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# Optical Dating of the Broom Palaeolithic sites, Devon and Dorset

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## Summary

The sand and gravel exposures at Broom, located on the River Axe, are of considerable significance in the context of the British Lower Palaeolithic and the fluvial terrace stratigraphy of southwest England. The archaeology is of both regional importance for the understanding of the Lower Palaeolithic (Acheulean) occupation of southwest Britain, and national significance with respect to the use of an atypical raw material (chert) in the manufacture of the majority of the lithic assemblage. The sediment sequence is broadly tripartite comprising Lower Gravels, Middle Beds (sand, silt and clay) and Upper Gravels; a pattern consistent with traditional models of fluvial terrace formation over a glacial - inter-glacial cycle. Additional intra-gravel lenses of fine-grained material may chronicle morphological response to oscillations of climate and/or local hydrology over shorter intervals. The prolific assemblage of Acheulean artefacts is dispersed throughout this sequence and represents a mixture of *in situ* and derived material, with deposition of both components considered relatively contemporaneous with episodic occupation. The principle aim of this report is to assess the length of hominid presence through direct dating of the Broom sedimentary sequence. Fifteen conventional samples from matrix-supported units and three non-conventional interstitial sand samples from clast-supported units were collected from the Middle Beds and Upper Gravels. These were optically dated using conventional multi-grain single aliquot regenerative-dose measurements. The majority of ages for matrix-supported units are internally consistent, displaying convergent estimates from stratigraphically equivalent sediment units of divergent dosimetry. However, interstitial sands generate ages that significantly overestimate those from underlying matrix-supported units. The consistency of single-grain aliquot minimum age estimates from interstitial sands with mean age estimates from matrix-supported samples suggests such age overestimation may be a product of partial bleaching. Bayesian analysis of the raw optical chronology demonstrates the stratigraphic consistency of age estimates between major units and refines sedimentary succession into intervals of 324 to 282 ka (Middle Beds) and 292 to 205 ka (Upper Gravels). This might suggest a prolonged hominid presence from <325 ka to 205 ka, yet the minimum limit contradicts the chronology of sedimentary succession extrapolated from terrace formation models. Given the apparent accuracy of the optical chronology, evidenced by internal and stratigraphic consistency, the minimum optically derived age of the Broom sequence is accepted tentatively.

## Keywords

Luminescence Dating
Geochronology

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## Introduction

The sand and gravel exposures at Broom, located on the River Axe along the Devon/Dorset border, are of considerable significance in the context of the British Lower Palaeolithic and the terrace stratigraphy of southwest England (Salter 1899, 1906; Ussher 1906; Woodward 1911; Reid Moir 1936; Green 1947; Green 1974, 1988; Stephens 1970, 1974, 1977; Shakesby and Stephens 1984).

The deposits, exposed in three commercial pits (Fig 1), have yielded 1807 Palaeolithic artefacts, an assemblage dominated by handaxes (Wessex Archaeology 1993, 163; Wymer 1999; Marshall 2001). As with the majority of Britain's river terrace Palaeolithic archaeology, the contextual information for the assemblage is sporadic. However, the C.E. Bean collections from Pratt's Old Pit are accompanied by excellent field records (Green 1988) that suggest artefacts were recovered from throughout the entire sediment sequence. The lithic assemblage features a variety of handaxe types, with significant numbers of cordate, cordate/ovate and pointed forms (Green 1988; Marshall 2001, table 8.2-8.3; Hosfield and Chambers 2004; table 139-140). The physical condition of the stone tool assemblage suggests a mixture of *in situ* artefacts and pieces that have been transported short distances downstream but whose deposition was relatively contemporaneous with episodic human occupation (Chambers and Hosfield 2004; Marshall 2001, fig 8.1). The archaeology is of both regional importance for the understanding of the Lower Palaeolithic (Acheulean) occupation of southwest Britain, and national significance with respect to the use of an atypical raw material (chert) in the manufacture of the majority of the lithic assemblage.

Traditional models of sediment evolution at Broom (Shakesby and Stephens 1984) have emphasised a tripartite sequence (Lower Gravels – fine grained Middle Beds – Upper Gravels), echoing Bridgland's (2000) model of fluvial terrace formation. Bridgland (1994, 1996, 2000, 2001) has provided a robust, macro-scale framework for the development of fluvial terrace sequences, associating major fluvial incision and aggradation with the cyclical shifts from glacial to interglacial stages (expressed in this report in terms of Marine Isotope Stages (MIS), even numbered MIS referring to glacials, odd numbered to interglacials; Shackleton *et al* 1990). The framework's chronological resolution is dictated by the *c* 70–100,000 year climatic cycles of the Middle to Late Pleistocene.

