Bayesian analysis of ESR dates, with application to Border Cave

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30 August 2011

For submission to *Quaternary Science Reviews*

Abstract

Methods for Bayesian statistical analysis of stratigraphically related radiocarbon dates have been in use for over a decade. This paper extends these techniques to stratigraphically related ESR dates, allowing estimation of the dates of events not directly dated. A hierarchical model of the uncertainties in ESR dating is developed, to account for the correlation of error terms between samples. Using the new method, an analysis is made of the dating at Border Cave, Kwa Zulu Natal, South Africa. The results for individual dates and the dating of layer boundaries are more precise than previously obtained. The hominid fossils BC1 and BC2 are placed at either 71-91ka (95% highest posterior density - hpd) or 152-171ka (95% hpd) depending on the stratigraphic provenance assigned. BC3 is dated to 66-90ka and BC5 to 61-72ka (both 95% hpd). The estimated duration of the Howieson's Poort industry at Border Cave is demonstrated to have significant uncertainty, and the ESR dates, even with the increased precision of this analysis, are unable to decide between hypotheses that the industry lasted 10ka and that it lasted 20ka.

Keywords: ESR dating, Bayesian analysis, stratigraphy, Border Cave

1. Introduction

Archaeologists and geologists have recognized for many years that chronometric dates and stratigraphic information need to be combined, if only to establish that the ordering of samples according to stratigraphy agrees with their ordering by chronometry. The last fifteen years have seen the development and now the routine application of Bayesian chronological modelling as means to go beyond this and actually use the stratigraphic (or other) prior chronological information to constrain and inform the quantitative estimates of time from radiocarbon dates on Holocene archaeological sites (see Buck, 2003) and extension of the idea to archaeomagnetic dating has been proposed (Lanos, 2001; 2003). The basic idea is a simple one and may be expressed as a form of Bayes' theorem:

$$p(\text{dates} \mid \text{chronometric data}) \propto p(\text{chronometric data} \mid \text{dates}) \times p(\text{dates})$$

where p(·) represents the probability of something, and the symbol | indicates that the probability is conditional on the item to the left of it being known. The *dates* are the true dates of the objects in question, and the *chronometric data* is the measurements we make (in ESR dating or other methods) to estimate the age of the objects. Then p(dates) expresses our prior beliefs (before obtaining chronometric data) about the probabilities of the dates of events having certain values, p(chronometric data | dates) is the likelihood which uses a mathematical model to express the probability of obtaining the chronometric data, if the dates were known and p(dates | chronometric data) is what we want to know, and expresses our posterior beliefs about the true dates of the objects incorporating our prior beliefs and the chronometric data. The prior beliefs can include statements about relative ordering of events, and thus incorporate stratigraphic information. In fact a small number of simple components can be combined to represent almost any stratigraphic relationship (Bronk Ramsey, 1995), just as in a Harris diagram (or Harris matrix) the stratigraphy of an archaeological site is summarised entirely as known earlier than/later than relationships or a lack of knowledge of temporal relation (Harris, 1989), in a form which minimises the number of relations that have to be stated. The mathematical models so constructed can also incorporate extra parameters representing undated events of interest (e.g. the age of the start of deposition of a stratum) and more sophisticated models of the type of processes generating the dated samples (e.g peat accumulation - Christen et al., 1995).

Dates from techniques other than radiocarbon can be incorporated into these analyses by expressing them as calendar dates. Software packages for Bayesian analysis such as BCal (Buck et al., 1999) and OxCal (Bronk Ramsey, 1995), allow this by expressing such dates simply as a calendar date with a normal uncertainty. This is satisfactory for single dates incorporated into a sequence with radiocarbon dates, but many other dating techniques produce non-normal uncertainties (e.g. uranium series dating) or include significant error terms which are not independent between dated samples and should be accounted for in any statistical analysis (e.g. luminescence dating, ESR dating). This approach has been applied to OSL dating by Rhodes et al (2003), but it is possible that their analyses underestimate the uncertainty by ignoring the commonality of parts of the uncertainty of the individual OSL dates.

In principle this methodology is applicable to any stratigraphically related set of dates. Extension from the realm of radiocarbon to the longer timescales of many other Quaternary dating techniques has been shown to be feasible, (Millard, 2003) but awaits substantive application. There are many questions and sites relating to the Pleistocene period which could benefit from such extensions. For example, it is rarely possible to directly date hominid fossils either because destructive sampling is not permitted or because non-destructive techniques are unsuitable for producing reliable dates (compare Schwarcz et al. (1998) with Millard and Pike (1999)). Similarly it is difficult with current methods to quantify the duration of the deposition of a particular deposit or the duration of a stone tool industry. It is also difficult at times to determine the likely ordering of events at different sites, for example, given indirect dating evidence for the dates of hominid remains at two sites we cannot quantify their likely ordering or time separation. However if we could estimate the dates (including uncertainty) of the remains using appropriate statistical models, then such comparisons could readily be made.

