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A re-analysis of the Lake Suigetsu terrestrial radiocarbon calibration dataset

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ABSTRACT

Lake Suigetsu, Honshu Island, Japan provides an ideal sedimentary sequence from which to derive a wholly terrestrial radiocarbon calibration curve back to the limits of radiocarbon detection (*circa* 60 ka bp). The presence of well-defined, annually-deposited laminae (varves) throughout the entirety of this period provides an independent, high resolution chronometer against which radiocarbon measurements of plant macrofossils from the sediment column can be directly related. However, data from the initial Lake Suigetsu project [1–3] were found to diverge significantly from alternative, marine-based calibration datasets released around the same time (e.g. [4,5]). The main source of this divergence is thought to be the result of inaccuracies in the absolute age profile of the Suigetsu project, caused by both varve counting uncertainties and gaps in the sediment column of unknown duration between successively-drilled core sections.

Here, a re-analysis of the previously-published Lake Suigetsu data is conducted. The most recent developments in Bayesian statistical modelling techniques (OxCal v4.1; [6]) are implemented to fit the Suigetsu data to the latest radiocarbon calibration datasets and thereby estimate the duration of the inter-core section gaps in the Suigetsu data. In this way, the absolute age of the Lake Suigetsu sediment profile is more accurately defined, providing significant information for both radiocarbon calibration and palaeoenvironmental reconstruction purposes.

1. Introduction

There are many useful archives from which radiocarbon (^{14}C) calibration curves can be developed. Tree-ring records provide an important repository of such information since their annual growth bands provide an almost perfect calendar year age, whilst the same material can be directly analysed for their ^{14}C measurements. At present, the limits of the absolute age scale of radiocarbon calibration based upon this dendro-record extends only to 12,593 calendar years bp ([7], an extension of 183 years from that included in IntCal04 [8]), however, and so other sources must be examined to extend radiocarbon calibration further back in time. Chief amongst these alternative archives is the partially varved sedimentary record from the Cariaco Basin [9]. Another such archive is provided by uranium series-dated corals (e.g. [10] working on sites in the Bahamas). Whilst extremely useful, such records provide information on radiocarbon calibration in the oceans, rather than the atmosphere. Although atmospheric ^{14}C concentration ($\Delta^{14}C$) can be approximated from such marine archives, a correction factor for the 'marine reservoir effect' of radiocarbon must necessarily be applied. Since the marine reservoir age is known to vary both temporally and spatially [11], such approximations for atmospheric radiocarbon therefore contain an additional tier of uncertainty.

The annually laminated (varved) sediments of Lake Suigetsu, Honshu Island, central Japan (35°35′N, 135°53′E, 0 m a.s.l.) provide an ideal sequence from which to derive a wholly terrestrial record for radiocarbon calibration through dating of plant macrofossils identified within its sedimentary strata. Such data were presented by Kitagawa and van der Plicht [1–3], however comparison with the aforementioned marine-derived calibration data [4,5] yielded unexplained discrepancies. Fig. 1 demonstrates the divergence of the original Lake Suigetsu data presented by Kitagawa and van der Plicht from the more recent marine-based calibration data of Hughen et al. [9] and Fairbanks et al. [10]. It can be seen that this divergence is particularly pronounced further back in time, especially beyond *circa* 25 cal. ka bp.

2. Main issues to be addressed

It is unlikely that such a systematic divergence between the Lake Suigetsu dataset and the marine-based radiocarbon calibration datasets represents a 'real' offset between these respective archives. The more likely causes of divergence are in

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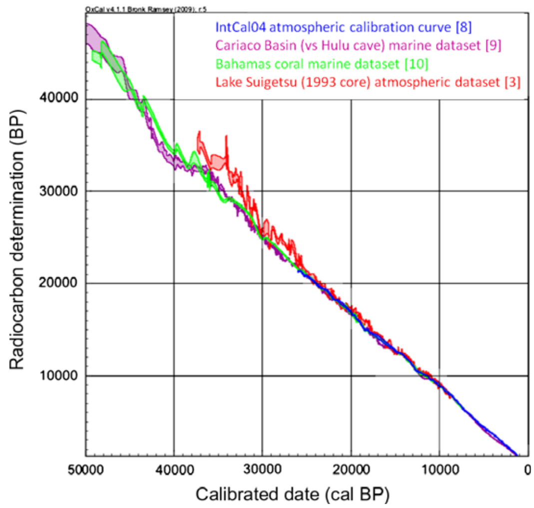

