivity change commonly observed in quartz TL/OSL has previously precluded meaningful results being obtained this way. A key development reported by Murray and Wintle (2000) is that sample (aliquot) sensitivity is monitored following each OSL measurement (L_i) using the OSL response to a common test dose (S_i). Plots of L_i / S_i provide the necessary (sensitivity change corrected) data for interpolation. The procedure is further outlined in Figure 5.

Steps 1–6 are repeated n times in order to produce the data points required for interpolation (the first dose β_1 being zero, to give a measure of the natural signal). Typically $n=7$ (ie the natural plus 6 regeneration points, including one zero dose point and one repeat point). PH_1 and PH_2 are usually different although Murray and Wintle (2000) report no dependence of the palaeodose on either (over the range of 200–280°C). The OSL signal is integrated over the initial part of the decay (to ~10% of initial intensity) and the background is taken as the light level measured at the end of each OSL measurement.

Murray and Wintle (2000) have introduced two further steps in to the measurement procedure. The first is the re-measurement of the first regenerated data point (indicated by the box in Figure 5). The ratio of the two points (the "recycling ratio") provides an assessment of the efficacy of the sensitivity correction and the accuracy of the technique (large differences being suggestive of an ineffective technique). The recycling ratio (ideally unity) is typically in the range 0.95–1.05. The second additional step is a measurement of the regenerated OSL due to zero dose. This value gives a measure of the degree of thermal transfer to the trap(s) responsible for OSL during pre-heating. The ratio of this value to the natural OSL value (both corrected for sensitivity change) gives the "thermal transfer ratio" and ideally this should be in the range of 0.005–0.020.

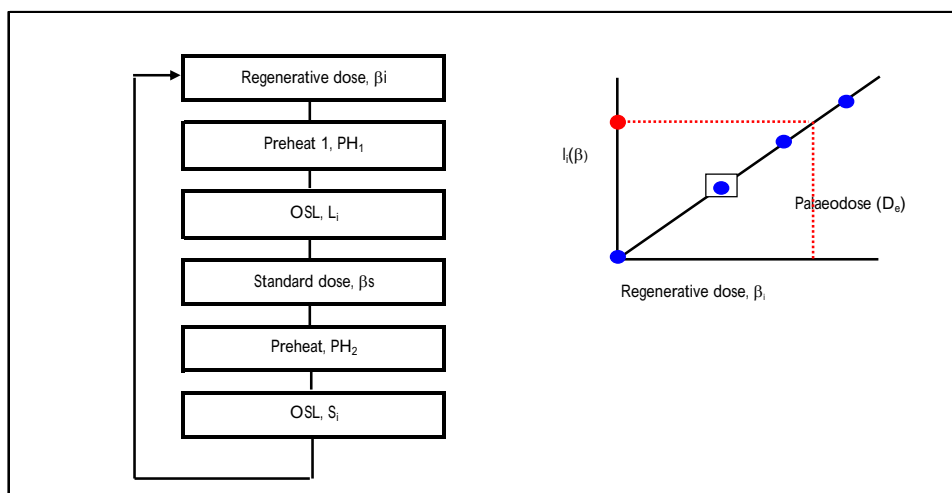


Figure 5: The SAR measurement procedure

2.4 Measurement procedures and conditions

Luminescence measurements were made using automated Risø luminescence measurement equipment (Bøtter-Jensen 1988, 1997; Bøtter-Jensen *et al* 2000). There are currently three different systems within the Luminescence Dating Laboratory that can be used for routine dating, the major difference between them being the optical stimulation sources. In two systems, optical excitation is provided by filtered blue diodes (emitting ~410–510nm), and in the third a filtered Halogen lamp (emitting ~420–560nm) is used. In all three systems, infrared stimulation is also provided using either an array of IR diodes or a single IR laser diode (depending on the measurement system). Luminescence is detected in the UV region on all systems, using EMI 9635Q bi-alkali photomultiplier tubes, filtered with Hoya U340 glass filters. Sample irradiation is provided in all cases by calibrated sealed ⁹⁰Sr sources at a rate of 1.5–4Gy/minute depending on the system used.