The 2000–2002 excavations of the Broom pits revealed a depositional complexity not appreciated within this model, with additional intra-gravel units of coarse and fine-grained sands, silts and clays. Recent work by Maddy *et al* (2001, Fig 5) on the Northmoor Gravel of the Upper Thames Valley has detected shorter-term fluvial aggradations and incisions that can be associated with brief stadial/interstadial climate oscillations. These studies support studies of the relationship between fluvial activity and climate at a variety of chronological scales (eg Vandenberghe 1993, 1995, 2001, 2002). The presence of these major and minor units at Broom might imply hominid presence over a glacial-interglacial-glacial cycle. However, there exists no chronometric dating control at Broom to verify terrace formation over such an interval or to establish when in time this occurred.

New excavations of the Broom gravel exposures were therefore conducted in the Railway Ballast Pit (ST 326 020), Pratt's New Pit and Pratt's Old Pit (ST 328 025) to investigate the chronology of hominid presence using optical dating. Given systematic errors limit the resolution of optical age estimates to a minimum of *c* 5%, a combined Optical dating-Bayesian analysis approach (Rhodes *et al* 2003) has been adopted to refine the raw optical chronology of the Middle Pleistocene sedimentary succession at Broom.

## Optical dating

Sedimentation ages generated by optical dating, the progeny of thermoluminescence dating, are premised upon

i) the reduction of the datable signal – optically stimulated luminescence – within naturally occurring minerals to zero through exposure to sunlight, and once buried,

ii) the reaccumulation of this signal by exposure to natural radiation existent within surrounding sediments and emanating from the cosmos.

If the amount of optically stimulated luminescence accrued is directly proportional to the total dose absorbed by minerals since burial then the age of sedimentation can be estimated using the expression,

$$\text{Age} = \frac{\text{Mean Total dose}}{\text{Mean Total Dose Rate}}$$

## Methodology

### Sample collection

Fifteen conventional sediment samples – those located within matrix-supported units composed predominantly of sand and silt (Plate 1)– were collected in daylight from sections by means of opaque plastic tubing (150x45 mm) forced into each face or carved as lithified blocks (75x75x50 mm). In addition three non-conventional samples (GL03001-GL03003; hereon termed interstitial sand samples, Plate 1), located within a clast-supported unit, were collected two hours after sunset by first removing *c* 0.2 m of the unit face and then scraping material into a lightproof bag. Each sample was wrapped in clingfilm and parcel tape in order to preserve moisture content and integrity until ready for laboratory preparation. Additional moisture content samples were collected from the rear of the cavity created by sampling and insertion of gamma spectrometer. These were double-bagged, again to maintain that moisture content existent within each unit at the time of sampling. The locations of optical dating samples obtained from Broom are shown within Table 1 and Fig 2.

### Sample preparation

Samples were processed under controlled laboratory lighting conditions provided by Encapsulite RB-10 (red) filters. To isolate that material potentially exposed to daylight during sampling, sediment located within 20 mm of each tube-end or the outermost 5 mm of each block face was removed. These 'end' samples along with the remaining 'core' and separate moisture content samples were assessed individually for moisture content in order to examine the consistency of this value. In the event of a discrepancy in these estimates, perhaps brought about by surface drying, the maximum value was incorporated into the dose rate calculation.

The 'core' content of each sample was dried at 40ºC for 48 hours and then dry sieved. Quartz within the fine sand (90-125 μm or 125-180 μm) or fine silt (5-15 μm) fraction was then isolated (Table 2). Fine sand fractions were treated with 10% hydrochloric acid (HCl) and 10% hydrogen peroxide ($H_2O_2$) to attain removal of carbonate and organic components. These samples were then etched for 40 to 60 minutes in 40% hydrofluoric acid (HF), in order to remove the outer 10-15 μm layer affected by alpha radiation and degrade each samples' feldspar content. Whilst in hydrofluoric acid, each sand sample was continuously stirred using a magnetic stirrer and follower apparatus in an attempt to achieve isotropic etching of grains. 10% hydrochloric acid was then added to remove acid soluble fluorides. Each sample was dried, re-sieved and quartz isolated from the remaining heavy mineral fraction using a sodium polytungstate density separation at 2.68g.cm$^{-3}$. Twelve multi-grain aliquots (*c* 6 mg, 4000 to 10,000 grains) of quartz from each sample were then mounted on aluminium discs for the determination of equivalent dose ($D_e$) values. In addition, with the assistance of a macroscope and filtered (LEE106, red) light, *c* 100 125-180 μm grains were located individually in 200 μm (diameter and depth) holes drilled as a 10x10 grid into six anodised aluminium discs (Duller *et al* 1999), evolving a maximum of 600 single grain $D_e$ values.