Fig. 1. The Lake Suigetsu radiocarbon calibration dataset of Kitagawa and van der Plicht [3] as compared with the alternative calibration data of IntCal04 [8], Hughen et al. [9], and Fairbanks et al. [10]. All curves are plotted with 1σ uncertainties.

the 'absolute age' of the Lake Suigetsu record: firstly, in the accuracy of the varve counting itself; and secondly, due to the core-drilling methodology applied [12]. The former issue is not due to the nature of the Suigetsu sediments themselves – the sediment profile still provides annual resolution throughout the time period in question – rather, it is a function of the varve counting methodology, which was only based on surface reflectance in the original study. The latter issue meant that since sediment was removed in sections from a single borehole, there was the potential for material to be lost from between core sections, generating gaps in the absolute age profile of the composite core of unknown duration. (Both matters have been remedied in the re-coring of Lake Suigetsu, as undertaken by Suigetsu 2006 Project Members, which should properly resolve the issues mentioned herein.)

The remainder of this paper provides a statistical modelling approach to demonstrate both the likely sources of error in the original Lake Suigetsu study, and the enduring usefulness of the information (over 280 radiocarbon determinations) pertaining to the extension of the ^{14}C calibration curve beyond the tree-ring limits that is nevertheless represented by the Kitagawa and van der Plicht dataset.

