RESEARCH REPORT SERIES no. 113-2011

DUNBRIDGE, HAMPSHIRE
OPTICALLY STIMULATED LUMINESCENCE DATING OF PLEISTOCENE FLUVIAL SAND AND GRAVEL DEPOSITS

SCIENTIFIC DATING REPORT

Jean-Luc Schwenninger, Phil Harding, David Bridgland, Peter Allen, Philippa Bradley, and David Peat

INTERVENTION AND ANALYSIS

ENGLISH HERITAGE

Research Report Series 113-2011

DUNBRIDGE
HAMPSHIRE

OPTICALLY STIMULATED LUMINESCENCE DATING OF PLEISTOCENE FLUVIAL SAND AND GRAVEL DEPOSITS

Jean-Luc Schwenninger, Phil Harding, David Bridgland
Peter Allen, Philippa Bradley, and David Peat

NGR: SU 321 255

ISSN 2046-9799 (Print)
ISSN 2046-9802 (Online)

The Research Report Series incorporates reports by the expert teams within the Investigation & Analysis Division of the Heritage Protection Department of English Heritage, alongside contributions from other parts of the organisation. It replaces the former Centre for Archaeology Reports Series, the Archaeological Investigation Report Series, the Architectural Investigation Report Series, and the Research Department Report Series.

Many of the Research Reports are of an interim nature and serve to make available the results of specialist investigations in advance of full publication. They are not usually subject to external refereeing, and their conclusions may sometimes have to be modified in the light of information not available at the time of the investigation. Where no final project report is available, readers must consult the author before citing these reports in any publication. Opinions expressed in Research Reports are those of the author(s) and are not necessarily those of English Heritage.

Requests for further hard copies, after the initial print run, can be made by emailing:
Res.reports@english-heritage.org.uk
or by writing to:
English Heritage, Fort Cumberland, Fort Cumberland Road, Eastney, Portsmouth PO4 9LD
Please note that a charge will be made to cover printing and postage.

SUMMARY

A series of 13 samples were collected from an exposed quarry face near Kimbridge Farm, Dunbridge for optically stimulated luminescence (OSL) dating. The Pleistocene sediments comprise terrace deposits of the River Test which have produced a large number of Palaeolithic handaxes. This dating study follows a geoarchaeological watching brief undertaken over a period of 17 years in which sections were recorded and sampled with the primary aim of enhancing the understanding of the geological context of the richest Lower Palaeolithic assemblage from Hampshire. Two gravel terraces have been confirmed: an upper Belbin Formation including archaeological finds demonstrating 'proto-Levallois' technology, and a lower Mottisfont Formation with a relatively sparse Palaeolithic content. Although, the majority of samples were shown to be affected by poor bleaching, previously published OSL dating, supplemented by new data, has been combined with uplift modelling to suggest dates of MIS 9b and MIS 8, respectively, for these two gravels. This fits well with evidence from other sites in England and the near Continent for the timing of the earliest Levallois at around MIS 9.

CONTRIBUTORS

Jean-Luc Schwenninger, (Research Laboratory for Archaeology and the History of Art, University of Oxford), Phil Harding (Wessex Archaeology), David Bridgland (Department of Geography, Durham University), Peter Allen (Department of Geography, Royal Holloway University of London), Philippa Bradley (Wessex Archaeology) and David Peat (Research Laboratory for Archaeology and the History of Art, University of Oxford).

ACKNOWLEDGEMENTS

Specific thanks are extended to English Heritage, who funded the post-excavation analysis, programme of OSL dating and full reporting of the project through the Aggregates Levy Sustainability Fund (ALSF). The help of English Heritage through the assessment, post-excavation and reporting process is gratefully acknowledged; in particular the late Sarah Jennings, Helen Keeley, Barney Sloane and Kath Buxton are thanked for their help during the project. David Hopkins (Hampshire County Council) provided funding for an initial study of the watching brief archive for which Wessex Archaeology is very grateful.

The watching brief could not have been undertaken without funding from Halls Aggregates (South Coast Ltd), specifically to Rosemary Box who coordinated its initial stages, and latterly to Cemex, especially to Richard Small for his help arranging access, for providing plant to collect OSL samples and for borehole data.

ARCHIVE LOCATION

Hampshire Archaeology & Historic Building Record
Landscape Planning & Heritage Group
Environment Department
Capital House
48-52 Andover Road
Winchester
SO23 7BH

DATE OF INVESTIGATION
2009–2011

CONTACT DETAILS
Jean-Luc Schwenninger
Research Laboratory for Archaeology and the History of Art,
University of Oxford
Dyson Perrins Building
South Parks Road
Oxford
OX1 3QY
01865 285224; jean-luc.schwenninger@rlaha.ox.ac.uk

CONTENTS

INTRODUCTION

General

An extensive record of Tertiary sands capped by Pleistocene fluvial sand and gravel (hoggin) is preserved in land adjacent to former pits at Kimbridge Farm near Dunbridge, Hampshire (Fig 1). These aggregate deposits comprise terrace sediments of the River Test and have produced the largest number of Palaeolithic handaxes from Hampshire (Roe 1968a; 1968b). The area is crucially important for the study of Palaeolithic archaeology particularly with respect to the debate regarding the development of Levallois technology in Britain.

Gravel extraction at the Cemex quarry site has been subjected to regular archaeological and geological monitoring by Phil Harding over a period of 17 years. A small number of Palaeolithic artefacts including handaxes and a Levallois core were recovered during the watching brief and the results demonstrated that the fluvial gravels incorporated bleached cryturbated material from secondary fluvial contexts thus refuting the presumed occurrence of *in-situ* stratified industries (Dale 1912; 1918; White 1912). To date, only brief interim statements have been published on the results (Bridgland and Harding 1993; Harding 1998) and until recently, dating of such deposits remained problematic and poorly understood. Within the last few years, the application of optically stimulated luminescence (OSL) dating has resulted in considerable progress being made towards refining and assessing the validity of established models of terrace development. The technique was successfully applied in previous Aggregate Levy Sustainability Fund (ALSF) studies including the Solent River system (Bates *et al* 2009a, 2009b, Briant *et al* 2006, 2009a, 2009b; Briant and Schwenninger 2009; Schwenninger *et al* 2006). The key objective of this study was to help secure a chronological framework for these archaeologically important Pleistocene sand and gravel deposits.

Sample collection

Thirteen samples including three replicates were collected in April 2009 in company of Dr Peter Allen, Pippa Bradley, Dr David Bridgland, Phil Harding, David Peat and Richard Small. The samples were collected from freshly cleaned coarse textured sandy units exposed in the best-preserved remaining gravel section at Dunbridge, a face located on the east side of the quarry (see Fig 2). The samples were all within the lower Mottisfont Formation. Samples OSL 1, 2, 7, 8 and 9 were taken from the lower gravel deposit (see Figs 3, 4, and 6) whereas samples OSL 3, 4, 5, and 6 were taken from sandy units in the upper part of the sequence (see Figs 3 and 7). Sample OSL 10 was collected from a small pocket of sand within the thick middle gravel deposit north-west of the main section (see Figs 4 and 7). In the case of OSL 1, three replicate samples (1a, 1b and 1c) were taken as this was considered to be one of the most important stratigraphic units. The distribution

of the samples within the exposed stratigraphy is indicated in Figure 7 (note that samples OSL 2 and OSL 9 were from the underlying Palaeogene sand (Reading Formation).

In-situ NaI γ-ray spectrometry measurements using a portable field spectrometer (EG&G Ortec micronomad) were made at five sampling locations (see Table 1) and the instrument was calibrated against the Oxford blocks (Rhodes and Schwenninger 2007). A lack of time and adverse weather conditions prevented the acquisition of spectra for all the sampling locations. Sample processing and luminescence measurements were made at the Research Laboratory for Archaeology & the History of Art, University of Oxford. Further details regarding individual samples are presented in Table 2.

Figure 1: Location of the study site at Kimbridge quarry near Dunbridge, Hampshire

Figure 2: Aerial view of the OSL sampling location inside the Kimbridge quarry (image: Google Earth)

Figure 3: General view of the OSL sampling location within the face of the Kimbridge quarry

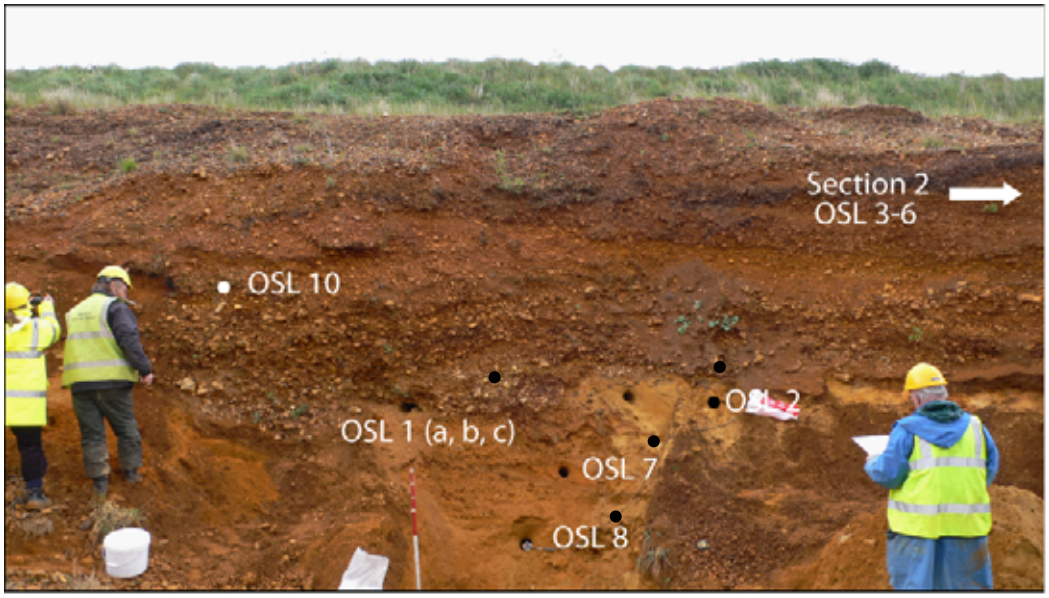


Figure 4: Location of OSL samples. A close-up of the location of samples 4 to 6 is shown in Figure 5. The position of sample 9 is featured in Figure 6

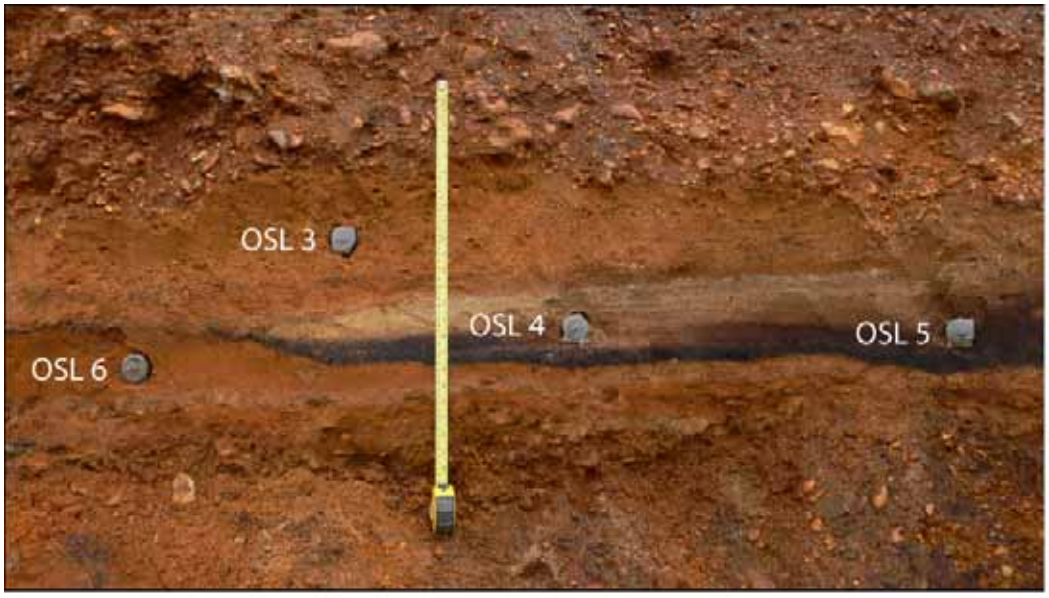


Figure 5: Location of OSL samples 3 to 6 in the upper gravel deposit.