1.1 Bayesian chronological models

In order to develop suitable models it is necessary to develop an appropriate mathematical apparatus for each dating technique. Given the factorisation in Bayes' theorem, this naturally divides into a technique-independent expression of prior knowledge of dates and a technique-dependent expression for likelihood.

A variety of models have already been developed to express our knowledge of the dating prior to chronometric measurements; some examples are given in Figure 1. Between the start of a phase (α_i) and its end (β_i) it is usually assumed that the chronometric samples are randomly sampled from a set of possible samples laid down at a uniform rate, though other models are possible (Christen et al., 1995). In addition we specify that *a priori* all sets of values of α_i and β_i are equally likely between broad limits. Having specified this prior knowledge, Bayes' Theorem is used to combine it with the chronometric measurements expressed as a likelihood.

Thus to apply Bayesian methods to Pleistocene sites we need only to develop likelihoods for the techniques used. This paper focuses on developing a likelihood for ESR dating and explores its application to the dates reported on excavated materials from Border Cave (Kwa Zulu Natal, South Africa). Section 2 develops a statistical model for ESR dating; section 3 discusses the deposits at Border Cave and a mathematical model for their accumulation; section 4 presents the results of the analysis of the Border Cave ESR dates using this model and discusses their robustness to changes in the assumptions; section 5 discusses the implications of the results for understanding the stone tool industries and hominid remains from Border Cave and more widely the benefits of the new method and future work needed in this area.

A statistical model of ESR Dating

ESR dating depends on the determination of the natural radiation dose to which a sample has been exposed during burial (D_E), and the rate at which that dose was acquired ($\dot{L}$). A more detailed treatment of the measurements and procedures required to obtain these quantities can be found in Rink (1997) and they are only outlined here. If the dose-rate were constant, the dating equation would be simply:

$$\text{age} = \frac{D}{\dot{L}} ,$$

but because of uranium uptake and the build –up of decay products, $\dot{L}$ varies with time, and the age, θ, must be estimated from the equation:

$$D_E = \int_0^{\theta} \cdot$$

Grün et al. (Grun et al., 1987) provide solutions to this equation for ESR dating.

The sample exhibits an ESR spectrum whose intensity depends on the radiation dose it has received since formation of the enamel. This dose, D_E, is determined in the laboratory by measurement of the natural ESR spectrum of the sample and the changes in intensity of the peaks in the spectrum with the application of additional doses of radiation from artificial sources.

The dose rate, $\dot{L}$, is the sum of the rates from a series of sources of radiation, which are measured in a variety of ways:

- the dose-rate from enamel itself, $\dot{D}_{\text{int}}$, determined by measuring the uranium content of the enamel and assuming an uptake history for that uranium;
- the gamma radiation dose-rate from the sediment, $\dot{D}_{\gamma}$, determined either by in-situ gamma-spectrometry measurements or from chemical analysis of the U, Th and K content of the sediment;
- the beta radiation dose-rate from the sediment, $\dot{D}_{\beta}$, estimated from the gamma-spectrometry measurements, or chemical analysis of the sediment, and adjusted for the geometry of the sample using an attenuation factor;
- the dose-rate from any attached dentine or cementum , $\dot{D}_{\text{DE}}$, determined by measuring the uranium content of the dentine or cementum and assuming an uptake history for that uranium.

All of these are measured with an associated error term. $\dot{D}_{\text{int}}$ and $\dot{D}_{\text{DE}}$ have errors unique to each sample. The same is assumed here for D_E although there will be some systematic error in this measurement, due to factors like calibration uncertainty of the artificial radiation sources; these are rarely published and only constitute a minor part of the overall uncertainty, most of which is due to scatter in the measurements and consequent uncertainty in fitting a line to them. $\dot{D}_\gamma$ and $\dot{D}_\beta$ determinations usually apply to groups of dates, so their errors are not independent (i.e. they are correlated or "systematic") between samples in a group. Such dependence needs to be taken into account in any analysis of dates. The values of $\dot{D}_{\text{int}}$ and $\dot{D}_{\text{DE}}$ may have additional uncertainty due to the unknown mode of uranium-uptake, but this will be sample specific. The forms used are usually early uptake (i.e. all U taken up at the time of burial) or linear uptake (U taken up at a constant rate since burial). More complex analyses combine ESR measurements with uranium-series measurements, to constrain the possibilities for U uptake.