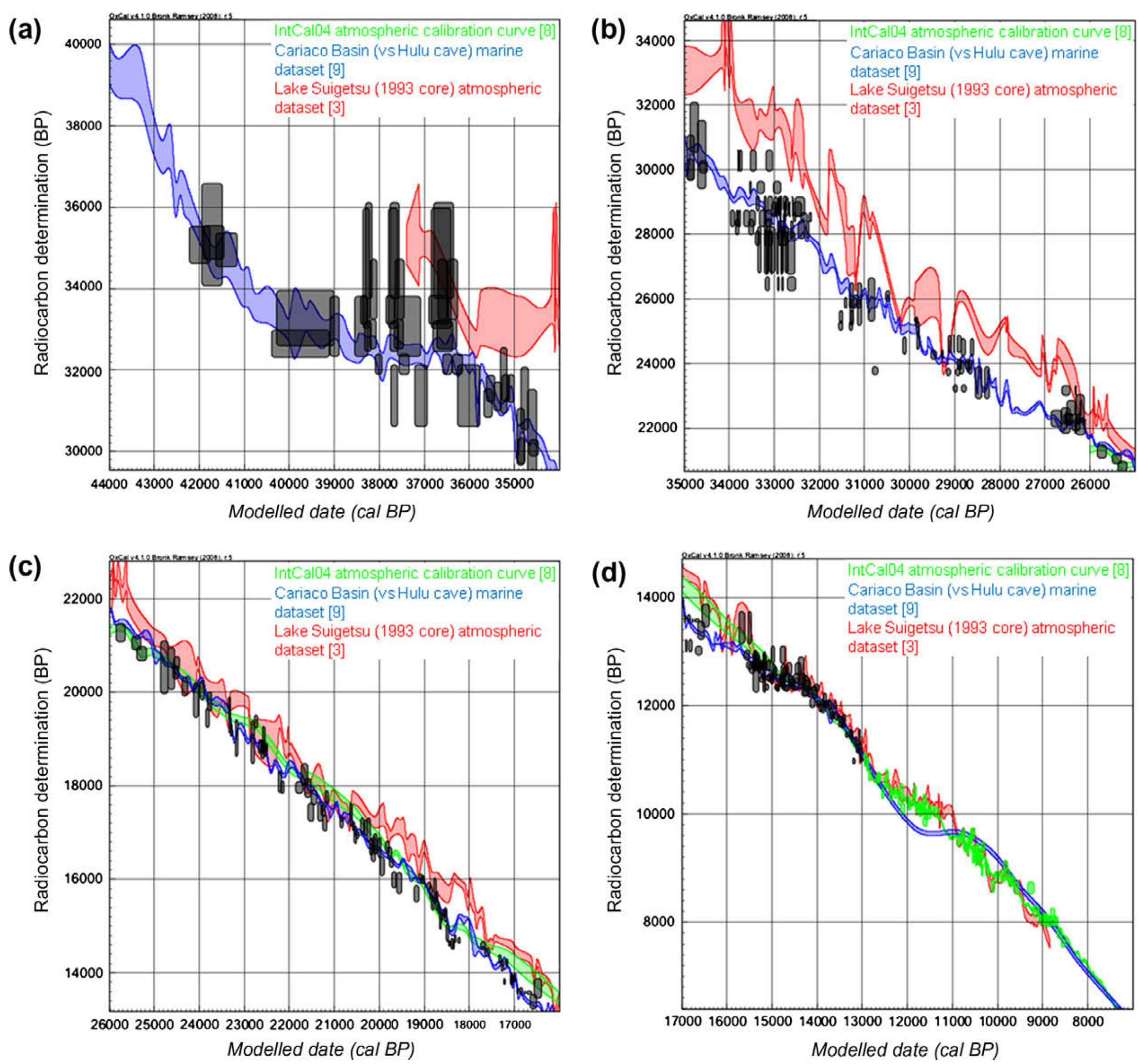

Fig. 2. The re-modelled data of Kitagawa and van der Plicht [3] as calibrated against IntCal04 [8] (Suigetsu core sections SG13 to SG17) and the Cariaco Basin record [9] (Suigetsu core sections SG18 to SG34) shown for: (a) 34–44 cal. ka bp; (b) 25–35 cal. ka bp; (c) 16–26 cal. ka bp; and (d) 7–17 cal. ka bp. The data are plotted with 1σ uncertainties shown, as are the original, unaltered Kitagawa and van der Plicht data (i.e. without intervals inserted between core sections).