All OSL measurements were made at a raised temperature of 125°C (to ensure no re-trapping of charge to the 110°C TL trap during measurement) for 100s. The signal detected in the initial 2 seconds (with the stable background count rate from the last 10 seconds subtracted) was corrected for sensitivity using the OSL signal regenerated by a subsequent beta dose (β_s). To ensure removal of unstable OSL components, removal of dose quenching effects, and to stimulate re-trapping and ensure meaningful comparison between naturally and laboratory irradiated signals, pre-heating was performed prior to each OSL measurement. Following each regenerative dose (β_i) and the natural dose, a pre-heat (PH₁) at 220°C for 10s was used. Following each test dose (β_s), a pre-heat (PH₂) of 200°C for 10s was applied. All the OSL measurements incorporated a post-IR blue

OSL stage in which each OSL measurement is preceded by an IRSL measurement at 50°C, to reduce the potential effects of any residual feldspar grains (Banerjee *et al*/2001) but the SAR procedure is otherwise unchanged. For each sample a typical set of 12 multi-grain aliquots was measured. Deliberate bleaching using blue LED illumination for 100 seconds was applied to two aliquots in order to erase the natural signal. These aliquots were then given a known laboratory dose corresponding to circa 14Gy in order to obtain a recovered dose. This provides a good additional means of testing whether or not the adopted measurement procedures and instrument settings are suited to the dating of a particular sample.

3.0 RESULTS AND DISCUSSION

A summary of the luminescence characteristics is presented in Table 2 and the results of the OSL measurements, radioactivity data, and age estimates are presented in Table 3. More detailed information pertaining to age calculations and geochemical composition of individual samples are provided in Appendices 1 and 2. Examples of OSL signal plots, growth curves, and palaeodose distributions can be found in Appendix 3.

The yield of quartz mineral grains derived from these samples was plentiful and aliquots generally showed good response to laboratory irradiation. Visual checks of the initial signal intensity and the form of the decay curve show a fast decrease in OSL intensity which is characteristic of quartz. This is further evidenced by a well defined 110°C TL peak and stimulation using infrared (IR) laser diodes also confirmed the purity of each aliquot with negligible contributions from potential feldspathic contaminants (<3%; see IRSL/OSL ratio in Table 2). In the SAR measurements a low irradiation dose was repeated (recycling point) at the end of the measurement cycle to test how well the SAR sensitivity correction procedure was working. If the sensitivity correction is adequate then the ratio of the signal from the repeated dose to that of the initial regeneration dose should fall within the range of 0.9–1.10. Good recycling ratios close to unity were recorded for all the Rotherwas samples (see Table 2). A further test on the thermal transfer also showed that no significant recuperation of the OSL signal was detected in the majority of aliquots in response to a zero dose. Dose response curves generally pass through the origin when a zero Gy beta dose is included thus indicating that thermal transfer of charge from optically insensitive traps into OSL traps is not a problem. Similarly, the results from the dose recovery tests (ratio of the given dose to the recovered dose) performed on two aliquots from each sample show good agreement (see Table 2) and give confidence in the adopted measurement procedures.

Table 2: Summary of luminescence characteristics including tests for recycling, recuperation, feldspar contamination, dose recovery as well as a qualitative assessment of sensitivity and signal saturation based on 12 separate measurements per sample. The results suggest that according to these criteria, the samples and the adopted measurement procedures are well suited for OSL dating

Sample code	Mean Recycling ratio	Mean IRSL/OSL ratio	Mean Dose recovery ratio	Thermal transfer	Sensitivity	Signal saturation
OSL 02 [X3899]	1.03	0.017	0.97	Negligible	Very good	No
OSL 10 [X3916]	1.05	0.032	-	Negligible	Very good	No
OSL 11 [X3917]	1.00	0.018	0.99	Negligible	Very good	No
OSL 12 [X3918]	1.06	0.001	1.02	Negligible	Very good	No
OSL 23 [X3929]	-	0.014	-	Negligible	Very good	No
OSL 24 [X3930]	1.03	0.001	1.02	Negligible	Very good	No

Table 3: Summary of the optically stimulated luminescence (OSL) dating results. The results are based on luminescence measurements of sand-sized quartz (180–255µm) mounted on medium sized aliquots (4–5mm). All samples were measured in an automated Risø luminescence readers (Bøtter-Jensen 1988, 1997, 2000) using a SAR post-IR blue OSL measurement protocol (Murray and Wintle 2000; Banerjee et al 2001; Wintle and Murray 2006). Dose rate calculations are based on in-situ radioactivity measurements used to derive the external dose gamma-dose rate, as well as the concentration of radioactive elements (potassium, thorium, and uranium) derived from elemental analysis by ICP-MS/AES using a fusion sample preparation technique (used for beta dose rate calculations). The final OSL age estimates include an additional 2% systematic error to account for uncertainties in source calibration. Dose rate calculations are based on Aitken (1985). These incorporated beta attenuation factors (Mejdahl 1979), dose rate conversion factors (Adamiec and Aitken 1998), and an absorption coefficient for the water content (Zimmerman 1971). The contribution of cosmic radiation to the total dose rate was calculated as a function of latitude, altitude, burial depth, and average over-burden density based on data by Prescott and Hutton (1994). Further details pertaining to individual samples are presented in Appendix I