A likelihood for ESR dating

The likelihood expresses the probability of the observed D_E values if we knew the true date and the true values of the components of the dose rate. Consideration of the components of the dose rate shows that where there are multiple samples they fall into a hierarchy of groups for these parameters (Figure 2), and therefore also for the associated uncertainties. Until recently (Grün et al., 2003) analyses of ESR dates treated all dates as independent estimates, however it is important to distinguish between dates on several teeth and dates on several samples from a single tooth. In the latter case, the true date underlying the ESR dates must be the same and many of the parameters are the same, so the uncertainty estimates are not independent; in the former case the true dates may differ, but there may be common parameters in the date estimation and therefore the uncertainty estimates are not entirely independent. It is clear that the values for $\dot{D}_{\text{int}}$, $\dot{D}_{\text{DE}}$, and the beta attenuation factor are unique to a measured sample, whilst one true (but unknown) date, θ, is shared by samples from the same tooth. The other parameters derive from measurements on the environment around the samples and are common to different sets of samples. The beta dose-rate from the sediment is estimated from a chemical analysis of the sediment, and is usually applied to several sub-samples of one tooth, or even to several different teeth. However, this assumes that the sediment is homogeneous enough that the single chemical analysis is representative of the dose-rates received by all samples, which may well not be true. Sediment heterogeneity as a potential source of uncertainty is currently not included in ESR date calculations, though it may account for some of the observed scatter in dates from sub-samples of one tooth. Here I follow the assumption that the beta dose-rate from the sediment is common to a group of samples from the same sediment, but each experiences a different attenuation to give $\dot{D}_\beta$. Similar considerations apply to the possible heterogeneity of gamma dose-rates, but on a larger spatial scale. Again these uncertainties are currently unquantified and so I follow the usual assumption that the gamma dose-rate, $\dot{D}_\gamma$, is homogenous on a larger spatial scale, often for all samples from a stratum; this implies that all samples with the same unattenuated sediment beta dose-rate will have the same sediment gamma dose-rate. Finally there is a dose-rate component from cosmic rays, $\dot{D}_{\text{cosmic}}$ which is the same for the whole site, but may be attenuated by differing overburdens of sediment for different samples.

These differing associations of parameter determinations with different subsets of the dated samples are expressed in a statistical model with a hierarchy of parameters. This model is mathematically similar to that derived for archaeomagnetic dating (Lanos, 2001; 2003), though the physical reasons for the hierarchy of uncertainties are different. Thus the model may be expressed as:

$$m_E^{(ijkl)} \,\big|\, \theta \quad {}^{ijkl)}, s_E^{(ijkl)}$$

$$D_E^{(ijkl)} =$$

$$m_\gamma^{(l)} \quad \dot{} \quad {}_\gamma \quad {}_\gamma$$

$$\dot{L}_\beta$$

$$m_\beta^{(kl)} \quad \beta$$

$$m_{\text{int}}^{(ijkl)} \sim N \; \dot{L}_{\text{int}} \quad {}_{\text{int}}$$

$$m_{\text{DE}}^{(ijkl)} \sim N \; \left(\dot{}_{\text{DE}} \quad {}_{\text{DE}} \right)$$

$$m_{\text{cosmic}}^{(l)} \sim N \; \left(\dot{}_{\text{cosmic}} \quad {}_{\text{cosmic}} \right)$$

where i indexes over subsamples of tooth j, from group k of samples with common observed sediment beta dose-rate $m_\beta^{(kl)}$, and from group l of samples with a common gamma dose-rate. Each subsample has a unique beta attenuation factor, $b^{(ijkl)}$ and observed radiation dose, $m_E^{(ijkl)}$. Depending on the site, the cosmic radiation dose-rate may be common to all samples or particular samples. The equation as written assumes that it is common to the same groups as gamma dose-rate. For any source of radiation, Z, m_Z is the observed rate associated with a true underlying value $\dot{L}_Z$, and s_Z is its measured standard deviation. $\beta^{(kl)}$ represents the unattenuated sediment beta dose-rate to a subsample. Following the methods used for radiocarbon dating it is assumed that s_Z is known, and the minor element of uncertainty in this value is ignored. The uncertainties are all assumed to be normally distributed. Ultimately it is the values of the true dates of the teeth, $\theta^{(jkl)}$, and other dates that will be of interest, and calculated by combining the measurements with prior knowledge specified as a probability distribution.

The Bayesian analysis also requires prior probability distributions to be specified for all the unknown, true underlying values of the various $\dot{L}_Z$. Although there may be prior information on these, the calculations are greatly simplified by assuming that all values are equally likely *a priori.* In this case, the prior probability distributions for the $\dot{L}_Z$ can be neglected and the statistical model simplifies with the reversal of many of the equations for m_Z given above, so that general $\dot{L}_Z$ [illegible] $\ldots_Z, s_Z)$, with the slightly modified form $\dot{L}_Z$ [illegible] $b^{(ijkl)} m_\beta^{(kl)}$ [illegible] $_\beta^{(kl)})$, for sediment beta dose-rate.

This set of assumptions and relationships follows those normally used for ESR dating, with the additions of recognising the hierarchically correlated uncertainties and of prior knowledge of dates. There are likely to be systematic biases which are not accounted for in Figure 2, but as these are currently not quantified as uncertainties they cannot be incorporated in any calculation. As always, the results of the analysis cannot be better than its assumptions.