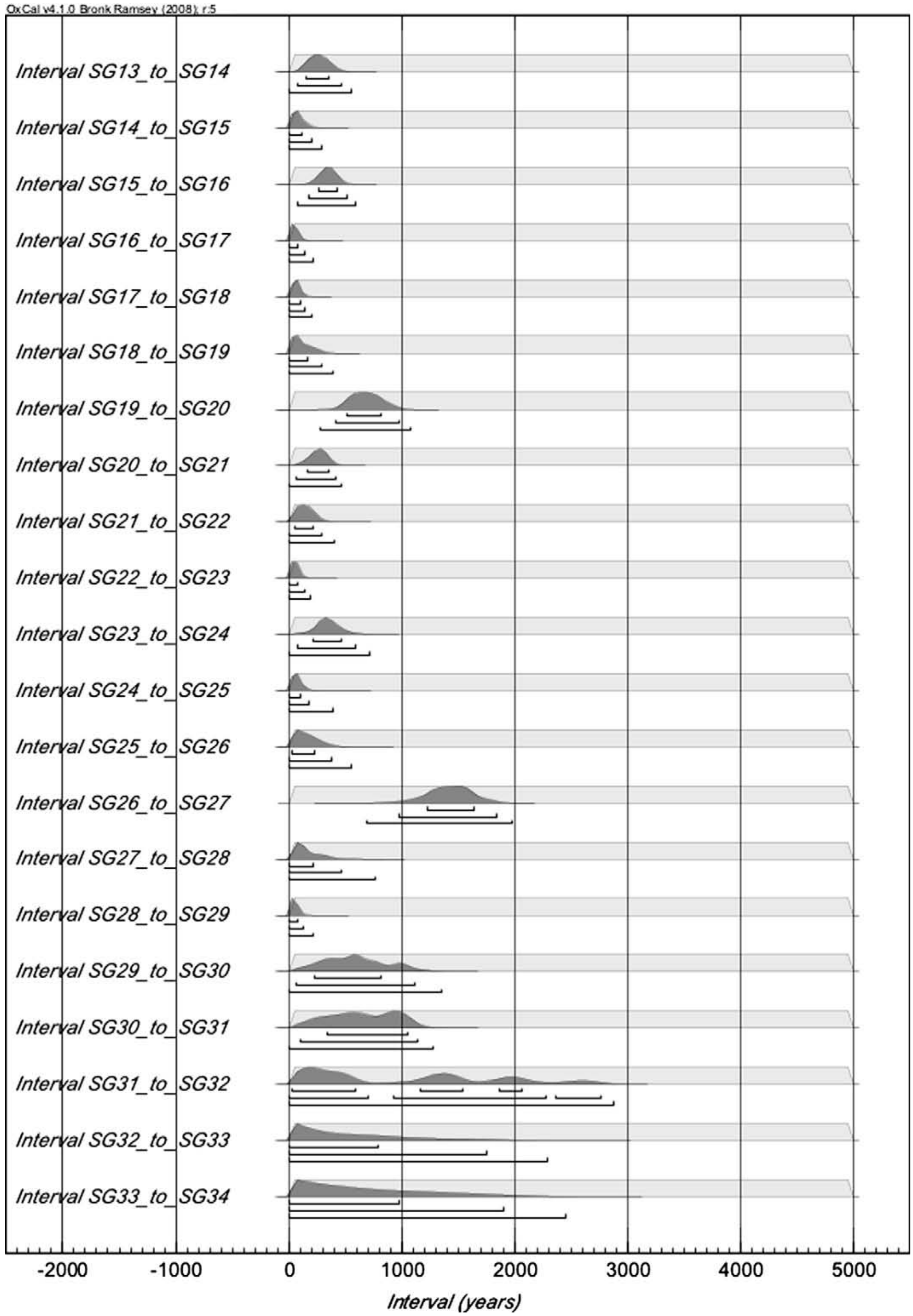

Fig. 3. The inter-core section gaps identified in the Lake Suigetsu dataset [3]. The prior distributions are given in light grey, whilst in darker grey the posterior distributions are shown, taking into account the full gamut of information contained within the model. Whilst the majority of intervals are found to be short, there are examples where the gaps are found to exceed 1000 years in duration (e.g. between core sections SG26 and SG27). The horizontal bars below each probability distribution represent the posterior 1σ, 2σ, and 3σ probability ranges, respectively.

3. Bayesian modelling

The original Lake Suigetsu data (kindly provided by Kitagawa and van der Plicht) were re-modelled, using the latest version of the Bayesian calibration program OxCal (version 4.1, [6]). All 280 radiocarbon determinations were included, with outlier analysis applied to objectively down-weight those dates most likely to be suspect. For the younger portion of the Lake Suigetsu dataset, the IntCal04 [8] calibration curve was applied. Beyond the portion of IntCal04 based upon the tree ring record, the Lake Suigetsu data were calibrated to the Cariaco Basin dataset, as matched to the Hulu cave $^{230}Th/^{234}U$ timescale [9].