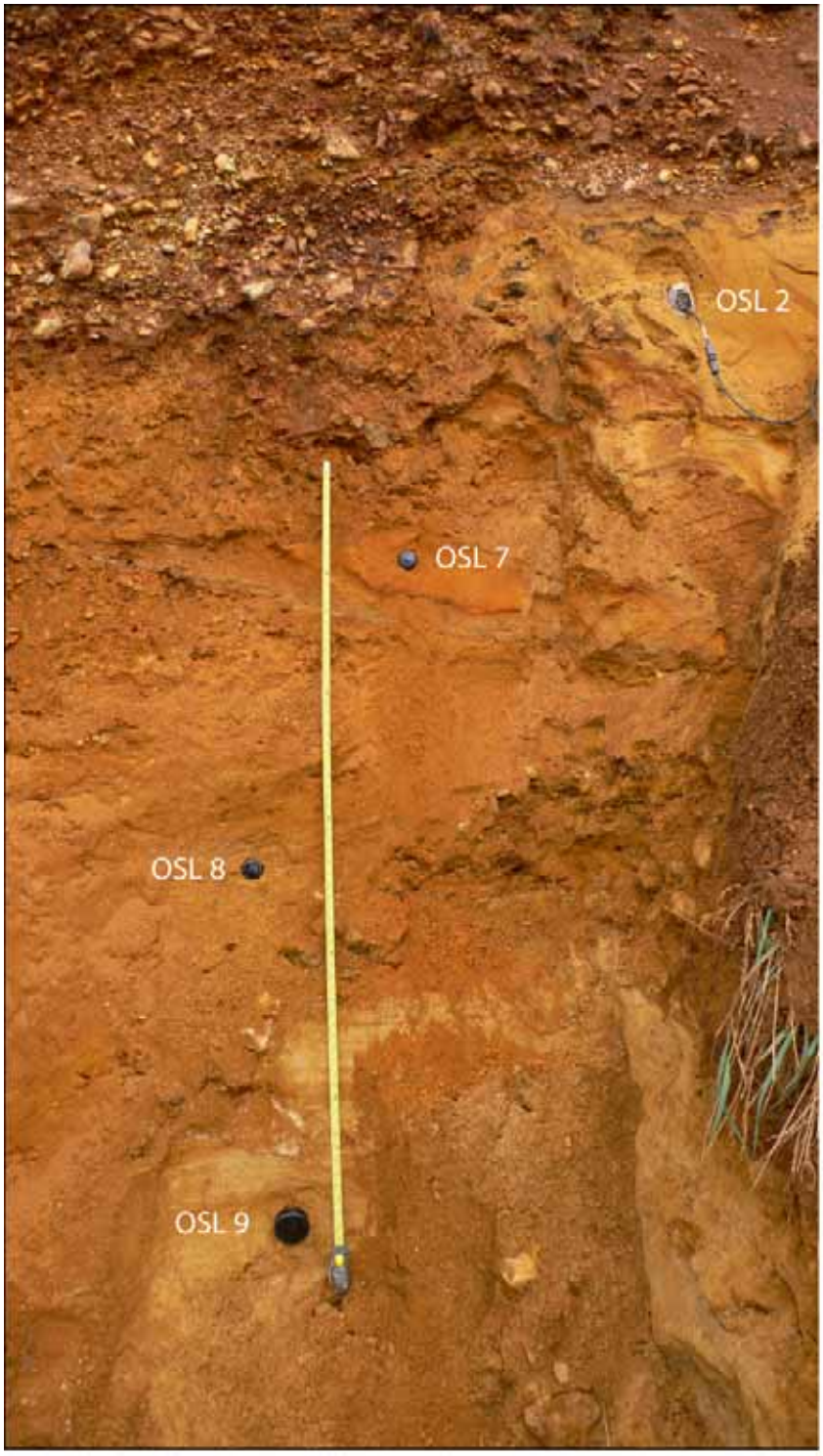


Figure 6: Location of OSL samples 2, 7, 8 and 9 within the lower part of the gravel deposit. Samples OSL 2 and OSL 9 were collected from presumed Palaeogene sands

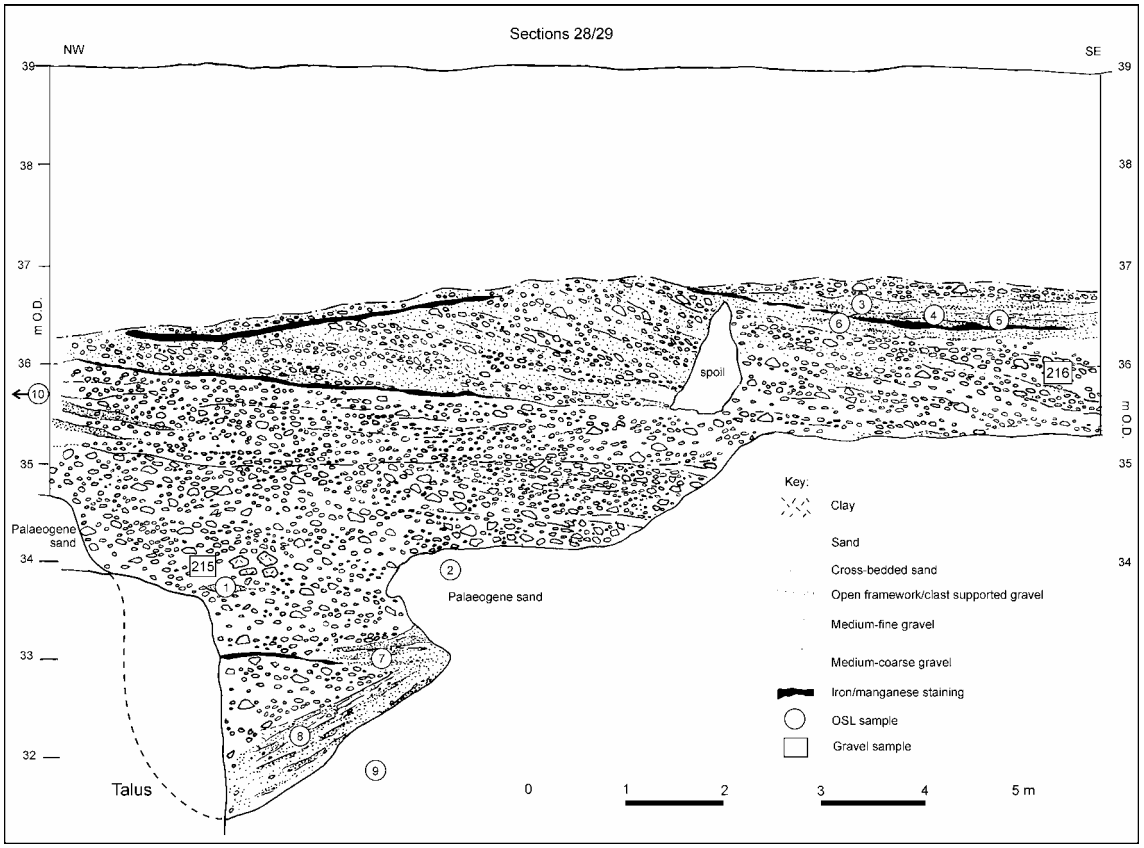


Figure 7: Section drawing featuring the location of all OSL samples within the Mottisfont Gravel deposit. Samples OSL 2 and OSL 9 were collected from underlying bedrock sands (Palaeogene). Sample OSL 10 was taken from a small pocket of sand within the gravel and located circa 3m to the north-west

Table 1: OSL sample details. A total of 13 samples (including three replicates for OSL 1) were collected. The precise location of individual samples is shown in Figures 4 to 7

Field code	Laboratory code	*In situ* NaI γ-ray spectrometry
OSL 1a	X3641	No
OSL 1b	X3642	No
OSL 1c	X3643	No
OSL 2	X3644	Yes
OSL 3	X3645	No
OSL 4	X3646	No
OSL 5	X3647	Yes
OSL 6	X3648	Yes
OSL 7	X3649	No
OSL 8	X3650	Yes
OSL 9	X3651	No
OSL 10	X3652	No

METHODS

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' (De). 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 μGy/a) is measured (or calculated from measured concentrations of radionuclides), the duration of the dosing period can be calculated using the equation:

Duration of dosing period = Palaeodose ÷ 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 by Smith *et al* (1990), and has further proved to provide useful age estimates for a range of sedimentary contexts ranging from aeolian (eg Stokes *et al* 1997), to fluvial (Wallinga 2001), and glacial contexts (Owen *et al* 1997). 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 De 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.

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 588 nm).

After removal of the exposed ends of the sampling containers, the unexposed central portion of the sample was wet-sieved and the 180-255 μm 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 2.68 $g.cm^{-3}$. 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 1cm diameter aluminium discs for luminescence measurement using viscous silicone oil. Because of suspected partial bleaching problems we reduced the aliquot size to 3-5mm in order to improve the detection of poorly bleached grains (through the spread and symmetry of individual palaeodose estimates) and to help reduce the effects on potential age overestimation.

Various tests for sample purity are made. Sub-samples of the prepared material are examined using optical microscopy and the sample is 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 Dunbridge, no prolonged etching in H2SiF6 was required as samples generally were found to have IRSL/OSL ratios below 0.01 (IRSL <1% of OSL).

The measurement sequence adopted for providing palaeodose estimates 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 circa 12 individual aliquots w 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 (see Table 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 (Li) using the OSL response to a common test dose (Si). Plots of Li/Si provide the necessary (sensitivity change corrected) data for interpolation. The procedure is further outlined in Figure 8.

Steps 1-6 are repeated n times in order to produce the data points required for interpolation (the first dose $\beta 1$ 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). PH1 and PH2 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 the explanatory Figure 8 below). 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.

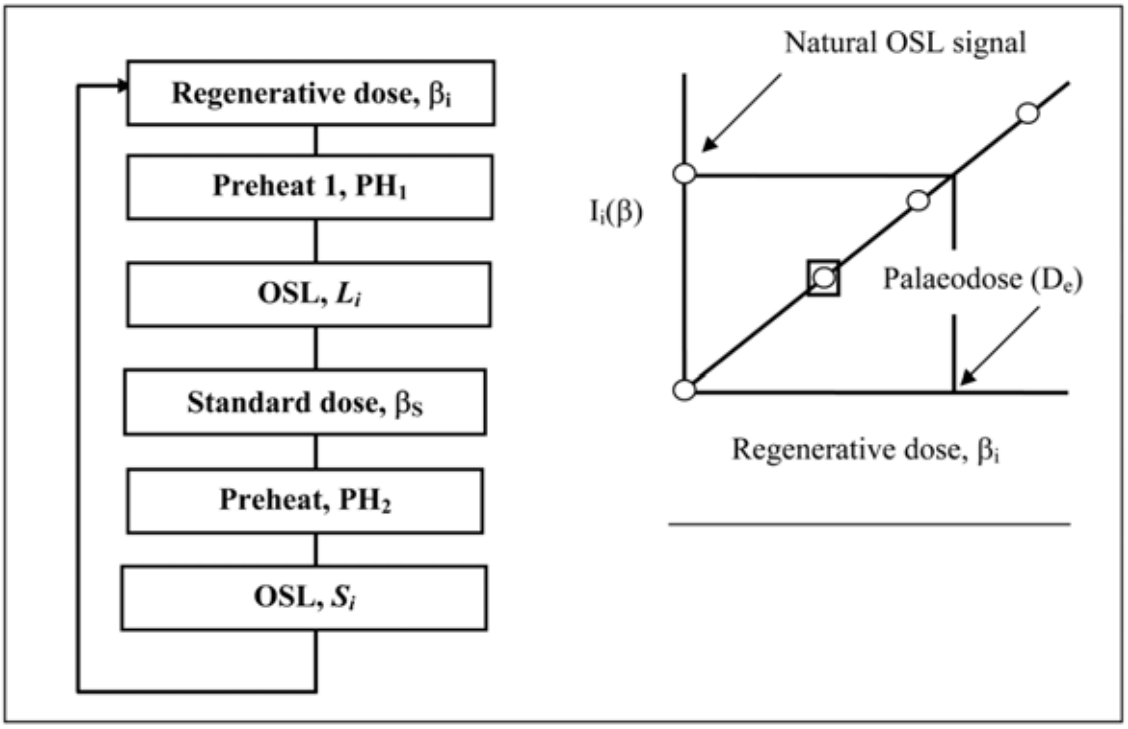


Figure 8: The SAR measurement procedure

Measurement procedures and conditions

Luminescence measurements were made using automated Risø luminescence measurement equipment. 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 bialkali photomultiplier tubes, filtered with Hoya U340 glass filters.