Sedimentation of the <90 μm fraction in a 10 cm column of acetone facilitated the isolation of 5-15 μm quartz grains (<15 μm in 2 min 20 s, >5 μm in 21 mins at 20°C) and other mineral grains of varying density and size. Further pretreatments included immersion in 10% HCl to dissolve carbonate materials, whilst feldspars and amorphous silica were removed from the remaining fraction through digestion in 35% $H_2SiF_6$ for two weeks (Jackson *et al* 1976; Berger *et al* 1980). Following addition of 10% HCl to remove acid soluble fluorides, grains degraded to <5 μm as a result of acid pretreatment were removed by acetone sedimentation. Six aliquots (*c* 1.5 mg, 3 million grains) were mounted on aluminium discs for $D_e$ measurement.

Quartz was used as the minerogenic dosimeter primarily because of the stability of its datable signal over the mid to late Quaternary period, predicted through isothermal decay studies (eg Smith *et al* 1990; retention lifetime 630 Ma at 20°C) and evidenced by optical age estimates concordant with independent chronological controls (Wallinga *et al* 2001; Murray *et al* 2002; Murray and Olley 2002; Stokes *et al* 2003; Watanuki *et al* submitted). This stability is in contrast to the anomalous fading of comparable signals commonly observed for other ubiquitous sedimentary minerals such as feldspar and zircon (Wintle 1973; Templer 1985; Spooner 1993).

## Equivalent Dose ($D_e$) acquisition

Conventional luminescence measurements, generating $D_e$ values from multi-grain aliquots, were made using an automated TL-DA-15 Risø set (Markey *et al* 1997).

Optical stimulation of luminescence was provided by a 150 W tungsten halogen lamp, filtered to a broad blue-green light, 420-560 nm (2.21-2.95 eV) conveying 16 mWcm$^{-2}$, using three 2 mm Schott GG420 and a broadband interference filter. Infrared stimulation, provided by 13 IR diodes (Telefunken TSHA 6203) stimulating at 875Δ80nm delivering ~5 mWcm$^{-2}$, was used to indicate the presence of contaminant feldspars (Hütt *et al* 1988). This diagnostic, applied to both the natural and laboratory signals (to accommodate potential fading of IRSL signals), indicated such contamination to be absent from aliquots of each sample. Stimulated photon emissions from the quartz aliquots were filtered by 5 mm of HOYA U-340 glass filters.

Non-conventional luminescence measurements, evolving $D_e$ values from single grain aliquots, were made using an alternative illumination source, the Risø single grain laser luminescence system described by Duller *et al* (1999). Optical stimulation emanated from a focussed solid state 532 nm (green), 10 mW stabilised laser (Laser 2000 LCL-LCM-T-11ccs) scanned across holes of single grain aliquots (outlined above) by means of mirrors mounted on and moved by motorised linear stages.

All (UV) emissions were detected by an EMI 9235QA photomultiplier fitted with a blue-green sensitive bialkali photocathode. Regenerated optical signals were obtained by irradiation using a 40 mCi $^{90}$Sr/$^{90}$Y beta source incorporated within the Risø set and calibrated for 5-15 μm, 90-125 μm, 125-180 μm multi-grain and 125-180 μm single grain aliquots of quartz against the 'Hotspot 800' $^{60}$Co gamma source located at the National Physical Laboratory, UK.

$D_e$ values were obtained through calibrating the 'natural' optical signal (Figs 3-9, *left column*), acquired during burial, against 'regenerated' optical signals obtained by administering known amounts of laboratory dose. Specifically, $D_e$ estimates were obtained using a Single-Aliquot Regenerative-dose (SAR) protocol, similar to that proposed by Murray and Wintle (2000).