3. The Deposits at Border Cave

The deposits at Border Cave (Kwa Zulu Natal, South Africa) span the Middle (MSA) and Later (LSA) Stone Ages, and have yielded a long sequence of Palaeolithic stone tool industries and four ancient anatomically modern hominid specimens (Grün et al., 1990). The stratigraphic sequence consists of an alternating series of Brown Sands (BS) and White Ashes (WA) with clear boundaries, and differing modes of deposition. Of the hominid remains BC1 and BC2 are of uncertain provenance, they have been linked to either layer 4BS or layer 5BS on the basis of adhering sediment; BC3 is an infant from a grave cut into 4BS which may have been dug during the deposition of layer

1RGBS; BC5 has a secure provenance of layer 3WA (Grün and Beaumont, 2001). All these remains are of undoubted anatomically modern appearance, and thus given that their age indicates contemporaneity with Neanderthals in Europe, they are important in understanding the evolution of modern humans (Stringer, 2002).

The material culture includes a significant deposit of material from the Howieson's Poort (or MSA2) lithic industry, which is considered by some to show a number of 'advanced' aspects with similarities to the African LSA and European Upper Palaeolithic. This industry is thus argued to have a key role in developing our understanding the emergence of modern human behaviour (see for example the discussion in Ambrose and Lorenz, 1990).

3.1 Dating at Border Cave

The sequence is dated by luminescence ages (unpublished), amino-acid racemisation measurements on ostrich eggshells (published only as averages ages for each layer dated - Miller et al., 1999), a few bulk charcoal conventional radiocarbon ages and a series of AMS radiocarbon ages for the upper part (Bird et al., 2003), and a series of 71 ESR determinations (Grün and Beaumont, 2001), making it the most detailed ESR dating sequence available for any site. The ESR chronology of Grün & Beaumont (2001) and the AAR chronology of Miller *et al.* (1999) are summarised as the mean and standard deviation for each stratum are shown in Figure 3. The radiocarbon chronology is not shown as it is currently not possible to calibrate radiocarbon dates beyond 26000BP (van der Plicht et al., 2004). In addition Grün & Beaumont (2001) estimate that hominids BC1 and BC2 date from about 82ka if their provenance is layer 4BS, or 170 ka if their provenance is 5BS, that BC3 is about 76ka old and BC5 66ka. They put the beginning of the Howieson's Poort at Border Cave at 79ka and the end at 60ka, stating that "the duration of the Howieson's Poort seems somewhat longer (around 20 ka) than usually assumed (around 10 ka…)". More recently (Grün et al., 2003) have directly analysed a fragment of enamel from the BC5 specimen and obtained an ESR date of 74 ± 5 ka, confirming its provenance and disproving claims that it could be Iron Age in date (Sillen and Morris, 1996). Grün et al. (2003) have also added a cosmic ray dose contribution to the date calculation, which decreases their previously reported ages by 2-4%.

3.2 Stratigraphic model

The stratigraphic model adopted is a simple one of continuous deposition with no hiatus between adjacent strata, with within stratum deposition continuous and uniform in rate (c.f. Zeidler et al., 1998). (Figure 1 top). This is not the only possible model: eventually it would be worth comparing with a model which allowed for some hiatus between the major strata, as Grün & Beaumont (2001) suggest that there is evidence from the dates for four hiatuses, although I cannot identify them visually on plots that include all dates with uncertainties (e.g. Figure 4 thin bars), except possibly from the spread of dates for layer 4WA. Thus the analysis here assumes that the end of one WA or BS stratum is at the same time as the beginning of the next, and that the deposition within one of those strata is continuous and relatively uniform in rate. The hierarchy of beta and gamma dose-rate estimates in common was derived from the published sediment U, Th & K contents. The dose and dose-rate data of Grün & Beaumont (2001) were used with the addition of cosmic ray dose-rate from (Grün et al., 2003). The direct date for BC5 was not included in the analysis.

The statistical model is used to directly estimate the dates of the samples and the stratigraphic boundaries, given the dating information and stratigraphic ordering. In addition, it is possible to calculate other figures derived from these dates, giving date estimates for the hominids (assuming that they lie within a certain strata) and for the beginning, end and duration of Howieson's Poort Industry.

In order to test the sensitivity of the results to changes in the assumptions, various different analyses were conducted. All analyses were conducted assuming continuous deposition, as described above. In addition, as there is very little uranium uptake in these samples, the analyses follow Grün & Beaumont (2001) in using only early uptake dose-rate estimates. The primary analysis divided the site by the WA and BS divisions of the stratigraphy and omitted two outlying ESR dates identified by Grün & Beaumont (2001). In addition analyses were conducted with the two outliers included, and dividing the site into larger units according to the archaeologically identified industries. For comparison, analyses were also conducted in OxCal, treating the ESR dates reported in Grün & Beaumont (2001) as independent age estimates.