Sample irradiation is provided in all cases by calibrated sealed 90Sr sources at a rate of 1.5-4 Gy/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 (βs). 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 (βi) and the natural dose, a pre-heat (PH1) at 260°C for 10s was used. Following each test dose (βs), a pre-heat (PH2) of 220°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 8-16 multigrain aliquots were 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 110Gy 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.

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. Typical OSL signal plots, growth curves and palaeodose distributions can be found in Appendix 3.

As expected, the yield of quartz mineral grains derived from these fluvial samples was plentiful and aliquots 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 absolutely negligible contributions from potential feldspathic contaminants (<1%; 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 Dunbridge samples. A further test on the thermal

transfer also showed that no significant recuperation of the OSL signal was detected in the majority of aliquots. 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 excellent agreement 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 8-16 separate measurements per sample. The results suggest that according to these criteria, the samples and the adopted measurement procedures appear to be well suited for OSL dating

Sample code	Mean Recycling ratio	Mean IRSL/OSL ratio	Mean Dose recovery ratio	Thermal transfer	Sensitivity	Signal saturation
OSL 1a [X3641]	0.99	0.004	-	Negligible	Very good	No
OSL 1b [X3642]	1.03	0.003	1.009	Negligible	Very good	No
OSL 1c [X3643]	1.00	0.001	1.012	Negligible	Very good	No
OSL 2 [X3644]	1.01	0.003	1.058	Negligible	Very good	Some aliquots
OSL 3 [X3645]	1.01	0.002	0.995	Negligible	Very good	Some aliquots
OSL 4 [X3646]	0.98	0.001	-	Negligible	Very good	No
OSL 5 [X3647]	0.96	0.001	-	Negligible	Very good	No
OSL 6 [X3648]	0.97	0.002	0.999	Negligible	Very good	No
OSL 7 [X3649]	0.97	0.004	0.982	Negligible	Very good	Some aliquots
OSL 8 [X3650]	1.00	0.013	0.978	Negligible	Very good	Some aliquots
OSL 9 [X3651]	1.01	0.006	0.976	Negligible	Very good	Some aliquots
OSL 10 [X3652]	0.99	0.004	1.009	Negligible	Very good	Some aliquots

The radioactivity data (*in-situ* gamma-ray spectroscopy measurements and elemental analysis by ICP-MS indicate that concentrations of radioisotopes (K, Th, and U) are generally low. These findings combined with the coarse textured nature of the sediments are suitable conditions for keeping the environmental dose rate to a minimum, thereby creating favourable conditions for extending the OSL age range beyond 500ka. However, a note of caution needs to be introduced here given that these modern determinations may not necessarily provide an accurate dose rate for the time averaged mean dose experienced by the quartz mineral grains over long time intervals during which potential leaching of radioisotopes (especially potassium) or translocation of fine textured mineral components (ie clays and silts) could have occurred. The lack of *in-situ* radioactivity measurements for all the samples in this series is unfortunate and was caused by time constraints and technical difficulties of operating the spectrometer in rainy weather conditions. However, given the homogenous sandy nature of the sediments and the fact that most samples were derived from relatively thick sedimentary units this is not expected to be a major cause for concern except perhaps for sample OSL 10 which was collected from a thin pocket of sand surrounded by gravel. Unfortunately, it was not

possible to make follow-up gamma-ray spectrometry measurements during an intended return visit to the quarry.

Excluding the two samples (OSL 2 and OSL 9) derived from local bedrock, the results presented in Table 3 above show age estimates for the Mottisfont Gravel ranging from 456±101 to 262±43 ka. There appears to be no stratigraphical consistency, with these oldest and youngest age estimates (samples OSL 10 and OSL 1, respectively) both coming from horizontally bedded sandy gravel midway within the sequence: the former from near the top and the latter from near the bottom of this unit, in a clear age inversion. The majority of the intermediate age estimates are indistinguishable at 1σ. Somewhat surprisingly, the two samples from bedrock sand have yielded finite ages, older than any from the Mottisfont Gravel but still within the Pleistocene (1.15±0.11 and 0.73±0.15 Ma). Whereas these age estimates are considerably younger than the anticipated age of the Reading Formation (~55 Ma), the results from the Mottisfont Gravel are all rather older than anticipated for this formation if the Westaway *et al* (2006) modelled age of MIS 8 is correct. Excluding the bedrock samples, as well as sample OSL 3 (which yielded very scattered palaeodose values and is thus considered to be unreliable) and sample OSL 10 (which yielded such a high numerical age that it may well not have been reset during deposition), the weighted mean age of the remaining eight measurements is 314±24 ka (±2σ), which by coincidence is the same as for the dates by Bates *et al.* (2010) from a higher terrace deposit. This is older than the anticipated age for this terrace deposit, in MIS 8, based on the previous analysis by Westaway *et al* (2006), which used calibration from a range of available evidence, including archaeological and palaeontological assemblages. This leads to the conclusion that a substantial number of samples from the Mottisfont gravel at Dunbridge have been affected by systematic error, which has caused the numerical ages of the samples to exceed the true age of the deposit.

The most coherent and reliable set of dates from Dunbridge were obtained from samples OSL 1A, OSL 1B, and OSL 1C, all collected within a sandy lens in the lower Mottisfont gravel. These samples were characterized by the lowest degree of variability between individual palaeodose determinations. Two of the splits of sample OSL 1 have yielded numerical ages that are noticeably younger than any of the other samples; as a result, sample 1 overall yielded an age range of 311–267 ka at ±1σ, which overlaps the MIS 9–8 boundary at 277 ka. A mean weighted OSL date can also be calculated from the individual palaeodose estimates and the mean dosimetry results (elemental concentrations of K, Th and U) of the three replicate samples (OSL 1A, 1B, and 1C). This provides a more appropriate method than referring to a simple arithmetic mean of the dates from the three splits and this gives an age of 267±30 ka.

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 small aliquots. 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 the concentration of radioactive elements (potassium, thorium and uranium) derived from elemental analysis by ICP-MS/AES using a fusion sample preparation technique. 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 1 and 2

Field code	Lab code.	K (%)	Th (ppm)	U (ppm)	Field water (%)	External –γ-dose rate[§] Gy/ka)	Cosmic dose rate (Gy/ka)	Total dose rate (Gy/ka)	Palaeodose[♦] (Gy)	OSL date (ka)
OSL 1a[‡]	X3641	0.42	2.3	0.5	12±5	0.210 ±0.021	0.082 ± 0.012	0.65±0.04	183.06 ± 11.43	283 ± 26
OSL 1b[‡]	X3642	0.43	2.4	0.5	12±5	0.210 ±0.021	0.082 ± 0.012	0.65 ± 0.04	202.86 ± 30.43	310 ± 51
OSL 1c[‡]	X3643	0.55	2.8	0.6	12±5	0.210 ±0.021	0.082 ± 0.012	0.75 ± 0.05	195.55 ± 29.33	262 ± 43
OSL 2	X3644	0.23	1.5	0.4	6±3	0.183 ±0.018	0.086 ± 0.013	0.36 ± 0.02	260.87 ± 49.88	(733 ± 149)
OSL 3	X3645	0.35	2.3	0.5	10±3	0.280 ±0.028	0.120 ± 0.028	0.72 ± 0.05	284.67 ± 98.92	(396 ± 140)
OSL 4	X3646	0.38	2.3	0.4	10±3	0.280 ±0.028	0.117 ± 0.026	0.72 ± 0.05	247.02 ± 12.65	341 ± 29
OSL 5	X3647	0.41	2.8	0.5	10±3	0.290 ±0.029	0.117 ± 0.026	0.77 ± 0.05	233.41 ± 6.04	302 ± 21
OSL 6	X3648	0.54	4.0	0.8	12±5	0.269 ±0.027	0.115 ± 0.025	0.87 ± 0.05	293.20 ± 33.77	335 ± 45
OSL 7	X3649	0.20	1.4	0.5	6±3	0.236 ±0.024	0.080 ± 0.011	0.54 ± 0.03	229.22 ± 27.60	428 ± 58)
OSL 8	X3650	0.22	1.4	0.6	6±3	0.236 ±0.024	0.074 ± 0.010	0.55 ± 0.09	218.00 ± 32.50	(393 ± 62)
OSL 9	X3651	0.19	1.1	0.3	6±3	0.124 ±0.013	0.069 ± 0.009	0.38± 0.02	433.10 ±32.04	(1152 ± 108)
OSL 10	X3652	0.12	0.8	0.3	6±3	0.280 ±0.028	0.107±0.021	0.52±0.04	235.85±49.33	(456 ± 101)

‡ Samples X3641, X3642 and X3643 are near replicates taken from the same stratigraphic unit

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 γ-ray spectrometer equipped with a 3x3 inch NaI (Tl) scintillator crystal and calibrated against the Oxford calibration blocks (Rhodes and Schwenninger 2007). Due to adverse weather conditions, *in situ* γ-ray spectroscopy measurements could only be obtained for samples X3644, X3647, X3648 and X3650. For sample X3651 which was collected from a thick homogenous sand unit the external dose rate was calculated from the concentrations of radioisotopes determined by fusion ICP-MS. For samples X3641, X3642 and X3643 the external dose rate is based on the mean value of readings made for samples X3644 and X3650 and in the case of samples X3645 and X3646 it was based on readings made from nearby samples X3647 and X3648.

♦ Values highlighted in italics are problematic mainly as a result of suspected partial bleaching and consequently, the calculated age estimates inserted in brackets are considered to be unreliable.

In general, two effects can cause OSL dates to exceed the true age of a deposit: (1) incomplete bleaching of the sample material on deposition (Olley *et al* 1998); (2) leaching by groundwater of radioactive elements from the sediment, which results in the present-day measured radiation dose rate being less than the time-averaged dose rate since deposition and thus the calculation of an overestimated age (Li *et al* 2007; 2008). The opposite effect, of OSL dates underestimating the probable ages of samples, has also been recognized in samples from southern England, and has been tentatively attributed to uptake of radioactive elements (Brown *et al* 2010).

In the case of Dunbridge, it is also possible that the OSL age estimates are affected by a systematic offset in the water content. Sampling was undertaken during a period of adverse weather and the sediment from the exposed sloping section may have experienced an excess uptake of water during the days preceding the sampling. The reported values presented in Table 3 may thus represent artificially inflated moisture contents. Due to the attenuating effect of water, this would cause an underestimation of the received dose and thus lead to an age overestimate. For samples OSL 1A, OSL 1B, and OSL 1C a reduction in the mean water content from 12 to 10% would have reduced the dates by 5 ka. It is intriguing to note that, despite the sandy texture of all the samples, some were found to have substantially lower water contents, down to 4–6% (see Table 3). It is worth pointing out, however, that the errors attached to the modern-day moisture contents are sufficiently large (±5%) to accommodate for such variations and therefore such an effect should not cause major concern.

The most plausible interpretation of the Mottisfont Gravel dates, however, is that the majority of samples generally suffer from incomplete bleaching of the mineral grains during Pleistocene fluvial deposition. The superposition of the Mottisfont Gravel above Palaeogene sandy bedrock means that much of the sand in this Middle Pleistocene fluvial deposit has probably been reworked from the underlying sediment. The proximity of the source material, the likelihood of the sediment not having been transported over a long distance as well as fast conditions of water flow are factors which are likely to have reduced the full resetting of the luminescence signal. Residual trapped charge remaining at the time of deposition will result in an overestimation of the true age of a deposit and may also be picked up by a high degree of inter aliquot scatter as is the case for samples OSL 3, 6, 7, 8 and 10. It has already been suggested that sample OSL 10 may not have been completely reset (ie not fully bleached) during emplacement in the fluvial terrace deposit, on account of its extreme numerical age. Furthermore, the elemental concentrations of K, Th, and U for this sample are very similar to those recorded for the sandy bedrock (OSL 2 and OSL 9). This reinforces the view that the bulk of the sediment contains grains directly derived from the underlying Reading Formation. Samples OSL 7 and OSL 8, which came from the basal part of the Mottisfont Gravel, have also yielded particularly high numerical ages with large errors on the De distributions, suggesting that they too may include significant proportions of incompletely bleached sand grains. Both samples were located adjacent to an area in which the bedrock is considered to be

affected by pronounced scouring (see Fig 6) and therefore it is not surprising that the dating should turn out to be problematic. By analogy, the remaining samples, especially those characterized by a high degree of scatter in the palaeodose values, may likewise contain smaller, but variable, proportions of grains having retained a residual 'geological' signal from the presumed Tertiary parent material, the lowest proportion being evidently in sample OSL 1A, OSL1B, and OSL 1C, which have yielded the lowest numerical age (Table 3) and the closest to the expected age of the deposit. Westaway *et al* (2006) noted that some of the OSL dates for terrace deposits of the main Solent River, reported by Briant *et al* (2006), were much older than the expected ages of the fluvial deposits, likewise suggesting poor resetting of the OSL signal at deposition.