Field code	Lab. code	Radioisotopes [†]			Field water %	External y-dose rate [§] (Gy/ka)	Cosmic dose rate (Gy/ka)	Total dose rate (Gy/ka)	Palaeodose (Gy)	OSL date (years)
		K %	Th ppm	U ppm						
OSL 02	X3899	1.23	9.1	2.2	14±3	0.816 ± 0.041	0.195 ± 0.021	2.14 ± 0.09	9.05±0.32	4235 ± 235
OSL 10	X3916	1.39	9.9	2.3	14±3	0.759 ± 0.038	0.192 ± 0.019	2.20 ± 0.10	>20gy	>9100
OSL 11	X3917	0.92	6.3	1.9	17±3	0.716 ± 0.036	0.194 ± 0.020	1.73 ± 0.07	9.68±4.02	[5585 ± 2335]
Minimum age model:									(7.73±0.19)	(4460 ± 230)
OSL 12	X3918	1.10	8.0	2.3	16±3	0.714 ± 0.036	0.195 ± 0.021	1.93 ± 0.08	4.63 ± 0.23	2405 ± 165
OSL 23	X3929	1.16	8.5	2.4	14±3	0.857 ± 0.043	0.196 ± 0.022	2.15 ± 0.09	20.40 ± 6.20	9500 ± 2920
OSL 24	X3930	1.51	10.1	3.1	15±3	0.858 ± 0.043	0.202 ± 0.032	2.44 ± 0.11	6.65 ± 0.120	2720 ± 145

[†]Measurements were made on dried, homogenised and powdered material by fusion ICP-MS with an assigned systematic uncertainty of ±5%. Dry beta dose rates calculated from these activities were adjusted for the measured field water content expressed as a percentage of the dry mass of the sample.

[§]Based on in situ measurements using a portable y-ray spectrometer equipped with a 3x3 inch NaI (TI) scintillator crystal and calibrated against the Oxford calibration blocks (Rhodes and Schwenninger 2007).

The radioactivity data (in situ gamma-ray spectroscopy measurements and laboratory based elemental analysis by ICP-MS) indicate that concentrations of radioisotopes (K, Th, and U) are generally high (see Table 3) with a total dose rate generally above 2 Gy/ka [1.9–2.4G/ka]. These high values offer advantageous conditions for dating young samples as this should insure that the intensity of the natural signal should be well above background photomultiplier counts.

The OSL age estimates obtained for samples OSL 10 and OSL 23 are in excess of 9000 years and suggest that these sediments are not directly related to the archaeological feature of interest. Instead, they are likely to represent the depositional age of the naturally emplaced gravel deposit. The age estimate (>10ka) derived from sample OSL 10

(context 3552 in Trench 3) fits well with on site categorization of this sedimentary unit and, given the aims of the investigation, provides useful confirmation of this being a natural deposit. In the case of OSL 23, collected from context 4532 in Trench 5, the dating results are at odds with the provisional relative archaeological understanding of the site. The suggested late Pleistocene/early Holocene date does not immediately seem to sit easily with the presence of bone on top of the lower stone surface which this context seals. However, it is worth highlighting the relatively large error of ~30% associated with this date and OSL signal contributions from grains having retained a residual signal from a previous depositional event cannot be excluded. In the case of sample OSL 23, the young end of the age distribution would offer a better potential fit with the preliminary archaeological observations. The obvious way forward would be to undertake further AMS dating of bone from context 4515 (subject to suitable collagen preservation).