Because in this statistical model complex numerical integration is required to obtain the posterior distribution, Markov-Chain Monte Carlo (MCMC) methods are used to evaluate it. MCMC is a method for simulating possible values from the posterior distribution and is particularly suited to problems where this distribution cannot be written as an explicit mathematical function. Many thousands of draws are made and the resulting distribution of values is a good approximation to the true distribution. This model has been evaluated using WinBUGS, a program which allows the MCMC technique to be conducted in a user-friendly environment (Lunn et al., 2000;

Spiegelhalter et al., 2000; Spiegelhalter et al., 2004). WinBUGS code for the implementation of the models described is available from http://www.dur.ac.uk/a.r.millard/BUGS4Arch/ . All results are reported here as 95% highest posterior density (HPD) estimates, which is both the shortest range where the posterior distribution has 95% probability and a range where the probability density is always higher within the range than outside it.

Results

Results derived using the primary model of geological strata with the omission of the outliers are shown in Figure 4 as posterior estimates for the dates and phase boundaries after taking into account our prior knowledge of the stratigraphy. Table 1 shows the 95% HPD for other dates and spans of interest. Before discussing these results in detail, it is necessary to examine their sensitivity to some of the modelling assumptions.

Sensitivity tests

The addition of the two outliers to the dataset makes little difference to the estimates of the parameters of interest, except the dates of layer boundaries close to the dates, which shift by up to 3ka, or less than 6%, and whose mean values for one analysis lie within the 95% HPD for the other analysis. (Result not shown.)

Simplifying the stratigraphic scheme to the archaeological periods rather than the excavated strata alters the results for the start and end dates of the periods slightly. The dates for the beginning and end of the Howieson's Poort results in this case are most sensitive to the inclusion of the outliers, and so the duration of that industry becomes quite sensitive. The estimated duration of the Howieson's Poort industry is reduced quite significantly for the archaeological period model (from a mean of 14.1ka with 95% HPD 6.3-22ka for the primary model to mean 7.7ka and 95% HPD 0.3-16.6ka), but increases again when the outliers are included with archaeological periods (mean 11.5ka, 95% HPD 3.0-19ka). An analysis in *OxCal* treating the published dates as independent and normally distributed gives very similar mean values for the estimates of the phase boundaries (within 1ka whichever model is used), but reduced uncertainties on those estimates, as is to be expected when the correlations in the uncertainties of the dates are ignored.

There is therefore some sensitivity to the choice of model, but in the parameters of interest, only the length of the Howieson's Poort industry shows significant sensitivity. Full results for all models are therefore not shown, and the results discussed below were derived using the primary model of geological strata and omitting the outliers, unless otherwise indicated.

Discussion

The results show that incorporation of evidence for the ordering of dates is now possible for sites with ESR chronologies, and allows reduction in the uncertainties associated with individual dates, and the estimation of dates for events which cannot be directly dated. These results are achieved by a statistical model with minimal additional assumptions (e.g. a roughly uniform rate of deposition in a stratum, and reliability of the provenance of dated samples). With radiocarbon dates these assumptions can interact with the calibration curve to produce undesirable effects (Steier and Rom, 2000) but for ESR dates there is no calibration curve with plateaux to cause lengthening of chronologies. Nicholls and Jones (2001) have shown that with few dates relative to the number of strata and short occupation of a site, the use of a prior probability on strata start and end dates which is uniform over a large span can lead to overestimation of the duration of occupation. This effect is in principle possible with ESR dates but will be minimal at sites like Border Cave where there are a large number of dates compared to the number of strata.

At Border Cave the results of the reanalysis of the ESR dates allows us to specify dates, including uncertainty for the hominid specimens (Table 1). Previous point estimates all fall within the 95% HPD of the new estimates, though Grün and Beaumont's (2001) date for fossils from layer 5BS appears somewhat old for a point estimate. The new dates have the advantage of a clear statement of uncertainty, allowing better comparisons with other sites, for example, BC1 and BC2, if derived from layer 4BS, are shown possibly to be contemporary with the remains from Qafzeh, Israel dated at 92±5 ka by TL dating of burnt flint (Valladas et al., 1988) with corroborating ESR dates (Schwarcz et al., 1988).

The statistical model also allows examination of the full probably distribution of a parameter. As an example the probability distribution for the length of the Howieson's Poort Industry is shown in Figure 5. Evaluation of the likely length of the Howieson's Poort is of particular interest given the debate about its duration. The results of this study show that the current dating evidence from Border Cave is not sufficient to resolve the question of a 10ka versus a 20ka length. The value obtained is quite sensitive to small changes in the model due to the fact that the length of the Howieson's Poort is found from the difference in dates of two events which themselves have uncertainties of a few millennia and changing the assumptions moves the estimates for each of these events by a couple of millennia in different directions. In fact it seems unlikely that ESR dating will ever resolve the difference between the difference between the 10ka and 20ka estimates for the duration of HP. Consider that if we knew the start and end dates of the HP with a standard deviation of just 3ka, then the length estimate will have a standard deviation of approximately 4.2ka and the 95% confidence interval for the length will be of the order of 17ka centred on some mean value. With such imprecision we are unlikely to be able to decide between hypotheses which differ by only 10ka.