Further indications of potential systematic errors in the full set of OSL dates now available for the River Test, from Bates *et al* (2010) and from the present study, are also evident. For example, as already noted, the weighted mean of the three dates from the Ganger Wood–Mallards Moor terrace deposit (expected age: MIS 10) is indistinguishable from the weighted mean of the new OSL dates from the Mottisfont Gravel (expected age: MIS 8), whereas the terrace stratigraphy precludes the possibility that these distinct fluvial deposits are of the same age. It is indeed evident that the earlier phase of OSL dating has overestimated the age of the Hamble terrace deposits as well as the Mottisfont Gravel, but has underestimated the ages of the Bitterne and Ganger Wood–Mallards Moor terrace deposits.

These observations indicate that caution is required regarding the use and interpretation of OSL dating results from fluvial deposits, especially in a system such as the Solent, where more than one fluvial terrace has formed during some 100 ka climate cycles. It is evident from this, as well as previous studies, that standard OSL dating techniques can result in numerical ages that are neither precise (ie reproducible) nor accurate (ie corresponding to the true ages of the sediments). Some of the dates are nonetheless of value in providing a general indication of the true ages; for example, the weighted mean age of the samples from the Mottisfont gravel is within one climate cycle of the expected age of the deposit. However, uncritical use of the extant OSL dataset or over interpretation of optical age estimates and reliance on single samples from terrace deposits in this study region, without due consideration to specific sedimentological or geomorphic processes as well as age-constraints provided by archaeology, biostratigraphy or from uplift modelling, could result in unnecessary confusion.

In exploring the suitability of OSL dating for establishing chronologies for old river systems such as the Solent, the limits of standard OSL dating techniques have to be recognized. Validation of the use of optical dating of such sediments may require more advanced studies focusing in more detail on key samples (including samples from known age deposits) and the measurement of larger numbers of aliquots per sample. More sophisticated statistical analysis and single grain palaeodose determinations should also be considered.

CONCLUSIONS

Evidence from section monitoring during 17 years of gravel extraction at Kimbridge Farm quarry has provided significant insights into the context of a large assemblage of Palaeolithic artefacts from Hampshire. Coupled with the results of digital terrain modeling (Harding et al submitted), this evidence has demonstrated that two distinct Pleistocene river terrace deposits were exploited by the quarry. The uppermost terrace can be equated with the Belbin Stage of White (1912), now termed the Belbin Gravel Formation. These sediments have yielded the majority of Palaeolithic finds from both the area of modern quarrying and from the neighbouring Dunbridge gravel pit SSSI. This terrace can be equated with Terrace 4 of the Westaway *et al* (2006) and Edwards and Freshney (1987) schemes and with Terrace 5 of Bates and Briant (2009). Although, the terrace numbers differ, in both previous schemes the Belbin Formation has been attributed to MIS 10. The identification of artefacts demonstrating features of 'proto-Levallois' technology from the main body of this gravel has led to reconsideration of its age, which is now considered to be MIS 9b. Westaway *et al* (2006) suggested that fully developed Levallois technology first appeared in the Solent in MIS 9b, based on their original modelling, although Ashton and Hosfield (2010) raised doubts about this conclusion, expressing concern over the low numbers of finds, the lack of scrutiny of the published identifications or actual contexts and the paucity of dating constraints. The Dunbridge project has addressed these concerns and although, most of the OSL samples were shown to be affected by poor bleaching, the study has provided more rigorous evidence in support of the occurrence of 'proto- Levallois' in quantity within this gravel formation.

Despite the reservations about the application of OSL dating, expressed above, the improved age constraints provided by the technique (cf. Bates *et al* 2010) have required modification of the terrace chronology for the Test and the Solent River downstream of its confluence with the Test; the remainder of the Solent system is, however, unaffected. The incorporation of this improved dating and the newly established constraint, from this present project, of "proto-Levallois" technology from within the body of the Belbin Gravel into revised uplift modelling (see above), has brought the terrace age model for the Test into line with that for other parts of the Solent river system, notably with regard to the age of the highest and oldest terrace (MIS 22). The lowermost terrace at Dunbridge can be correlated with White's (1912) Mottisfont Stage, based on its disposition, which implies equivalence with Terrace T3 of the Westaway *et al* (2006) and Edwards and Freshney (1987) schemes and Terrace T4 of the Bates and Briant (2009) scheme. The dating for this lower terrace is again largely in agreement between the two schemes, both implying an age in MIS 8. Finds of Levallois flakes from the Kimbridge Pits (Roe 1968a), which are considered to have exploited this lower terrace, are potentially significant. Their origin and context are unclear, although Dale (1912) reported that flake implements, in a relatively fresh condition, were found with heavily rolled material towards the base of the Kimbridge pit. The MIS 8 age is confirmed in the revised uplift modelling undertaken as part of this ALSF funded project (Harding *et al* submitted) and is further supported by some of the new OSL age estimates presented here.

REFERENCES

Adamiec, G, and Aitken, M J, 1998 Dose-rate conversion factors: update, *Ancient TL*, **16**, 37–50

Aitken, M J, 1998 *Introduction to optical dating*, Oxford University Press, Oxford

Ashton, N, and Hosfield, R, 2010 Mapping the human record in the British early Palaeolithic: evidence from the Solent River system, *Journal of Quaternary Science*, **25**, 737–53

Banerjee, D, Murray, A S, Bøtter-Jensen, L, and Lang, A, 2001 Equivalent dose estimation using a single aliquot of polymineral fine grains, *Radiation Measurements*, **33**, 73–94

Bates, M R, and Briant, R M, 2009 Quaternary sediments of the Sussex/Hampshire Coastal Corridor: a brief overview, in *The Quaternary of the Solent Basin and West Sussex raised beaches: field guide* (eds R M Briant, M R Bates, R T Hosfield, and F F Wenban-Smith), Quaternary Research Association, 21–41, London

Bates, M R, Bates, C R, Bates, S. Jones, S, Schwenninger, J-L, Walker, M J C, and Whittaker, J E, 2009a Cold stage deposits of the West Sussex Coastal Plain: the evidence from Warblington, Hampshire, in *The Quaternary of the Solent Basin and West Sussex raised beaches: field guide* (eds R M Briant, M R Bates, R T Hosfield, and F F Wenban-Smith), Quaternary Research Association, 60–72, London

Bates, M R, Bates, C R, Gibbard, P L, Keen, D H, Parfitt, S A, Peglar, S M, Schwenninger, J-L, Wenban-Smith F F, and Whittaker J E, 2009b West Street, Selsey, in *The Quaternary of the Solent Basin and West Sussex raised beaches: field guide* (eds R M Briant, M R Bates, R T Hosfield, and F F Wenban-Smith), Quaternary Research Association, 73–95, London

Bates, M R, Briant, R M, Rhodes, E J, Schwenninger, J-L, and Whittaker, J E, 2010 A new chronological framework for Middle and Upper Pleistocene landscape evolution in the Sussex/Hampshire coastal corridor, UK, *Proceedings of the Geologists' Association*, **121**, 369–392

Bøtter-Jensen, L, 1988 The automated Riso TL dating reader system, *Nuclear Tracks and Radiation Measurements*, **14**, 177–80

Bøtter-Jensen, L, 1997 Luminescence techniques: instrumentation and methods, *Radiation Measurements*, **27**, 749–768

Bøtter-Jensen, L, Bulur, E, Duller, G A T, and Murray, A S, 2000. Advances in luminescence instrument systems, *Radiation Measurements*, **32**, 523–28

Briant, R M, and Schwenninger, J-L, 2009 Solent river gravels at Badminston Farm, Hampshire (SU463 019), in *The Quaternary of the Solent Basin and West Sussex raised beaches: field guide* (eds R M Briant, M R Bates, R T Hosfield, and F F Wenban-Smith), Quaternary Research Association, 189–97, London

Briant, R M, Bates, M R, Schwenninger, J-L, and Wenban-Smith, F, 2006 An optically stimulated luminescence dated Middle to Late Pleistocene fluvial sequence from the western Solent Basin, southern England, *Journal of Quaternary Science*, **21**, 507–23

Briant, R M, Wenban-Smith F F, and Schwenninger J-L, 2009a Solent River gravels at Barton on Sea, Hampshire (SZ 230 930), in *The Quaternary of the Solent Basin and West Sussex raised beaches: field guide* (eds R M Briant, M R Bates, R T Hosfield, and F F Wenban-Smith), Quaternary Research Association, 161–70, London

Briant, R M, Bates, M, Boreham, S, Cameron, N G, Coope, G R, Field, M H, Keen, D H, Simmons, R M J, Schwenninger, J-L, Wenban-Smith, F F, and Whittaker, J H, 2009b Gravels and interglacial sediments at Stone Point Site of Special Scientific Interest, Lepe Country Park, Hampshire, in *The Quaternary of the Solent Basin and West Sussex raised beaches: field guide* (eds R M Briant, M R Bates, R T Hosfield, and F F Wenban-Smith), Quaternary Research Association, 171–88, London

Bridgland, D R, and Harding, P, 1993 Preliminary observations at the Kimbridge Farm quarry, Dunbridge, Hampshire: early results of a watching brief, *Quaternary Newsletter*, **69**, 1–9

Brown, A G, Basell, L S, Toms, P S, Bennett, J A, Hosfield, R T, and Scrivener, R C, 2010 Later Pleistocene evolution of the Exe valley: a chronostratigraphic model of terrace formation and its implications for Palaeolithic archaeology, *Quaternary Science Reviews*, **29**, 897–912

Dale, W, 1912 On the implement-bearing gravel beds of the lower valley of the Test, *Proceedings of the Society of Antiquaries*, *London Series 2*, **24**, 108–16

Dale, W, 1918 Report as local secretary for Hampshire, *Proceedings of the Society of Antiquaries, London Series 2,* **30**, 20–32

Edwards, R A, and Freshney, E.C, 1987 *Geology of the Country around Southampton*. Memoir for 1:50,000 Geological Map Sheet 315 (England and Wales), HMSO, London

Harding, P A 1998 An interim report of an archaeological watching brief on Palaeolithic deposits at Dunbridge, Hants, in *Stone Age Archaeology: Essays in Honour of John Wymer* (eds N M Ahton, F Healy, and P B Pettitt) Oxbow, 72–76, Oxford

Harding, P , Bridgland, D R, Allen, P, Bradley, P, Grant, M J, Peat, D, Schwenninger, J-L, Scott, R, Westaway, R, and White, T, submitted Chronology of the Lower and Middle

Palaeolithic in NW Europe: developer-funded investigations at Dunbridge, Hampshire, southern England, *Proceedings of the Geologists Association*

Huntley, D J, Godfrey-Smith, D I, and Thewalt, M L W, 1985 Optical dating of sediments, *Nature*, **313**, 105–7

Li, B, Li, S-H, and Wintle, A G, 2007 Overcoming environmental dose rate changes in luminescence dating of waterlain deposits, *Geochronometria*, **30**, 33–40

Li, B, Li, S-H, Wintle, A G, and Zhao, H, 2008 Isochron dating of sediments using luminescence of K-feldspar grains. *Journal of Geophysical Research*, **113**, F02026, Doi: 10.1029/2007JF000900

Mejdahl, V, 1979 Thermoluminescence dating: beta dose attenuation in quartz grains, *Archaeometry* **21**, 61–73