Samples OSL 2 and OSL 11 taken from immediately above the stone surface (context 3017 in Trench 2 and context 3545 in Trench 3), provided late Neolithic/early Bronze Age dates of respectively 4235 ± 235 and 5585 ± 2335 years. However, the latter result is not considered to be reliable due to the large scatter on the individual palaeodose determinations, which explains the large error (~42%) associated with the calculated age estimate. This could be caused by the presence of incompletely bleached grains and/or small-scale variations in the beta dose rate (micro dosimetric effects). In the case of OSL 11, it is interesting to note that by using a minimum age model a revised date of 4460 ± 230 years is obtained. This 'minimum date' is based on the mean results of 6 aliquots following the rejection of 4 'outliers'. This is very similar to the result obtained for sample OSL 2 in Trench 2, which appears to sit in the same late Neolithic/early Bronze Age time frame. The sample seems to have been collected from an equivalent stratigraphic position, but this does not imply any direct connection between those respective contexts (ie context 3017 in Trench 2 and context 3545 in Trench 3). Although, investigations are still ongoing, the OSL dating is further supported by the finding of probable early Bronze Age cultural material (flint), as well as prehistoric pottery (undiagnostic) and bone, within context 3545 in Trench 3. Future AMS dating of the bone could provide further clarification.

The results obtained on samples OSL 2 and OSL 11 also suggest that the Romano-British (or later) context closely overlies a late Neolithic/early Bronze Age context and this pattern has potential implications for the wider understanding of the site.

Samples OSL 12 and OSL 24, which were collected from sandy sedimentary units located higher up in the stratigraphic sequence and which overly the linear paved feature, provide a pair of results centred around 500 BC. This is in good agreement with the presumed early Iron Age activity at the site. The tightly defined Bronze Age/early Iron Age result from the buried soil horizon sealing the middle surface (OSL 24 from context 4507 in Trench 5) usefully clarifies the chronology of the sedimentary sequence in Trench 5. The dated deposit is sealed by an archaeological feature interpreted by the excavators as a burnt mound.

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APPENDIX I

	Sample Field code Laboratory code	OSL 2 X3899	OSL 10 X3916	OSL 11 X3917
Palaeodose (Gy)		9.350	>20.00 0	9.68 [min. age:7.73]
Uncertainty		3.315		4.025
Measured uncertainty		3.310		4.02 [min. age: 0.18]
Source calibration error (2%)		0.187		0.194
Grain size				
Min. grain size (µm)		180	180	180
Max grain size (µm)		255	255	255
External gamma-dose (Gy/ka)		0.816	0.759	0.716
Error (10%)		0.041	0.038	0.036
Measured concentrations				
standard fractional error		0.050	0.050	0.050
% K		1.230	1.390	0.920
Error (%K)		0.062	0.070	0.046
Th (ppm)		9.100	9.900	6.300
Error (ppm)		0.455	0.495	0.315
U (ppm)		2.200	2.300	1.900
Error (ppm)		0.110	0.115	0.095
Cosmic dose calculations				
Depth (m)		0.610	0.740	0.670
Error (m)		0.050	0.050	0.050
Average overburden density (g.cm ³)		1.900	1.900	1.900
Error (g.cm ³)		0.100	0.100	0.100
Latitude (deg.), north positive		52	52	52
Longitude (deg.), east positive		3	3	3
Altitude (m above sea-level))		50	50	50
Cosmic dose rate (µGy/ka)		0.195	0.192	0.194
Error		0.021	0.019	0.020
Moisture content				
Measured water in tubes (% of wet sediment)		13.200	7.770	11.700
Measured water in water content bags (% wet sediment)		13.860	13.880	17.370
Moisture (water / wet sediment)		0.140	0.140	0.170
Error		0.030	0.030	0.030
Total dose rate, Gy/ka		2.14	2.20	1.73
Error		0.09	0.10	0.07
AGE (ka)		4.23	>9.10	5.58 [min. age: 4.46]
Error		0.24		2.33 [min. age: 0.23]

Appendix 1 (continued)

Sample Field code Laboratory code	OSL 12 X3918	OSL 23 X3929	OSL 24 X3930
Palaeodose (Gy)	4.840	20.400	8.190
Uncertainty	0.248	6.213	1.429
Measured uncertainty	1.43	6.200	1.420
Source calibration error (2%)	0.093	0.408	0.164
Grain size			
Min. grain size (µm)	180	180	180
Max grain size (µm)	255	255	255
External gamma-dose (Gy/ka)	0.714	0.857	0.858
Error (10%)	0.036	0.043	0.043
Measured concentrations			
standard fractional error	0.050	0.050	0.050
% K	1.110	1.160	1.510
Error (%K)	0.056	0.058	0.076
Th (ppm)	8.000	8.500	10.100
Error (ppm)	0.400	0.425	0.505
U (ppm)	2.300	2.400	3.100
Error (ppm)	0.115	0.120	0.155
Cosmic dose calculations			
Depth (m)	0.610	0.590	0.360
Error (m)	0.050	0.050	0.050
Average overburden density (g.cm ³)	1.900	1.900	1.900
Error (g.cm ³)	0.100	0.100	0.100
Latitude (deg.), north positive	52	52	52
Longitude (deg.), east positive	3	3	3
Altitude (m above sea-level))	50	50	50
Cosmic dose rate (µGy/ka)	0.195	0.196	0.202
Error	0.021	0.022	0.032
Moisture content			
Measured water in tubes (% of wet sediment)	12.260	13.560	12.400
Measured water in water content bags (% wet sediment)	16.140	13.970	15.020
Moisture (water / wet sediment)	0.160	0.140	0.150
Error	0.030	0.030	0.030
Total dose rate, Gy/ka	1.93	2.15	2.44
Error	0.08	0.09	0.11
AGE (ka)	2.40	9.50	3.35
Error	0.16	2.92	0.60