Up to six different regenerative-doses were administered so as to image dose response and define that portion of linear response bracketing the natural signal, from which $D_e$ were interpolated and associated errors (counting and fitting) calculated by way of linear regression (Green and Margerison 1978; Figs 3 to 9, *inset left column*). An additional error of 3.5 % was incorporated into single grain $D_e$ estimates to account for variations induced by laser repositioning (Truscott *et al.*, 2000). A test dose of 5 Gy was used in monitoring and correcting for sensitivity change resulting from the process of $D_e$ acquisition. Preheating prior to measurement of natural and regenerated signals was 260°C for 10 s and 180°C for 10 s before test dose signal readout. Optical stimulation of each aliquot occurred at 160°C in order to minimise effects associated with photo-transferred thermoluminescence and maximise signal to noise ratios.

The ratio of repeat regenerative-doses (approximating $D_e$ values) was obtained for each aliquot in order to clarify the success of sensitivity correction. Repeat ratios approximating unity, as in the case of samples in the present study – 0.91-1.07 ($1.01 \pm 0.04$, $1\sigma$ standard deviation) for multi-grain aliquots – are taken as indicative of accurate sensitivity correction. Zero-dose signal response was used as a measure of thermal transfer relating to test dose preheating and subtracted from regenerative-dose responses. $D_e$ values generated by both single and multi-grain aliquots were accepted if their associated error was ≤20%. Given that $D_e$ values in this study are located in the high dose-response range, visual clarification of growth in dose response beyond $D_e$ values formed an additional acceptance criterion. Further, for single grain aliquots, supplemental filters of $D_e$ values included natural and test dose response exceeding 150 counts (Toms 2002) and repeat regenerative-dose ratios statistically concordant with the range 0.9-1.1.

Mean $D_e$ values, given in Table 2, are the weighted (geometric) mean $D_e$ determined from multi-grain aliquots, fulfilling acceptance criteria, calculated using the Central Age Model outlined by Galbraith *et al* (1999) and are quoted at $1\sigma$ confidence (standard error). Minimum $D_e$ estimates are derived from measurements of single grain aliquots and calculated using the three parameter Minimum Age Model described by Galbraith et al (1999).

### Acquisition of dose rate value

Table 2 also details dose rate information. Mean gamma ($\gamma$) dose rate contributions to each sample have been derived from measurements of U, Th and K concentrations collected *in-situ* using an EG&G μNomad portable NaI gamma spectrometer, calibrated using the block standards at the Research Laboratory for Archaeology and History of Art, Oxford University. These *in situ* measurements of $\gamma$ spectra reduce the uncertainty relating to potential heterogeneity in the $\gamma$ dose field surrounding each sample. For conventional samples, Neutron Activation Analysis (NAA) was performed by Becquerel Laboratories, Australia, on sub-samples of 'core' material to determine the mean beta (β) dose rate and, in respect of samples where $D_e$ values were evolved from 5-15 μm aliquots, mean alpha (α) dose rate to each.

For the interstitial sand samples, the bias towards larger particle sizes within clast-supported units may create a bias in β dose rate. However, the dimensions of interstices can exceed the penetration range of clast-emitted β particles; in these instances interstitial material will influence sample β dose. Accurate quantification of mean β dose rate therefore entails assessment of average β emission rates from clasts and interstitial material, factoring in the mean interstitial volume. β dose rate from five clasts and interstitial material (<2 mm) of each interstitial sand sample was assessed. Flint and chert dominate the clast lithologies, each of which commonly has low concentrations of U, Th and K (Mercier *et al* 1995). Therefore, radionuclide concentration was assessed by Inductively Coupled Plasma Mass Spectrometry (ICP-MS, School of Geography, Oxford University), offering the required parts per billion detection capability. Table 3 shows the β dosimetry data for the interstitial sand samples. The estimates of mean β dose rate are comparable between clast and interstitial fractions and significantly smaller than those presented for matrix-supported samples (Table 2). This suggests that grains of clast material dominate interstitial β emissions. Given the similarity of mean β dose rate in clast and interstitial fractions, mean interstitial volume should not significantly impact upon mean β dose rate. β dosimetry was therefore estimated from a mass-weighted combination of clast and interstitial material. For each sample, several grain fractions were sieved, the relative mass of each determined, then ground and finally recombined in respective proportions in order to ensure a representative sample was analysed for calculation of mean β dose rate.