Murray, A S, and Wintle, A G, 2000 Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol, *Radiation Measurements*, **32**, 57–73

Olley, J, Caitchoeon, G, and Murray, A S, 1998 The distribution of apparent dose as determined by optically stimulated luminescence in small aliquots of fluvial quartz: Implications for dating young sediments, *Quaternary Science Reviews*, **17**, 1033–40

Owen, L A, Mitchell, W A, Bailey, R M, Coxon, P, and Rhodes, E J, 1997 Style and timing of glaciation in the Lahul Himalaya, northern India: a frame work for reconstructing Late Quaternary palaeoclimatic change in the western Himalayas, *Journal of Quaternary Science*, **12**, 83–109

Prescott, J R, and Hutton, J T, 1994 Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long term time variations, *Radiation Measurements*, **23**, 497–500

Rhodes, E J, 1988 Methodological considerations in the optical dating of quartz, *Quaternary Science Reviews*, **7**, 395–400

Rhodes, E J, and Schwenninger, J-L, 2007 Dose rates and radioisotope concentrations in the concrete calibration blocks at Oxford, *Ancient TL*, **25**, 5–8

Roe, D A, 1968a *A Gazetteer of the British Lower and Middle Palaeolithic Sites*, Council for British Archaeology Research Report **8**, Council for British Archaeology, London

Roe, D A, 1968b British Lower and Middle Palaeolithic handaxe groups, *Proceedings of the Prehistoric Society*, **34**, 1–82

Schwenninger, J-L, Rhodes, E J, Bates, M R, Briant, R M. and Wenban-Smith, F, 2006 *Optically stimulated luminescence (OSL) dating of Quaternary deposits from the Sussex/Hampshire coastal corridor*., EH Res Dep Ser, **20/2006**

Smith, B W, Aitken, M J, Rhodes, E J, Robinson, P D, and Geldard, D M, 1986 Optical dating: methodological aspects, *Radiation Protection Dosimetry*, **17**, 229–33

Smith, B W, Rhodes, E J, Stokes, S, Spooner, N A, and Aitken, M J, 1990 Optical dating of sediments: initial results from Oxford, *Archaeometry*, **32**, 19–31

Stokes, S, Thomas, D S G, and Washington R W, 1997 Multiple episodes of aridity in southern Africa since the last interglacial period, *Nature*, **388**, 154–9

Wallinga, J. 2001 *The Rhine-Meuse system in a new light: optically stimulated luminescence dating and its application to fluvial deposits*, Netherlands Geographical Studies **290**, The Royal Dutch Geographical Society

Westaway, R, Bridgland, D, and White, M, 2006 The Quaternary uplift history of central southern England: evidence from the terraces of the Solent River system and nearby raised beaches, Quaternary *Science Reviews*, **25**, 2212–50

White, H JO, 1912 *The Geology of the Country around Winchester and Stockbridge*, Memoir of the Geological Survey, London

Wintle, A G, and Murray, A S, 2006 A review of quartz optically stimulated luminescence characteristics and their relevance in single-aliquot regeneration dating protocols, *Radiation Measurements*, **41**, 369–391

Zimmermann, D W, 1971 Thermoluminescent dating using fine grains from pottery, *Archaeometry,* **13**, 29–52

APPENDIX 1 DETAILS OF RADIOACTIVITY DATA AND AGE CALCULATIONS

Sample Field code	DUN09-01A	DUN09-01B	DUN09-01C
Laboratory code	X3641	X3642	X3643
Palaeodose (Gy)	183.06	202.86	195.55
Uncertainty	12.00	30.70	29.59
Measured uncertainty	11.43	30.43	29.33
Source calibration error (2%)	3.66	4.06	3.91
Grain size			
Min. grain size (µm)	180	180	180
Max grain size (µm)	255	255	255
External gamma-dose (Gy/ka)	0.210	0.210	0.210
Error (10%)	0.021	0.021	0.021
Measured concentrations			
Standard fractional error	0.050	0.050	0.050
% K	0.420	0.430	0.550
Error (%K)	0.021	0.022	0.028
Th (ppm)	2.300	2.400	2.800
Error (ppm)	0.115	0.120	0.140
U (ppm)	0.500	0.500	0.600
Error (ppm)	0.025	0.025	0.030
Cosmic dose calculations			
Depth (m)	8.000	8.000	8.000
Error (m)	1.000	1.000	1.000
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	51	51	51
Longitude (deg.), east positive	2	2	2
Altitude (m above sea-level))	45	45	45
Cosmic dose rate (µGy/ka)	0.082	0.082	0.082
Error	0.012	0.012	0.012
Moisture content			
Measured water in tubes (% of wet sediment)	6.62	8.07	11.11
Measured water in water content bags (% wet sediment)	9.970	-	-
Moisture (water / wet sediment)	0.12	0.12	0.12
Error	0.05	0.05	0.05
Total dose rate, Gy/ka	0.65	0.65	0.75
Error	0.04	0.04	0.05
AGE (ka)	283.29	310.09	262.08
Error	25.55	50.72	43.05

Sample Field code	DUN09-01A&B&C combined	DUN09-02
Laboratory code	X3641, X3642 & X3643 combined	X3644
Palaeodose (Gy)	181.17	260.87
Uncertainty	17.12	50.15
Measured uncertainty	16.73	49.88
Source calibration error (2%)	3.62	5.22
Grain size		
Min. grain size (µm)	180	180
Max grain size (µm)	255	255
External gamma-dose (Gy/ka)	0.210	0.183
Error (10%)	0.021	0.018
Measured concentrations		
Standard fractional error	0.050	0.050
% K	0.460	0.230
Error (%K)	0.023	0.012
Th (ppm)	2.500	1.500
Error (ppm)	0.125	0.075
U (ppm)	0.530	0.400
Error (ppm)	0.027	0.020
Cosmic dose calculations		
Depth (m)	8.000	7.500
Error (m)	1.000	1.000
Average overburden density (g.cm^3)	1.900	1.900
Error (g.cm^3)	0.100	0.100
Latitude (deg.), north positive	51	51
Longitude (deg.), east positive	2	2
Altitude (m above sea-level))	45	45
Cosmic dose rate (µGy/ka)	0.082	0.086
Error	0.012	0.013
Moisture content		
Measured water in tubes (% of wet sediment)	8.60	2.63
Measured water in water content bags (% wet sediment)	9.97	3.32
Moisture (water / wet sediment)	0.12	0.60
Error	0.05	0.03
Total dose rate, Gy/ka	0.68	0.36
Error	0.04	0.02
AGE (ka)	267.32	733.35
Error	30.28	149.01

Sample Field code	DUN09-03	DUN09-04	DUN09-05
Laboratory code	X3645	X3646	X3647
Palaeodose (Gy)	284.67	247.02	233.41
Uncertainty	99.08	13.58	7.63
Measured uncertainty	98.92	12.65	6.04
Source calibration error (2%)	5.69	4.94	4.67
Grain size			
Min. grain size (µm)	180	180	180
Max grain size (µm)	255	255	255
External gamma-dose (Gy/ka)	0.280	0.280	0.290
Error (10%)	0.028	0.028	0.029
Measured concentrations			
Standard fractional error	0.050	0.050	0.050
% K	0.350	0.380	0.410
Error (%K)	0.018	0.019	0.021
Th (ppm)	2.300	2.300	2.800
Error (ppm)	0.115	0.115	0.140
U (ppm)	0.500	0.400	0.500
Error (ppm)	0.025	0.020	0.025
Cosmic dose calculations			
Depth (m)	4.500	4.700	4.700
Error (m)	1.000	1.000	1.000
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	51	51	51
Longitude (deg.), east positive	2	2	2
Altitude (m above sea-level))	45	45	45
Cosmic dose rate (µGy/ka)	0.120	0.117	0.117
Error	0.028	0.026	0.026
Moisture content			
Measured water in tubes (% of wet sediment)	9.32	8.49	8.55
Measured water in water content bags (% wet sediment)	8.92	6.05	8.34
Moisture (water / wet sediment)	0.10	0.10	0.10
Error	0.03	0.03	0.03
Total dose rate, Gy/ka	0.72	0.72	0.77
Error	0.05	0.05	0.05
AGE (ka)	395.61	340.72	301.60
Error	140.02	28.59	21.08

Sample Field code	DUN09-06	DUN09-07	DUN09-08
Laboratory code	X3648	X3649	X3650
Palaeodose (Gy)	293.20	229.22	218.00
Uncertainty	34.27	27.98	32.34
Measured uncertainty	33.77	27.60	32.05
Source calibration error (2%)	5.86	4.58	4.36
Grain size			
Min. grain size (µm)	180	180	180
Max grain size (µm)	255	255	255
External gamma-dose (Gy/ka)	0.269	0.236	0.236
Error (10%)	0.027	0.024	0.024
Measured concentrations			
Standard fractional error	0.050	0.050	0.050
% K	0.540	0.200	0.220
Error (%K)	0.027	0.010	0.011
Th (ppm)	4.000	1.400	1.400
Error (ppm)	0.200	0.070	0.070
U (ppm)	0.800	0.500	0.600
Error (ppm)	0.040	0.025	0.030
Cosmic dose calculations			
Depth (m)	4.900	8.200	9.000
Error (m)	1.000	1.000	1.000
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	51	51	51
Longitude (deg.), east positive	2	2	2
Altitude (m above sea-level)	45	45	45
Cosmic dose rate (µGy/ka)	0.115	0.080	0.074
Error	0.025	0.011	0.010
Moisture content			
Measured water in tubes (% of wet sediment)	11.01	6.24	5.35
Measured water in water content bags (% wet sediment)	11.86	not available	3.97
Moisture (water / wet sediment)	0.12	0.06	0.06
Error	0.05	0.03	0.03
Total dose rate, Gy/ka	0.87	0.54	0.55
Error	0.06	0.03	0.03
AGE (ka)	335.23	428.25	393.32
Error	44.73	57.75	62.37

Sample Field code	DUN09-09	DUN09-10
Laboratory code	X3651	X3652
Palaeodose (Gy)	433.10	235.85
Uncertainty	33.19	49.55
Measured uncertainty	32.04	49.33
Source calibration error (2%)	8.66	4.72
Grain size		
Min. grain size (µm)	180	180
Max grain size (µm)	255	255
External gamma-dose (Gy/ka)	0.236	0.280
Error (10%)	0.024	0.028
Measured concentrations		
Standard fractional error	0.050	0.050
% K	0.190	0.120
Error (%K)	0.010	0.006
Th (ppm)	1.100	0.800
Error (ppm)	0.055	0.040
U (ppm)	0.300	0.300
Error (ppm)	0.015	0.015
Cosmic dose calculations		
Depth (m)	9.750	5.500
Error (m)	1.000	1.000
Average overburden density (g.cm^3)	1.900	1.900
Error (g.cm^3)	0.100	0.100
Latitude (deg.), north positive	51	51
Longitude (deg.), east positive	2	2
Altitude (m above sea-level))	45	45
Cosmic dose rate (µGy/ka)	0.069	0.107
Error	0.009	0.021
Moisture content		
Measured water in tubes (% of wet sediment)	3.92	5.69
Measured water in water content bags (% wet sediment)	4.52	3.83
Moisture (water / wet sediment)	0.06	0.06
Error	0.03	0.03
Total dose rate, Gy/ka	0.38	0.52
Error	0.02	0.04
AGE (ka)	1151.96	455.70
Error	108.48	101.01