APPENDIX 2 ELEMENTAL ANALYSIS OF SAMPLES BY FUSION ICP-MS

Analyte Symbol		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃ (T)	MnO	MgO	CaO	Na ₂ O	K ₂ O	TiO ₂	P ₂ O ₅	LOI	Total
Unit Symbol		%	%	%	%	%	%	%	%	%	%	%	%
Detection Limit		0.01	0.01	0.01	0.001	0.01	0.01	0.01	0.01	0.001	0.01		0.01
OSL 2	X3899	78.18	8.75	4.79	0.062	1.44	0.49	1.1	1.48	0.591	0.14	3.93	100.9
OSL 10	X3916	73.19	11.14	5.02	0.066	1.29	0.5	1.2	1.67	0.627	0.2	4.11	99.01
OSL 11	X3917	82.55	6.94	3.46	0.046	0.81	0.35	1.08	1.11	0.462	0.1	2.88	99.78
OSL 12	X3918	80.12	8.29	3.1	0.044	1	0.41	1.12	1.34	0.578	0.09	3.79	99.88
OSL 23	X3929	77.99	8.74	4.07	0.067	1.1	0.43	1.08	1.4	0.615	0.08	3.84	99.41
OSL 24	X3930	71.56	11.42	4.35	0.141	1.55	0.61	1.09	1.82	0.779	0.12	6.54	99.97

Analyte Symbol		Sc	Be	V	Cr	Co	Ni	Cu	Zn	Ga	Ge	As	Rb
Unit Symbol		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Detection Limit		1	1	5	20	1	20	10	30	1	1	5	2
OSL 2	X3899	8	1	72	90	12	30	20	50	11	2	< 5	56
OSL 10	X3916	10	2	90	70	15	40	30	70	15	3	< 5	70
OSL 11	X3917	6	1	53	100	8	30	20	260	9	2	< 5	40
OSL 12	X3918	7	1	54	110	7	< 20	10	40	9	2	< 5	58
OSL 23	X3929	8	1	72	100	12	30	20	60	12	2	< 5	59
OSL 24	X3930	11	2	90	110	15	50	20	80	16	2	< 5	85

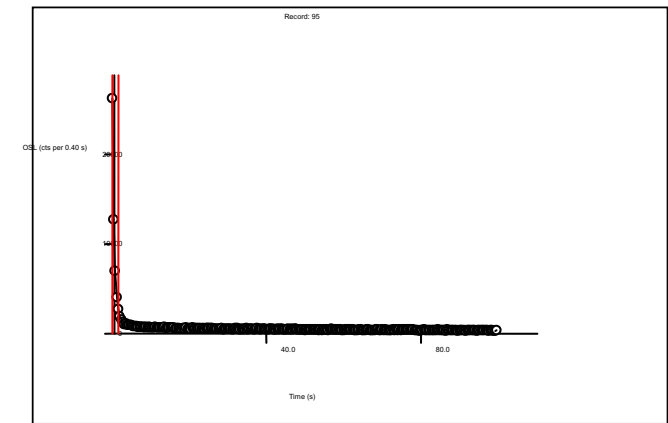
Analyte Symbol		Ga	Ge	As	Rb	Nb	Mo	Ag	In	Sn	Sb	Cs	Ba
Unit Symbol		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Detection Limit		1	1	5	2	1	2	0.5	0.2	1	0.5	0.5	3
OSL 2	X3899	55	25	309	11	< 2	1	< 0.2	2	< 0.5	2.8	316	316
OSL 10	X3916	69	34	200	12	< 2	0.6	< 0.2	2	< 0.5	3.4	464	464
OSL 11	X3917	53	22	318	9	< 2	0.9	< 0.2	1	< 0.5	1.6	320	320
OSL 12	X3918	60	24	378	9	< 2	0.9	< 0.2	2	< 0.5	2.3	378	378
OSL 23	X3929	61	26	347	12	< 2	1	< 0.2	2	< 0.5	2.8	403	403
OSL 24	X3930	71	33	329	14	< 2	0.9	< 0.2	3	< 0.5	4	636	636