At Border Cave it would be interesting and useful to incorporate all the other dating information into the analysis. Unfortunately it is not currently possible to calibrate reliably radiocarbon dates of greater than 26,000BP (van der Plicht et al., 2004), so they cannot be straightforwardly incorporated. The other dating information at Border Cave comes from unpublished TL dates, which are not available to the scientific community for evaluation, and AAR dates. Regrettably the AAR dates are available only as mean and standard deviation racemisation values (with corresponding ages) for each layer dated, which prevents their incorporation into a model which relies on evaluation of the distribution of dates. This contrasts with the ESR dates which analysed here which were published with full details of the parameters required for the calculation of individual ages.

Conclusion

This paper has shown that the tool currently used in Bayesian analysis of radiocarbon dates can be extended to ESR dating, introducing the benefits of stratigraphic analysis and improved precision to Pleistocene sites. With future development of statistical models to calculate appropriate likelihoods for other techniques it should be possible to create integrated chronologies incorporating all chronometric evidence, thus improving the resolution of dating and our understanding of processes.

Acknowledgements

This paper has its origins in a poster presented at the Quaternary Research Association Discussion Meeting in January 2002. It was written during research leave funded jointly by the University of Durham and the Arts and Humanities Research Board (award number RLS:APN15253/AN9564). The comments of an anonymous referee and Rainer Grün were helpful in clarifying the discussion of common beta and gamma dose-rates.

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Figure 1: Some possible models expressing prior knowledge of dating

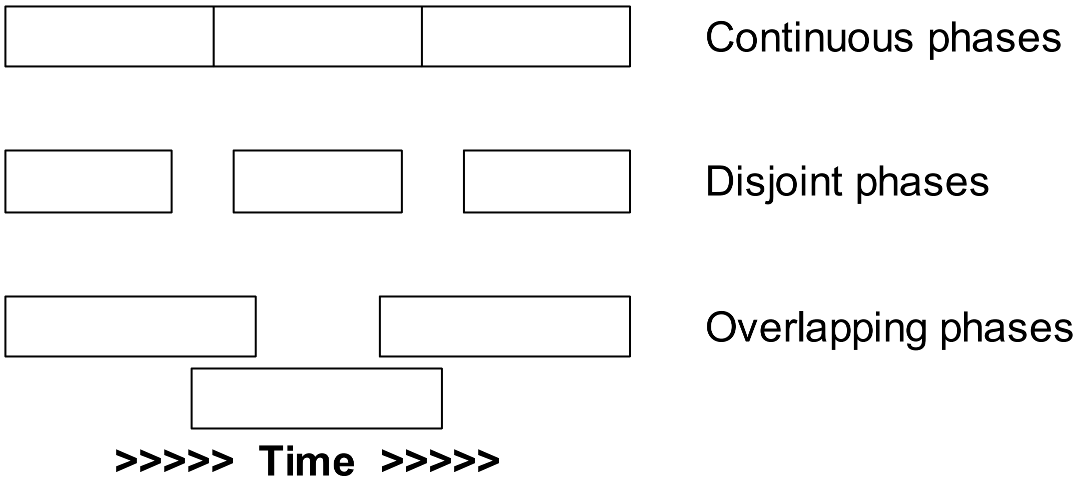

Figure 2: The hierarchy of parameters in common between different dating samples. Each inner box is repeated within the box surrounding it, with different values of the parameters for different samples.

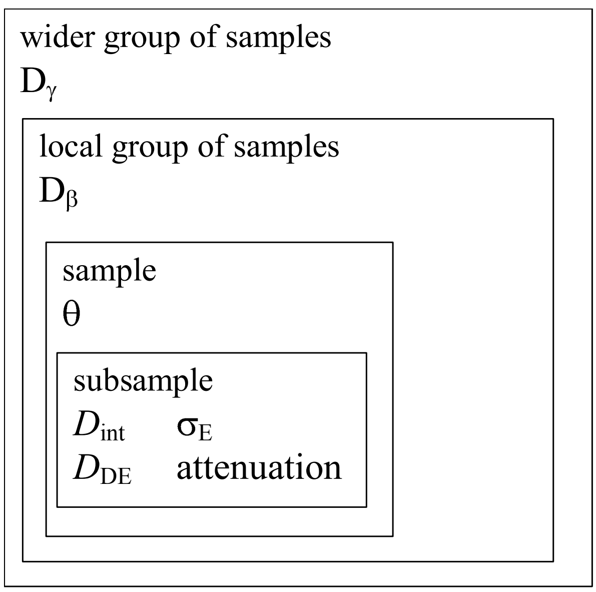

Figure 3: Previous estimates for the dates of strata at Border Cave, showing uncertainty at two standard deviations. Black lines: mean ESR dates (Grün and Beaumont, 2001). Grey lines: mean AAR dates (Miller et al., 1999).