APPENDIX 2 FULL ELEMENTAL ANALYSIS OF SAMPLES BY FUSION ICP-MS

Analyte Symbol	SiO2	Al2O3	Fe2O3(T)	MnO	MgO	CaO	Na2O	K2O	TiO2	P2O5	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 1A X3641	92.12	2.39	3.04	0.023	0.17	0.13	0.07	0.5	0.146	0.08	1.89	100.6
OSL 1B X3642	91.63	2.51	3.12	0.026	0.17	0.13	0.07	0.52	0.153	0.07	2.13	100.5
OSL 1C X3643	89.89	3.33	3.54	0.038	0.23	0.17	0.08	0.66	0.209	0.07	2.74	101
OSL 2 X3644	95.9	1.38	1.83	0.014	0.04	0.04	0.06	0.28	0.137	0.04	0.63	100.3
OSL 3 X3645	92.61	2.63	2.27	0.016	0.16	0.13	0.08	0.42	0.142	0.04	2.14	100.6
OSL 4 X3646	93.24	2.53	1.69	0.065	0.15	0.12	0.07	0.46	0.159	0.02	1.62	100.1
OSL 5 X3647	91.71	3.07	2.05	0.399	0.18	0.14	0.07	0.49	0.17	0.03	2.16	100.5
OSL 6 X3648	87.83	4.35	3.94	0.025	0.25	0.2	0.09	0.65	0.268	0.06	3.1	100.7
OSL 7 X3649	92.24	1.34	5.44	0.013	0.05	0.05	0.07	0.24	0.108	0.14	1.27	100.9
OSL 8 X3650	94.42	1.36	3.04	0.009	0.05	0.05	0.07	0.27	0.119	0.05	1.02	100.5
OSL 9 X3651	97.5	0.95	1.52	0.008	0.03	0.03	0.06	0.23	0.069	0.01	0.36	100.8
OSL 10 X3652	92.17	0.82	5.74	0.021	0.05	0.04	0.05	0.14	0.042	0.11	1.17	100.4

Analyte Symbol	Sc	Be	V	Ba	Sr	Y	Zr	Cr	Co	Ni	Cu	Zn
Unit Symbol	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Detection Limit	1	1	5	3	2	2	4	20	1	20	10	30
OSL 1A X3641	3	< 1	29	77	21	33	65	30	9	270	< 10	30
OSL 1B X3642	3	< 1	32	76	14	40	68	30	9	50	< 10	30
OSL 1C X3643	3	< 1	37	96	17	52	87	30	13	40	< 10	30
OSL 2 X3644	< 1	< 1	13	64	11	16	97	20	4	30	< 10	< 30
OSL 3 X3645	3	< 1	26	81	14	16	67	30	3	20	< 10	< 30
OSL 4 X3646	3	< 1	23	82	15	15	83	30	4	20	10	< 30
OSL 5 X3647	4	< 1	30	117	16	20	81	30	11	20	10	< 30
OSL 6 X3648	6	< 1	44	103	21	29	129	40	7	20	< 10	< 30
OSL 7 X3649	1	< 1	18	53	9	11	72	20	4	< 20	< 10	< 30
OSL 8 X3650	2	< 1	16	61	12	7	68	30	1	< 20	10	< 30
OSL 9 X3651	< 1	< 1	8	56	8	4	37	< 20	< 1	< 20	< 10	< 30
OSL 10 X3652	< 1	< 1	7	42	6	6	24	< 20	4	< 20	< 10	< 30

Analyte Symbol	Sc	Be	V	Ba	Sr	Y	Zr	Cr	Co	Ni	Cu	Zn
Unit Symbol	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Detection Limit	1	1	5	3	2	2	4	20	1	20	10	30
OSL 1A X3641	3	< 1	29	77	21	33	65	30	9	270	< 10	30
OSL 1B X3642	3	< 1	32	76	14	40	68	30	9	50	< 10	30
OSL 1C X3643	3	< 1	37	96	17	52	87	30	13	40	< 10	30
OSL 2 X3644	< 1	< 1	13	64	11	16	97	20	4	30	< 10	< 30
OSL 3 X3645	3	< 1	26	81	14	16	67	30	3	20	< 10	< 30
OSL 4 X3646	3	< 1	23	82	15	15	83	30	4	20	10	< 30
OSL 5 X3647	4	< 1	30	117	16	20	81	30	11	20	10	< 30
OSL 6 X3648	6	< 1	44	103	21	29	129	40	7	20	< 10	< 30
OSL 7 X3649	1	< 1	18	53	9	11	72	20	4	< 20	< 10	< 30
OSL 8 X3650	2	< 1	16	61	12	7	68	30	1	< 20	10	< 30
OSL 9 X3651	< 1	< 1	8	56	8	4	37	< 20	< 1	< 20	< 10	< 30
OSL 10 X3652	< 1	< 1	7	42	6	6	24	< 20	4	< 20	< 10	< 30

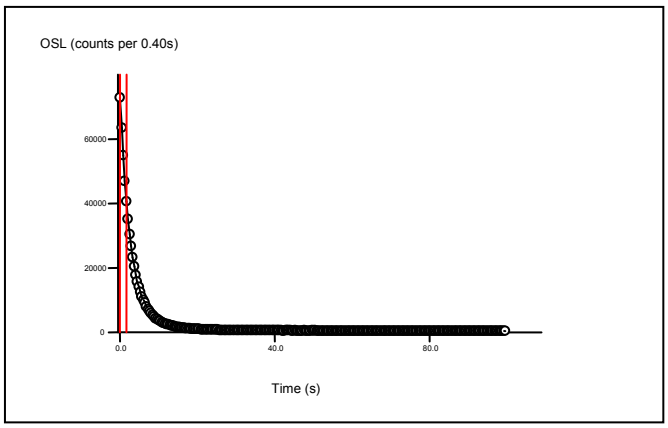
Analyte Symbol	Ga	Ge	As	Rb	Nb	Mo	Ag	In	Sn	Sb	Cs	La
Unit Symbol	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Detection Limit	1	1	5	2	1	2	0.5	0.2	1	0.5	0.5	0.1
OSL 1A X3641	3	2	< 5	23	3	< 2	< 0.5	< 0.2	1	< 0.5	1.3	26.7
OSL 1B X3642	3	2	< 5	24	3	< 2	< 0.5	< 0.2	< 1	< 0.5	1.3	24.3
OSL 1C X3643	4	2	< 5	30	4	< 2	< 0.5	< 0.2	1	< 0.5	1.7	41.6
OSL 2 X3644	2	2	< 5	12	2	< 2	0.5	< 0.2	< 1	< 0.5	0.6	16
OSL 3 X3645	4	2	< 5	23	2	< 2	< 0.5	< 0.2	< 1	< 0.5	1.3	19.4
OSL 4 X3646	3	2	< 5	23	3	< 2	< 0.5	< 0.2	1	< 0.5	1.2	20.9
OSL 5 X3647	4	2	< 5	26	3	< 2	< 0.5	< 0.2	1	< 0.5	1.4	22.8
OSL 6 X3648	5	2	< 5	35	5	< 2	0.7	< 0.2	2	< 0.5	2.2	32.3
OSL 7 X3649	2	2	< 5	11	2	< 2	< 0.5	< 0.2	2	< 0.5	< 0.5	12.2
OSL 8 X3650	2	2	8	12	2	< 2	< 0.5	< 0.2	2	< 0.5	0.6	8.9
OSL 9 X3651	1	2	< 5	11	1	< 2	< 0.5	< 0.2	1	< 0.5	< 0.5	6.9
OSL 10 X3652	1	2	< 5	8	1	< 2	< 0.5	< 0.2	< 1	< 0.5	< 0.5	6.8

Analyte Symbol		Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
Unit Symbol		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Detection Limit		0.1	0.05	0.1	0.1	0.05	0.1	0.1	0.1	0.1	0.1	0.05	0.1
OSL 1A	X3641	25.4	5.31	22.2	4.1	0.96	5.7	0.7	3.6	0.8	2.2	0.29	1.6
OSL 1B	X3642	25.1	4.9	20.8	4.1	0.96	5.6	0.7	3.7	0.8	2.3	0.31	1.8
OSL 1C	X3643	31.4	8.86	37.1	6.7	1.54	9.4	1.1	6.1	1.2	3.5	0.46	2.5
OSL 2	X3644	21.5	3.92	16.3	3	0.62	3.2	0.4	2	0.4	1.2	0.17	1
OSL 3	X3645	39.6	4.98	19.9	4.1	0.86	3.8	0.6	3.1	0.6	1.7	0.24	1.5
OSL 4	X3646	29.2	5.19	20.4	4.1	0.82	3.5	0.5	2.7	0.5	1.5	0.21	1.4
OSL 5	X3647	34.8	6.14	25.2	5.2	1.09	4.8	0.7	3.8	0.7	2.1	0.28	1.8
OSL 6	X3648	49.4	8.3	33.4	7	1.5	6.7	1	5.6	1.1	3	0.43	2.7
OSL 7	X3649	23.8	3.34	14	3.1	0.62	2.6	0.3	1.8	0.3	0.9	0.14	0.9
OSL 8	X3650	18	2.76	11.7	2.5	0.52	2.2	0.3	1.5	0.3	0.8	0.12	0.8
OSL 9	X3651	13.7	1.69	6.6	1.3	0.24	1.1	0.1	0.8	0.1	0.4	0.06	0.4
OSL 10	X3652	10	2.15	9.1	2.2	0.45	1.8	0.3	1.5	0.3	0.8	0.11	0.7

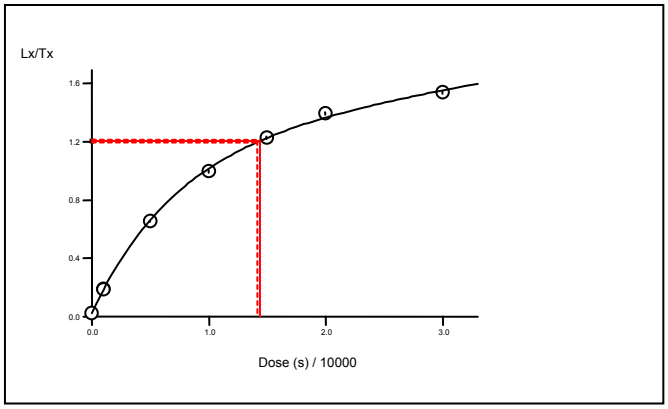
Analyte Symbol		Lu	Hf	Ta	W	Tl	Pb	Bi	Th	U			
Unit Symbol		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm			
Detection Limit		0.04	0.2	0.1	1	0.1	5	0.4	0.1	0.1			
OSL 1A	X3641	0.22	1.5	0.2	< 1	0.1	6	< 0.4	2.3	0.5			
OSL 1B	X3642	0.24	1.6	0.2	< 1	0.1	5	< 0.4	2.4	0.5			
OSL 1C	X3643	0.33	2.1	0.3	< 1	0.1	6	< 0.4	2.8	0.6			
OSL 2	X3644	0.14	2.2	0.2	< 1	< 0.1	< 5	< 0.4	1.5	0.4			
OSL 3	X3645	0.22	1.5	0.2	< 1	0.1	7	< 0.4	2.3	0.5			
OSL 4	X3646	0.21	1.9	0.2	< 1	0.1	7	< 0.4	2.3	0.4			
OSL 5	X3647	0.3	1.9	0.3	< 1	0.2	7	< 0.4	2.8	0.5			
OSL 6	X3648	0.42	3	0.4	< 1	0.2	8	< 0.4	4	0.8			
OSL 7	X3649	0.15	1.6	0.2	< 1	< 0.1	5	< 0.4	1.4	0.5			
OSL 8	X3650	0.14	1.6	0.2	< 1	< 0.1	< 5	< 0.4	1.4	0.6			
OSL 9	X3651	0.07	0.9	0.2	< 1	< 0.1	< 5	< 0.4	1.1	0.3			
OSL 10	X3652	0.11	0.6	< 0.1	< 1	< 0.1	< 5	< 0.4	0.8	0.3			