Analyte Symbol		La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm
Unit Symbol		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Detection Limit		0.1	0.1	0.05	0.1	0.1	0.05	0.1	0.1	0.1	0.1	0.1	0.05
OSL 2	X3899	38.8	79.5	9.62	32	6.4	1.3	5.3	0.9	4.7	0.9	2.6	0.4
OSL 10	X3916	60.2	131	17	58.5	12.5	2.6	9.3	1.4	6.9	1.3	3.3	0.48
OSL 11	X3917	34.5	68.6	8.3	27.3	5.4	1.16	4.3	0.7	3.9	0.8	2.2	0.34
OSL 12	X3918	32.5	65.3	7.81	26.4	4.9	1.02	4.1	0.7	4.4	0.9	2.7	0.42
OSL 23	X3929	39.1	81.6	9.54	31.5	6.2	1.25	5	0.8	4.7	0.9	2.8	0.43
OSL 24	X3930	44.6	91.2	11.1	37	7.5	1.54	5.9	1	5.5	1.1	3.2	0.49

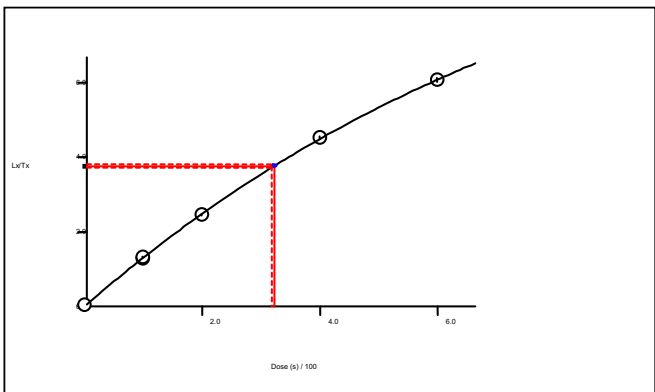
Analyte Symbol		Yb	Lu	Hf	Ta	W	Tl	Pb	Bi	Th	U
Unit Symbol		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Detection Limit		0.1	0.04	0.2	0.1	1	0.1	5	0.4	0.1	0.1
OSL 2	X3899	2.6	0.44	7.1	0.8	2	0.4	13	< 0.4	9.1	2.2
OSL 10	X3916	3.1	0.51	5.2	0.8	1	0.4	17	< 0.4	9.9	2.3
OSL 11	X3917	2.3	0.39	7.8	0.6	1	0.3	12	< 0.4	6.3	1.9
OSL 12	X3918	2.8	0.47	8.7	0.8	< 1	0.3	16	< 0.4	8	2.3
OSL 23	X3929	2.8	0.47	8.7	0.8	1	0.4	14	< 0.4	8.5	2.4
OSL 24	X3930	3.3	0.52	7.8	1	1	0.5	15	< 0.4	10.1	3.1

APPENDIX 3 TYPICAL OSL SHINE DOWN CURVES, GROWTH CURVES AND D_e DISTRIBUTIONS

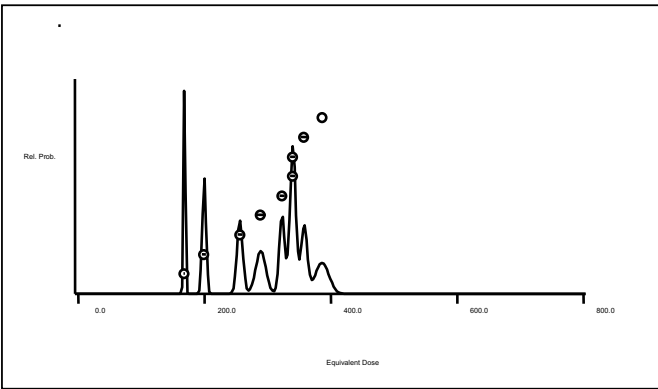
OSL 2 [X3899]