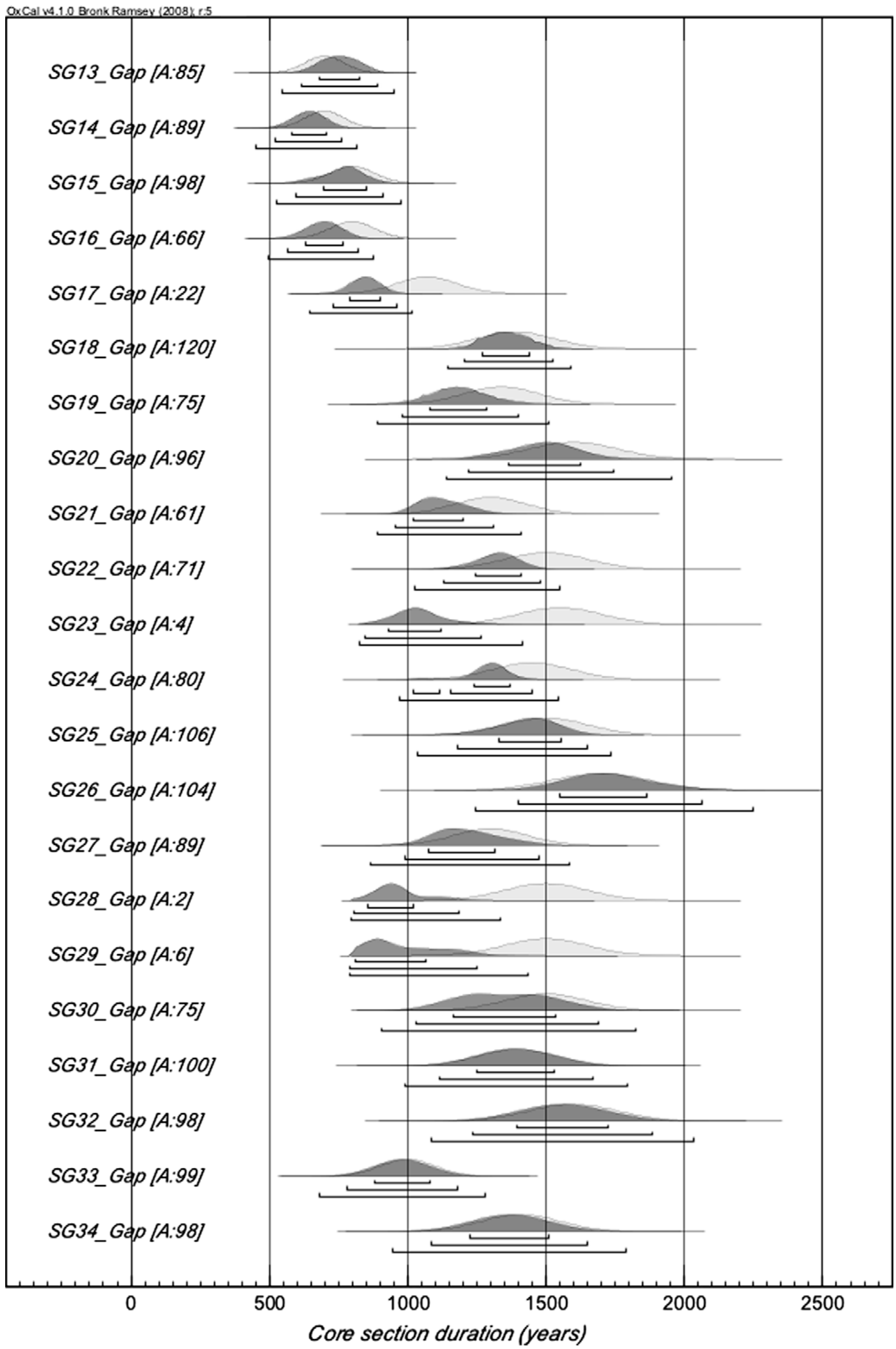

Fig. 4. Comparison of the prior distributions (light grey) for the duration of each Lake Suigetsu core section (as based upon the original varve-counted data), and the posterior distributions (dark grey, as generated from the modelling exercise described herein). Agreement indices (in parentheses) exceeding 60.0 represent a good fit, whilst those falling below this value represent ill-fitting data [14]. Here, such core-section examples (notably sections SG23, SG28 and SG29) are interpreted as areas where the reliability of the original varve counting should be questioned.

The model used the '*r-type*' outlier detection approach [6], which allows for short-term fluctuations in the ^{14}C concentrations between the respective radiocarbon reservoirs of the sample data (from Lake Suigetsu) and the calibration curve datasets (IntCal04 tree ring- and Cariaco Basin datasets). As with subsequent terms initially given in quotation marks and italics, '*r-type*' is a specific term to OxCal; however, in the majority of instances alternative calibration programs will have their own commands that essentially perform the same function. The scale of the outlier model was allowed to be anywhere in the range 10^0–10^4 years, and the student-*t* distribution (with 5 deg of freedom) applied to allow for longer tails on the outlier distributions. An arbitrary value of 5% was assigned to each of the 280 radiocarbon dates entered into the modelling exercise, giving each determination an equal *a priori* probability of being an outlier. Since none of the Suigetsu samples are from a questionable stratigraphic context, there is no reason to suppose that particular determinations are more likely to be 'rogue' than others.

The original varve-counted values were used as the unit of depth (so as to take account of such event layers as those related to earthquakes or floods, as well as the regular inter-annual variations in sedimentation rate). '*Boundaries*' were applied at the top and bottom of each of the 22 core sections from which the 280 radiocarbon dates were drawn, and '*intervals*' placed in between each. These *intervals* were given uniform distributions of between 0 and 5000 years, such that the values of the posterior probability distributions of the *intervals* generated were not curtailed.

The durations of each section of Suigetsu core were constrained to vary normally around the varve-counted values given by Kitagawa and van der Plicht. An arbitrary σ value of 10% was applied to this distribution to allow sufficient flexibility for divergence from those varve-counted values.

A '*P_sequence*' deposition model was applied [13]. Such a model was selected over the '*D_sequence*' or '*V_sequence*' specifications since these two alternatives require that the exact age differences between dates are known precisely, or at least that their uncertainties are very well-defined, and since the varve-counted depth scale was one of the most likely sources of error in the original study, the application of a *P_sequence* was deemed more appropriate. The '*k*' value applied to a *P_sequence* can be altered to determine how much the model allows the sedimentation rate to vary. Here, the value of *k* was determined to equal 0.4 (from Eq. (A.17) of [13]), such that the uncertainty at the mid-point of a core section of duration 1000 years (a representative value for the Suigetsu core sections) is 5% (consistent with the arbitrary 10% uncertainty applied to the duration of an entire core section).