APPENDIX 3 TYPICAL OSL SHINE DOWN CURVES, GROWTH CURVES AND PROBABILITY DENSITY DISTRIBUTIONS

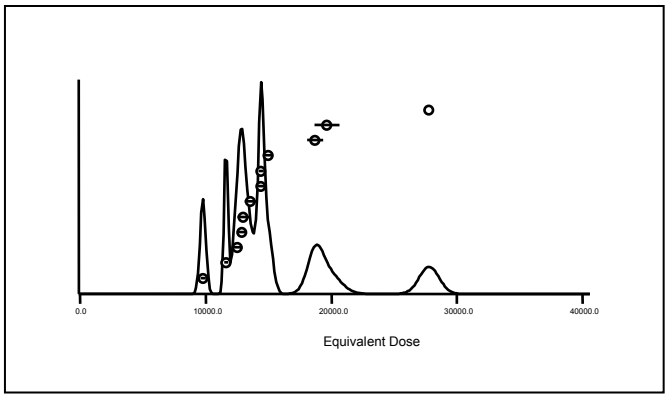
OSL 1A X3641



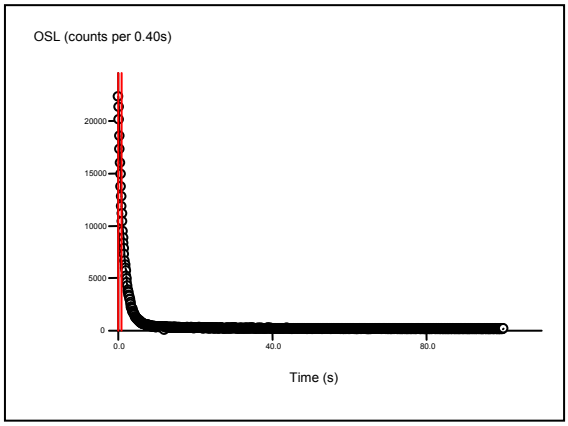
Shine down curve



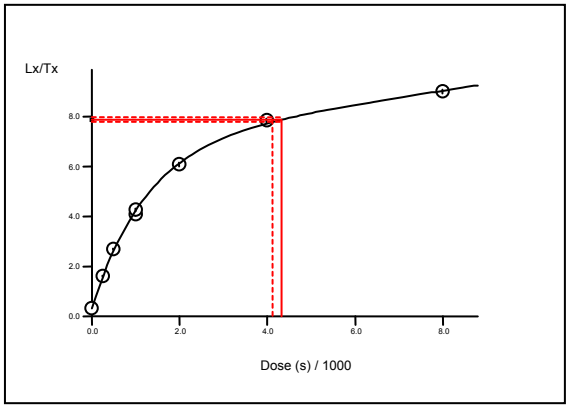
Growth curve



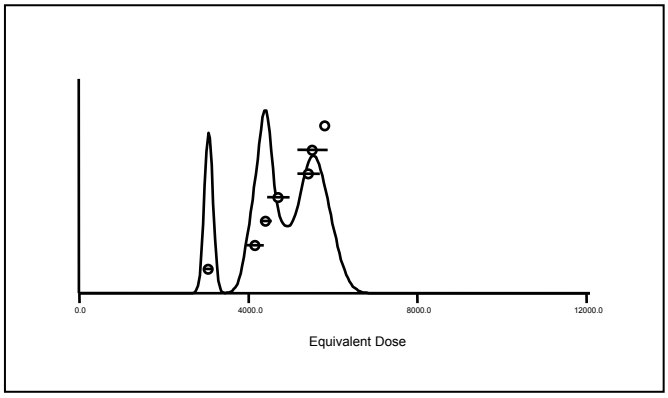
Palaeodose distribution



Shine down curve

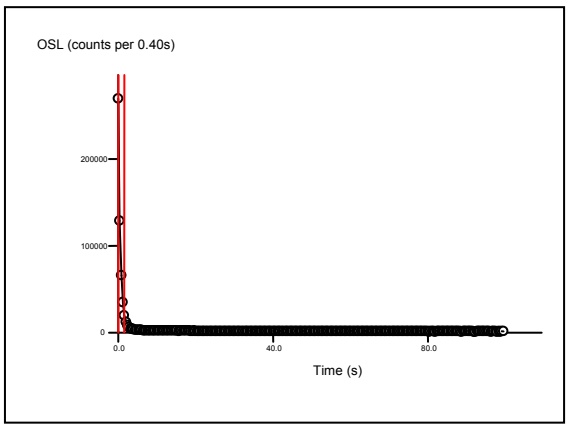


Growth curve

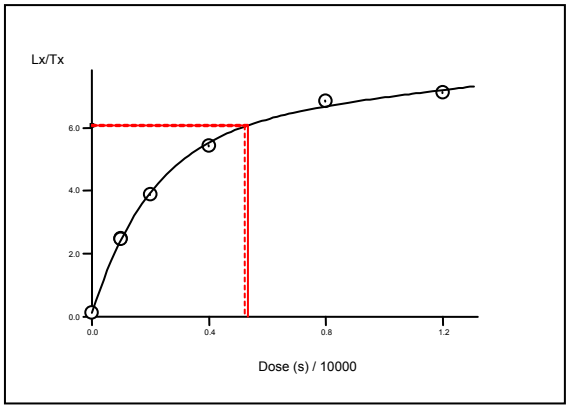


Palaeodose distribution

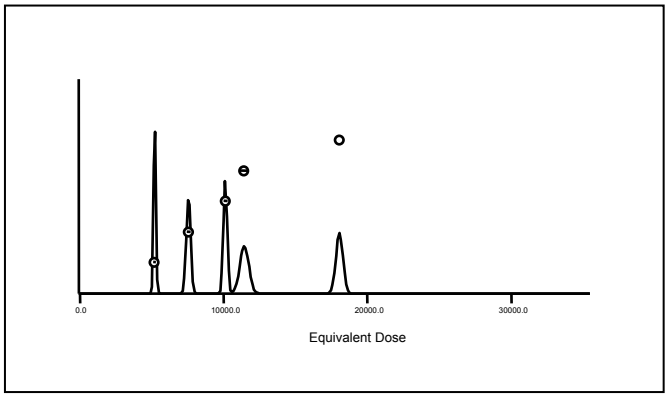
OSL 3 X3645



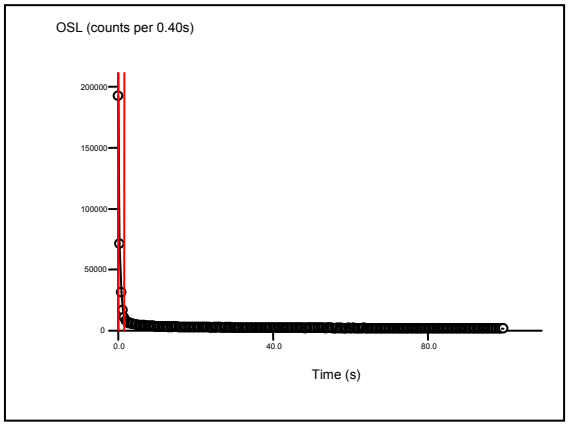
Shine down curve



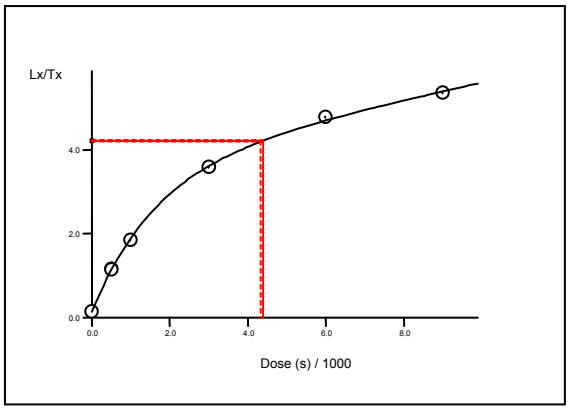
Growth curve



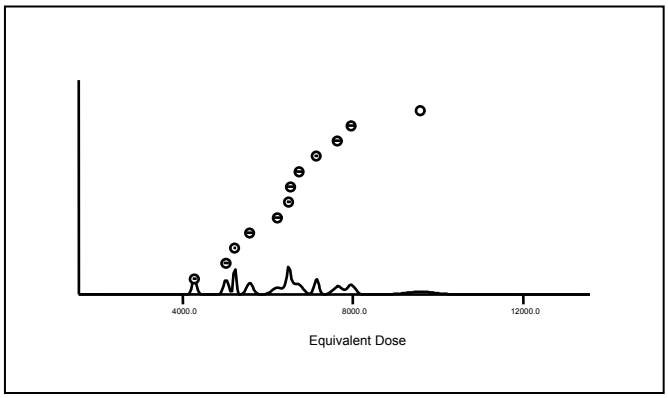
Palaeodose distribution



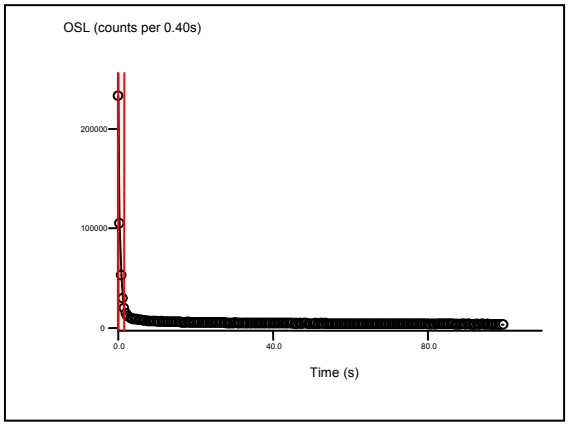
Shine down curve



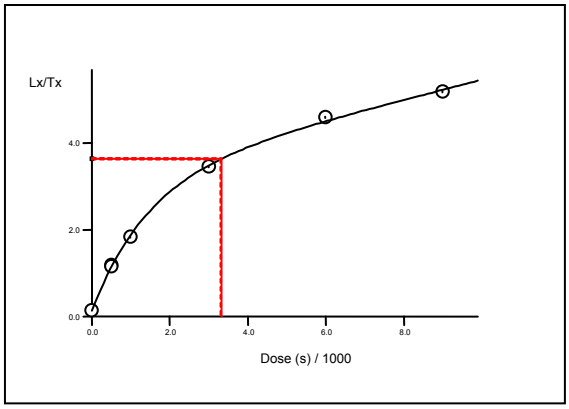
Growth curve



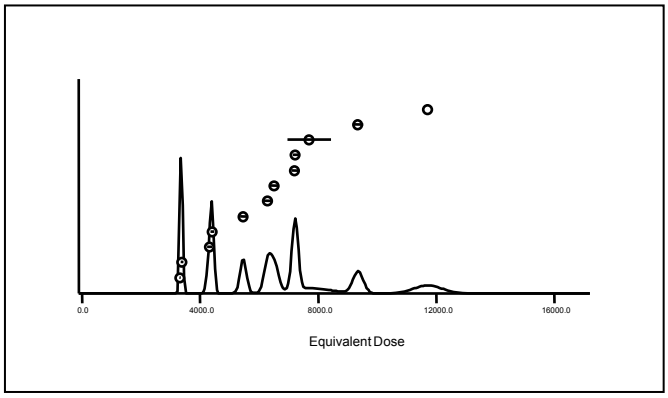
Palaeodose distribution



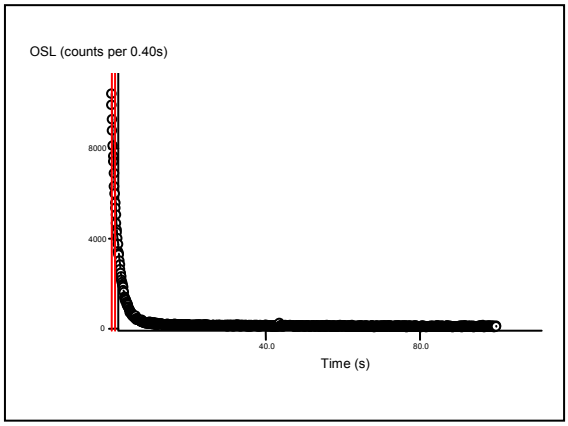
Shine down curve



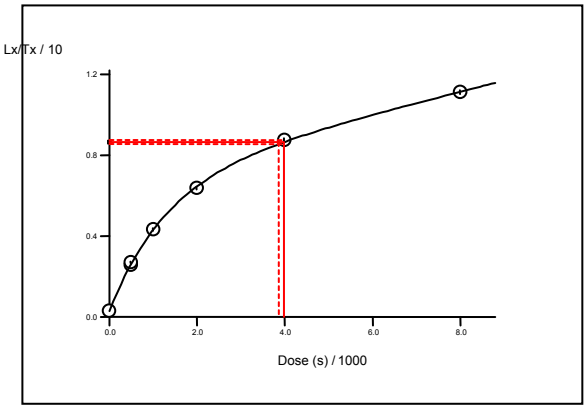
Growth curve



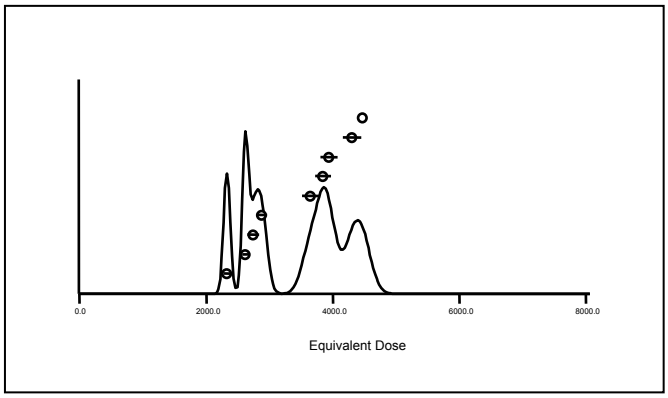
Palaeodose distribution



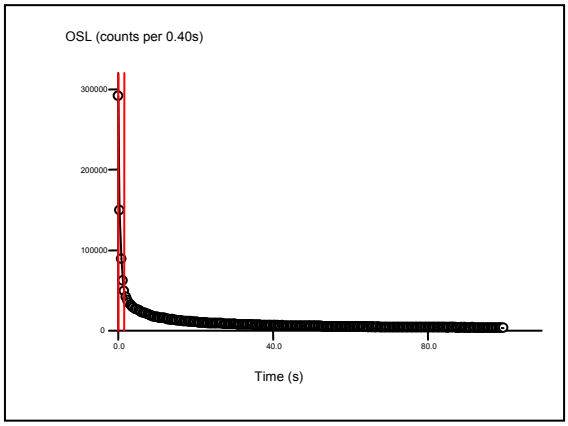
Shine down curve



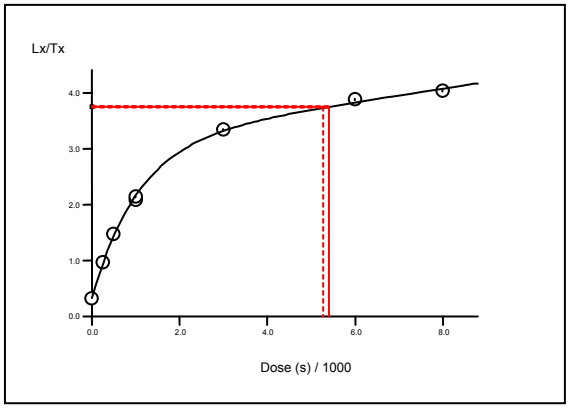
Growth curve



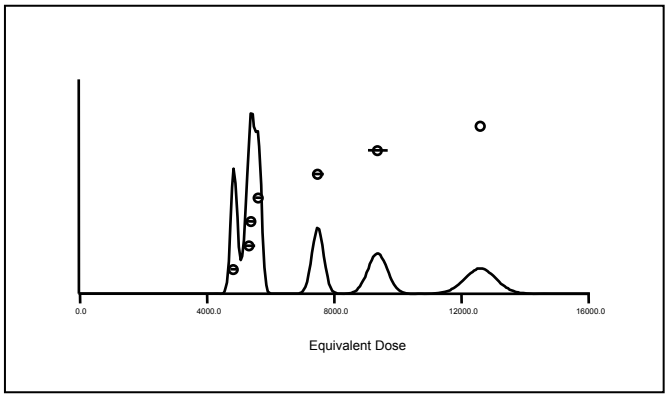
Palaeodose distribution



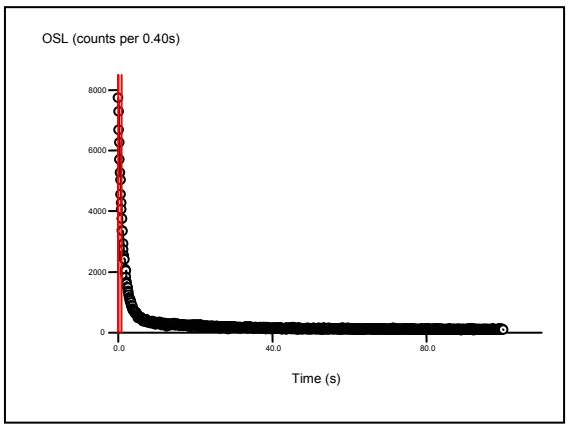
Shine down curve



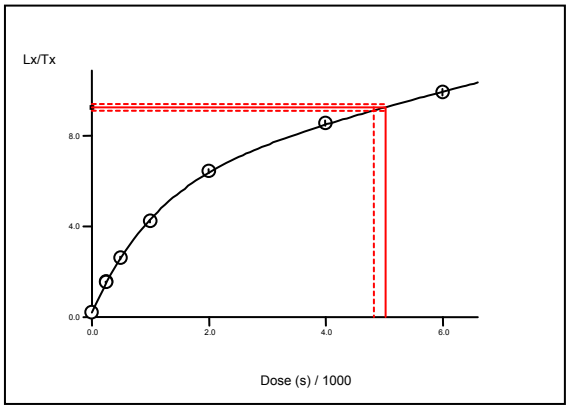
Growth curve



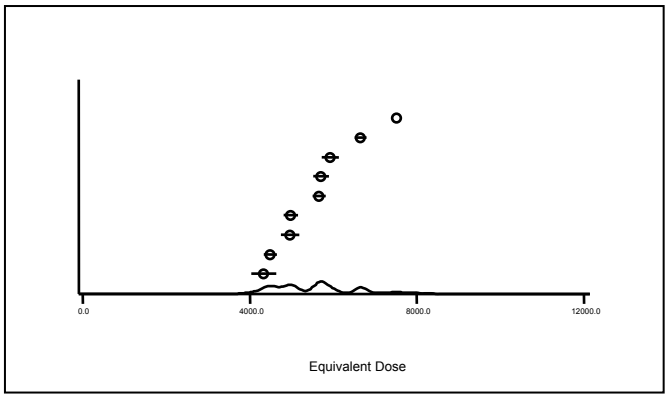
Palaeodose distribution



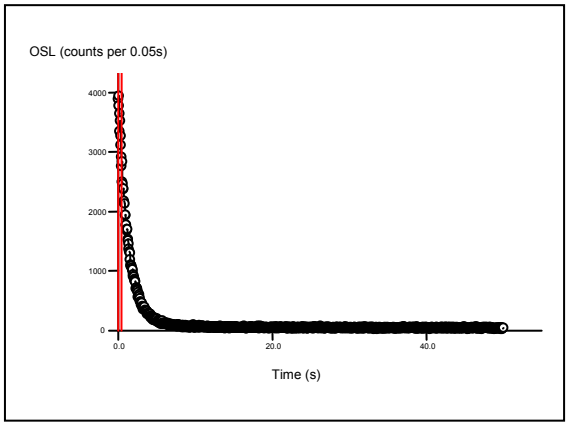
Shine down curve



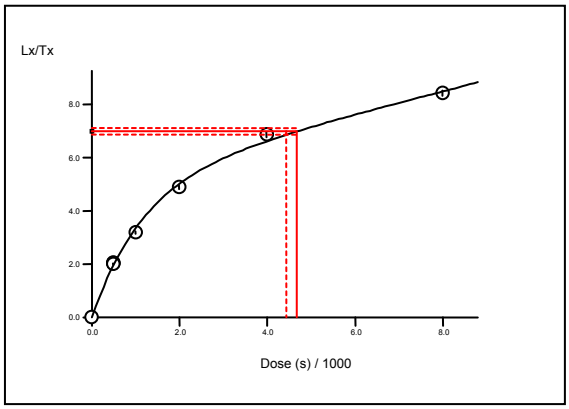
Growth curve



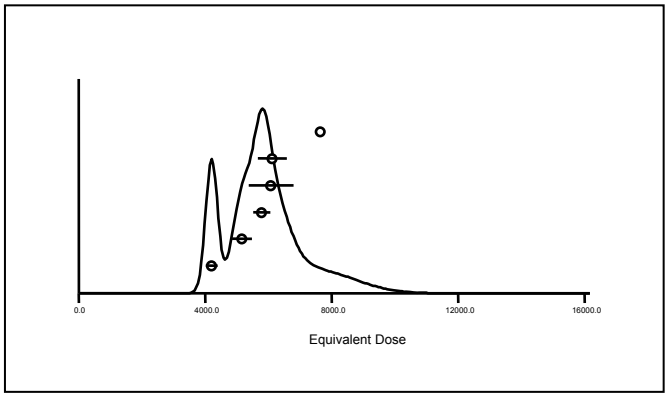
Palaeodose distribution



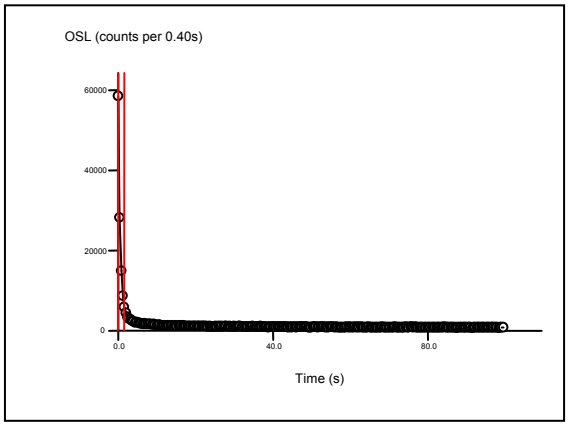
Shine down curve



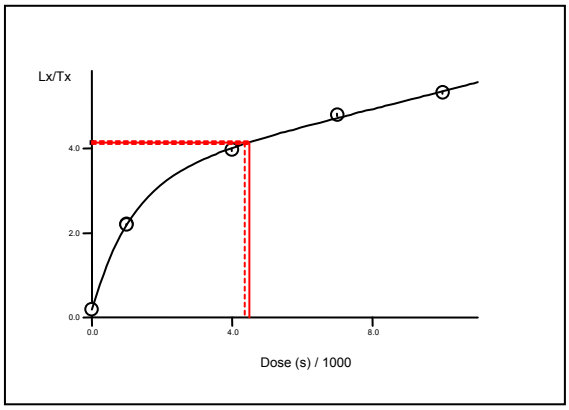
Growth curve



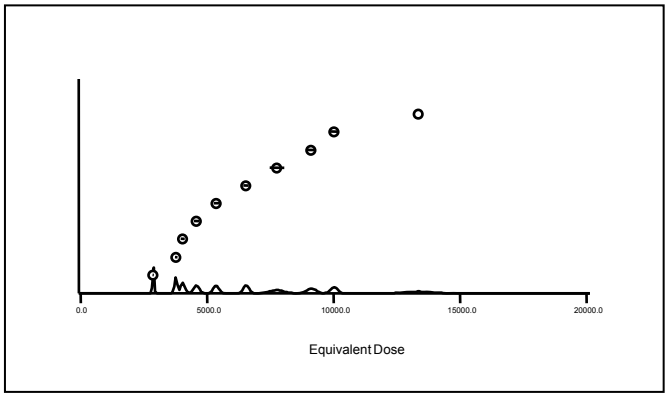
Palaeodose distribution



Shine down curve



Growth curve



Palaeodose distribution

ENGLISH HERITAGE RESEARCH AND THE HISTORIC ENVIRONMENT