Shine down curve

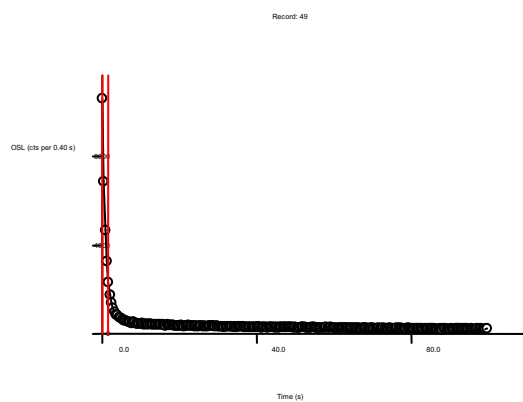


Growth curve

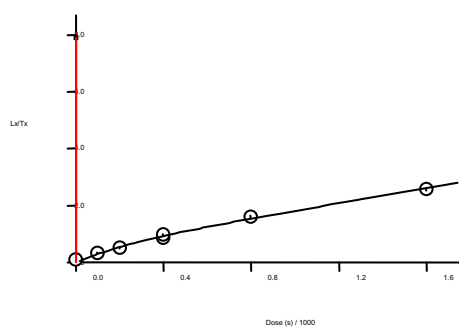


D_e distribution

OSL 10 [X3916]

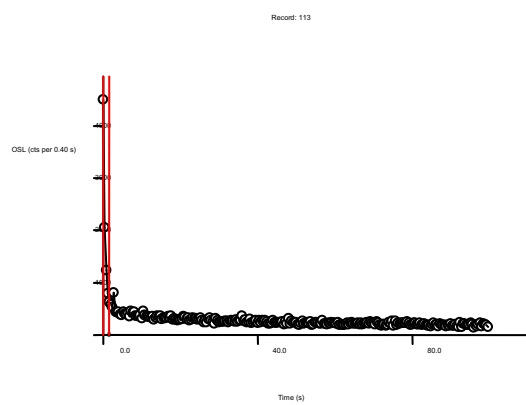


Shine down curve

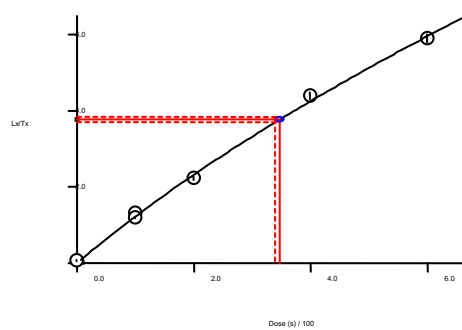


Growth curve

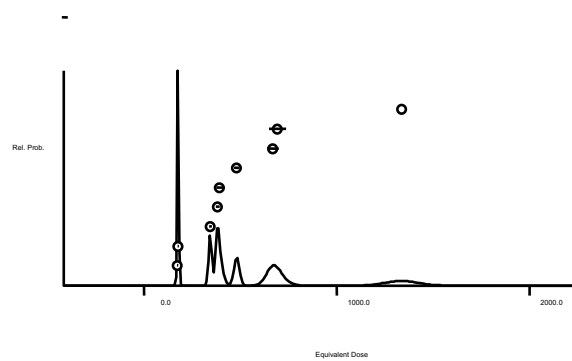
OSL 11 [X3917]