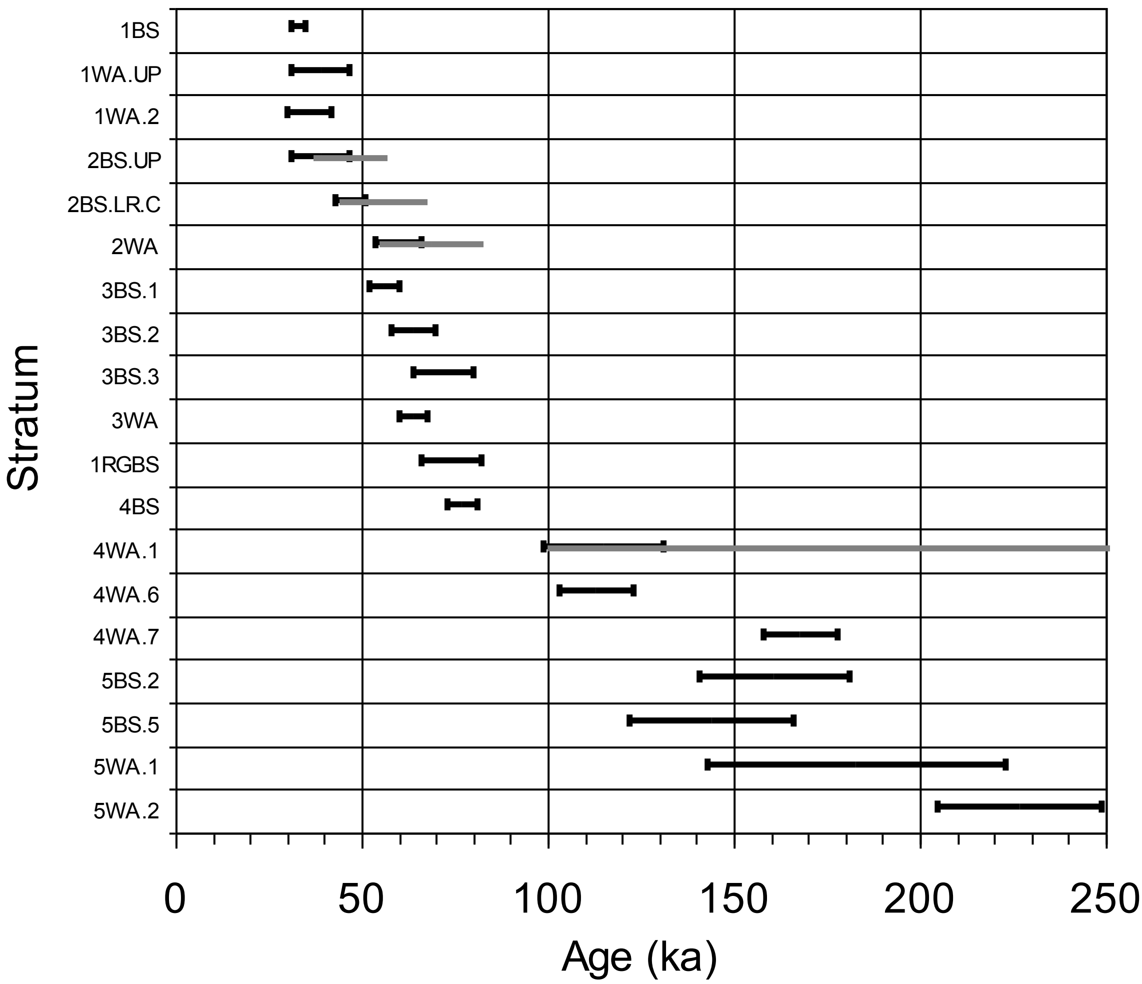

Figure 4: ESR dates and modelled chronology at Border Cave. Thin black lines: dates without model from Grün & Beaumont (2001), excluding two outliers (see text); thick black lines: dates with stratigraphic model; grey lines: modelled phase boundary dates. Modelled dates shown as 95% hpd ranges, original dates as plus or minus two standard deviations. Where there are sub-samples (a, b, c) from a tooth the single modelled date for the tooth is shown under sub-sample a.