Dose rate calculations, following those described by Aitken (1985), incorporated β-attenuation factors (Mejdahl 1979; for 90-180 μm grains only), dose rate conversion factors (Adamiec and Aitken 1998) and the absorption coefficient of present water content (Zimmerman 1971), with a 25% relative uncertainty attached to reflect potential temporal variations in past moisture content. Temporal variations in water content are limited by porosity, however saturated volume was probably only achieved during the period of deposition. This sedimentary phase was brief compared to the period of burial; therefore it is assumed that present water contents reflect the long-term average. For those samples where an assessment of alpha dose rate was pertinent, an a-value of 0.050 ± 0.002 (Toms unpubl) was factored into dose rate calculations to account for the low accumulation of datable signal through exposure to this radiation relative to ionisation by betas and gammas. Estimations of cosmic dose followed the calculations of Prescott and Hutton (1994); alterations in the thickness of overburden are taken to be minimal over the period of burial.

### Acquisition of Luminescence age

Luminescence ages were obtained through dividing the mean $D_e$ value (or minimum $D_e$ value where appropriate, see below) by the mean total dose rate value and are shown in Table 2. The standard error on luminescence age estimates is quoted at $1\sigma$ confidence and is premised upon the propagation of both systematic and experimental ($1\sigma$) standard errors associated with those parameters, outlined above, contributing to the calculation of $D_e$ and dose rate values. Fig. 10 shows the composite probability mass function of age obtained for each sample, relative to their location, incorporating $D_e$ and dose rate uncertainties for each multi-grain aliquot along with the $1\sigma$ standard error range about the mean age.

### Assessment of accuracy

There are two principal issues requiring consideration in assessing the accuracy of samples presented in this study. Firstly, the ages presented are the oldest reported for UK fluvial deposits, relative to published data. In this respect, matters of signal saturation and retention, leading to age underestimation, and incompatibility of large natural and laboratory induced signals, producing overestimates of age (Bailey 2004), are of concern. Referring to issues of signal saturation, Murray *et al* (2002) demonstrated that mean $D_e$ estimates corresponding with high-doses of 200-400 Gy, as occurs for 13 of the 18 samples presented in this study, generated ages concordant with independent chronological control. For all ages produced from multi-grain single-aliquot measurements herein, growth in laboratory dose response beyond that of each natural signal was observed. Considering the influence of signal retention; in contrast to the study of Murray *et al.* (2002; deposits dating to marine isotope stage 5e, *c* 125 ka), the age of the deposits at Broom in general appear twice as old. Watanuki *et al* (submitted) report multi-grain single-aliquot age estimates concordant with independent chronological controls for sediments dating to 500 ka, however it is accepted here that similar studies are limited in number. Aside from these extrapolations from previous studies to attest the accuracy of the Broom optical chronology, there are no direct extrinsic measures of the accuracy of its accuracy. However, there does exist a credible intrinsic gauge. Figure 11 shows the bivariation of each sample's $D_e$ and dose rate, the gradient to each data point reflecting sample age. The broad linear distribution of the majority of data from conventional samples illustrates the comparability of age estimates from units of contrasting dosimetry, signifying the accuracy of these old age estimates. Figure 11 also shows that GL03057 to GL03059 (section 14) are significantly younger than all other conventional age estimates and are indeed younger than the Middle Pleistocene age inferred from the site's Palaeolithic assemblage. These younger estimates likely reflect reworked material, possibly resulting from 20th century quarrying. In summary, convergent age estimates derived from units of divergent dosimetry suggest dose and/or age related caveats of optical dating do not have a significant detrimental effect on the Broom chronology.

The second consideration in the assessment of accuracy of optical age estimates for Broom relates to the fluvial genus of the deposits. Residual datable signals present subsequent to burial, due to pre-burial exposure to an attenuated spectrum, intensity and/or period of sunlight, will generate age overestimates. This effect is particularly acute for material eroded, transported and deposited sub-aqueously (Olley *et al* 1998, 1999; Wallinga 2002). Again, the data contained within Figure 11 testifies to the accuracy of the majority of conventional age estimates, suggesting a limited influence of partial bleaching. In contrast, Figure 11 also shows the age estimates generated by multi-grain aliquots of interstitial sand samples significantly overestimate those reported from the conventional samples. The possibility that this feature is resultant of partial resetting (or bleaching) of the time dependent signal prior to burial is investigated here.

Within optical dating there exist two sets of intrinsic measures of the occurrence of partially bleached sediments, signal analysis and inter-aliquot $D_e$ distribution studies, each consisting of several iterations (Huntley *et al* 1985; Agersnap-Larsen *et al* 2000; Rhodes 1990; Li 1994; Murray *et al* 1995). However, within the context of this study only those pertinent to single and multi-grain single-aliquot $D_e$ measurements are