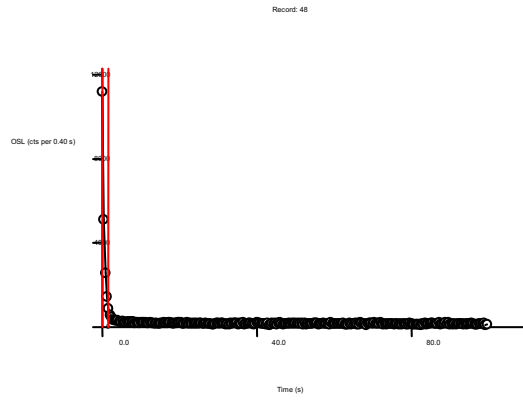
Shine down curve



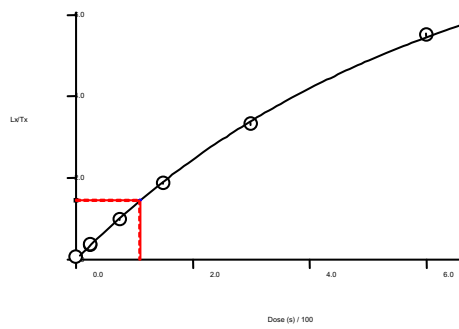
Growth curve



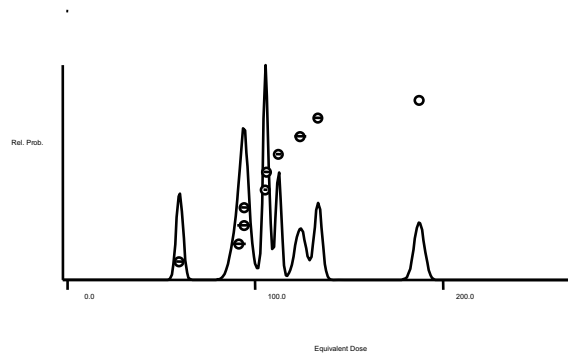
D_e distribution



Shine down curve

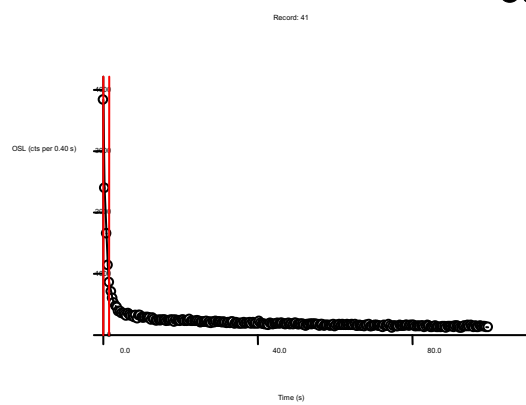


Growth curve

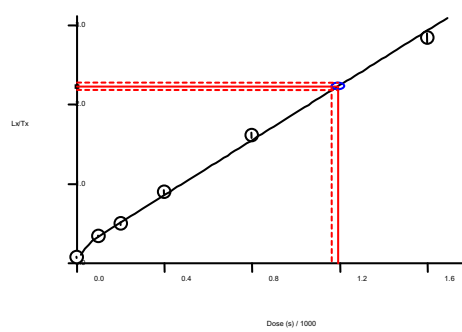


D_e distribution

OSL 23 [X3929]

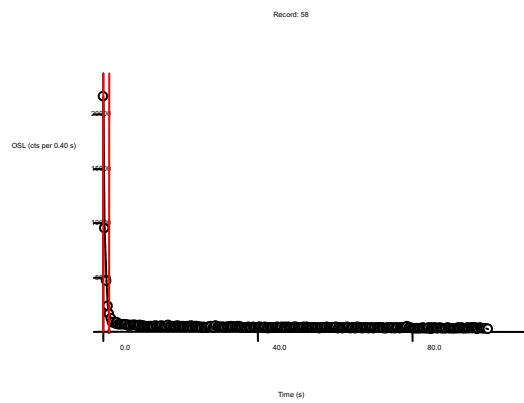


Shine down curve

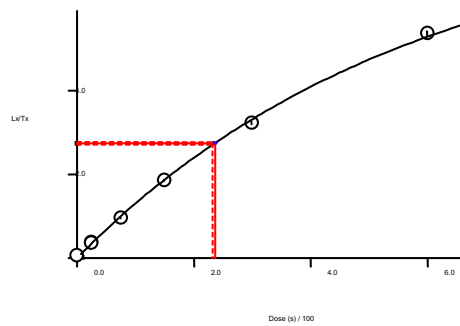


Growth curve

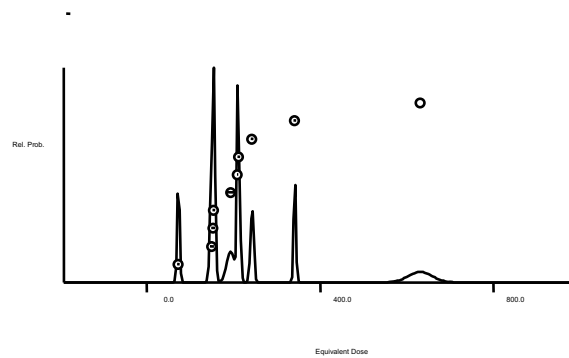
OSL 24 [X3930]



Shine down curve



Growth curve



D_e distribution



ENGLISH HERITAGE RESEARCH AND THE HISTORIC ENVIRONMENT

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- * Intervention and Analysis (including Archaeology Projects, Archives, Environmental Studies, Archaeological Conservation and Technology, and Scientific Dating)
- * Assessment (including Archaeological and Architectural Investigation, the Blue Plaques Team and the Survey of London)
- * Imaging and Visualisation (including Technical Survey, Graphics and Photography)
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