English Heritage undertakes and commissions research into the historic environment, and the issues that affect its condition and survival, in order to provide the understanding necessary for informed policy and decision making, for the protection and sustainable management of the resource, and to promote the widest access, appreciation and enjoyment of our heritage. Much of this work is conceived and implemented in the context of the National Heritage Protection Plan. For more information on the NHPP please go to http://www.english-heritage.org.uk/professional/protection/national-heritage-protection-plan/.

The Heritage Protection Department provides English Heritage with this capacity in the fields of building history, archaeology, archaeological science, imaging and visualisation, landscape history, and remote sensing. It brings together four teams with complementary investigative, analytical and technical skills to provide integrated applied research expertise across the range of the historic environment. These are:

* 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)
* Remote Sensing (including Mapping, Photogrammetry and Geophysics)

The Heritage Protection Department undertakes a wide range of investigative and analytical projects, and provides quality assurance and management support for externally-commissioned research. We aim for innovative work of the highest quality which will set agendas and standards for the historic environment sector. In support of this, and to build capacity and promote best practice in the sector, we also publish guidance and provide advice and training. We support community engagement and build this in to our projects and programmes wherever possible.

We make the results of our work available through the Research Report Series, and through journal publications and monographs. Our newsletter *Research News*, which appears twice a year, aims to keep our partners within and outside English Heritage up-to-date with our projects and activities.

A full list of Research Reports, with abstracts and information on how to obtain copies, may be found on www.english-heritage.org.uk/researchreports

For further information visit www.english-heritage.org.uk

ENGLISH HERITAGE

ISSN 2046-9799 (Print)
ISSN 2046-9802 (Online)