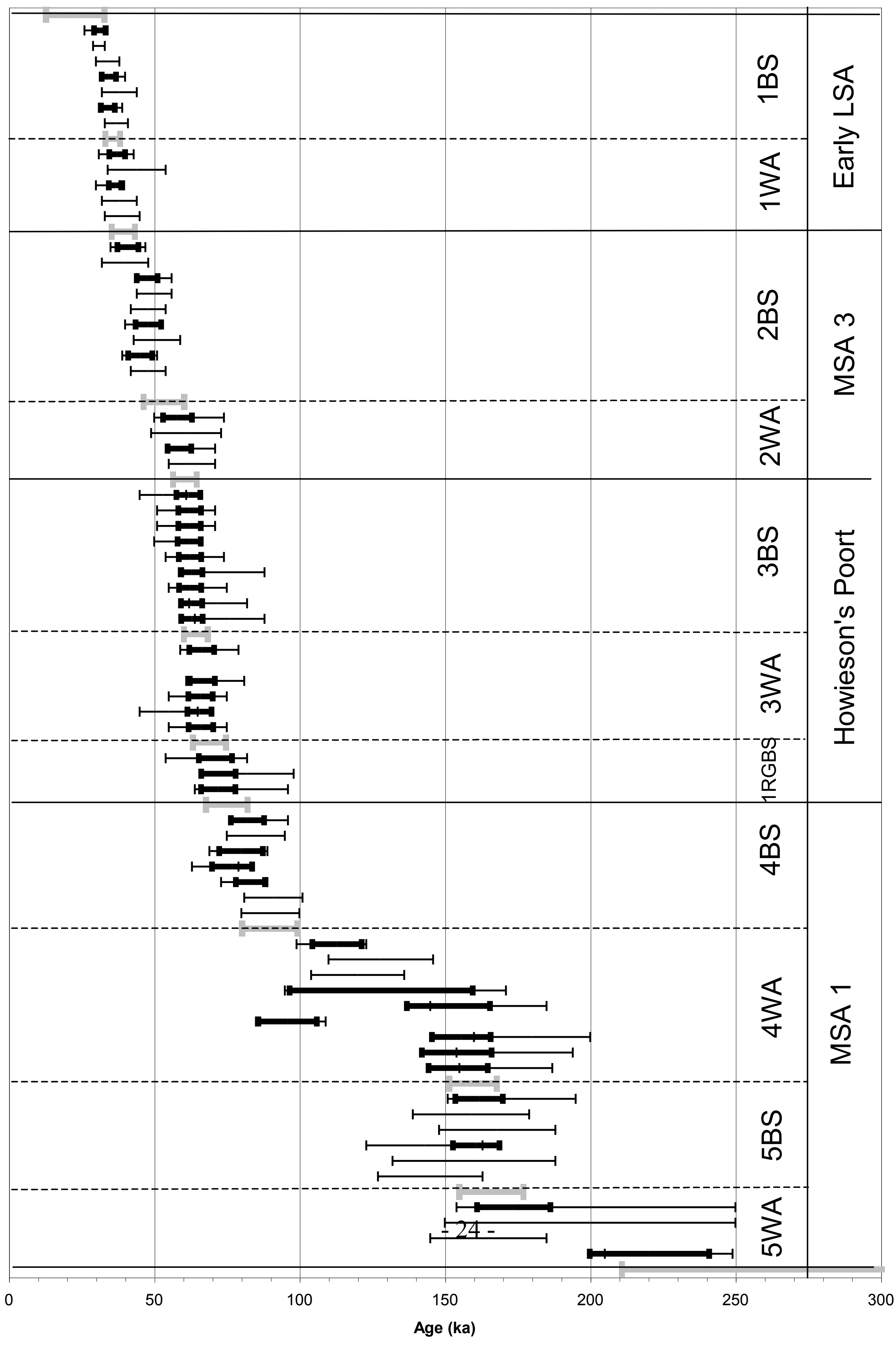

Figure 5: Probability distribution for the length of the Howeieson's Poort Industry at Border Cave.

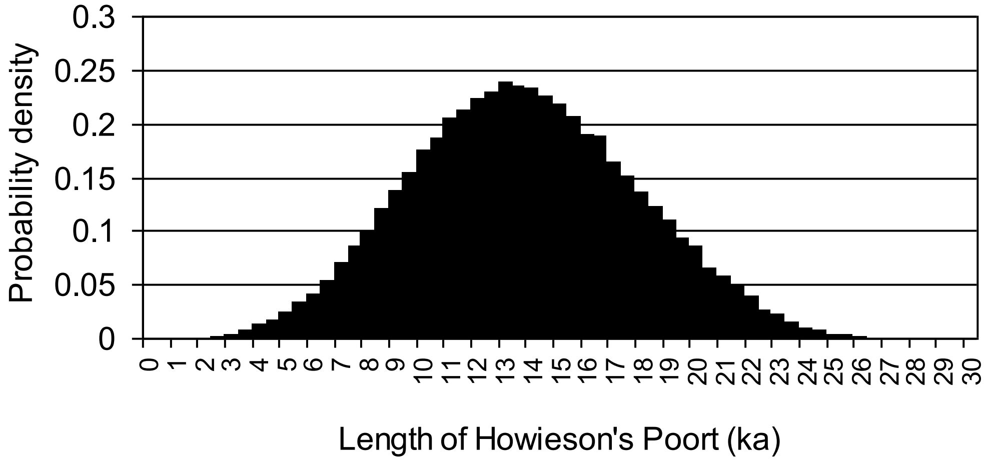

Table 1: 95% highest posterior density regions for the dates of selected events of interest at Border Cave.

	Grün and Beaumont (2001)	Miller *et al.* (1999)	Grün *et al.* 2003	This study (95% highest posterior density)
start of Howieson's Poort	79ka	80ka	76ka	68-82ka
end of Howieson's Poort	60ka	56ka	58ka	56-65ka
length of Howieson's Poort	20 not 10ka			6.3-22ka
BC 1 & 2 if from 4BS	82ka	>100ka		71-91ka
BC 1 & 2 if from 5BS	170ka			152-171ka
BC3	76ka			66-90ka
BC5	66ka		74±5ka	61-72ka