4. Results and discussion

With intervals of unknown duration inserted between core sections, the Lake Suigetsu data can be 'pulled' to match far more tightly the tree ring-/Cariaco Basin varve-based radiocarbon values to which the former data are calibrated (Fig. 2). It can be clearly seen (Fig. 3) that whilst some inter-core section intervals are minimal, others are much larger, with over 1000 year gaps predicted in certain instances. This represents a depth of over 50 cm of missing material from the sedimentary record (based upon a mean annual deposition of ~0.61 mm [1]).

The present exercise is purely statistical in nature, using only the original varve-counted depth information and ^{14}C determinations of [3]. It has been suggested by the original authors (Kitagawa, personal communication) that the more likely reason for the disagreements between the Suigetsu data and the alternative calibration datasets is error in the varve counting itself, rather than in missing sediment due to the core-drilling methodology. Agreement between the varve-counted core-section durations and that predicted by OxCal, based upon the radiocarbon determinations of macrofossils within it (Fig. 4), is generally very good, and would tend towards support for the original varve counting. Four of the 22 core sections are, however, found to demonstrate poor agreement between the prior and posterior information (as determined in OxCal by agreement indices, *A*, of <60.0 [14]). In each of these instances the modelled core-section durations are found to be shorter than the varve-counted values, suggesting that errors in varve counting are tending towards the inclusion of additional

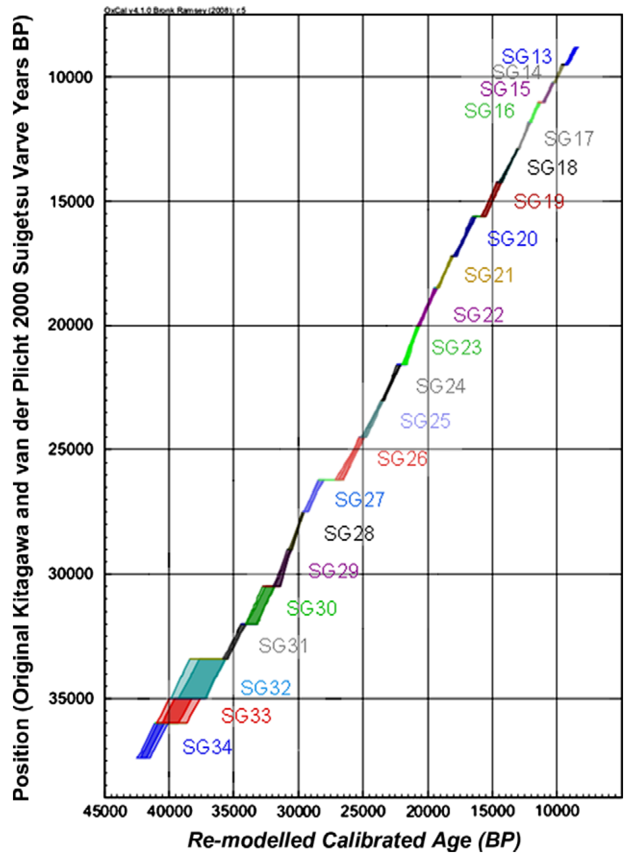

Fig. 5. Age-depth model output given at 1σ and 2σ ranges. The upper core sections (SG13 to SG16) are calibrated against IntCal04 [8] and the lower core sections (SG17 to SG34) against the Cariaco Basin record [9].

'years', perhaps through the inclusion of inter-annual laminations. Varve-count errors of this nature would not be responsible for the divergence of the original Lake Suigetsu data from the alternative calibration records since their correction would foreshorten the Suigetsu dataset yet further as compared to these records. From the present modelling exercise, therefore, it would appear that the explanation for the discordance of the Lake Suigetsu calibration dataset is that of missing sections of sediment.

In terms of the outlier analysis applied, only six of the 280 radiocarbon dates were found to yield $\geqslant$95% probability of being outlying (and only two further dates $\geqslant$90%), whilst 205 of the 280 dates were given a posterior probability of $\leqslant$5% of being outliers (as compared to the arbitrary 5% prior probability applied). Such findings support the validity of the individual radiocarbon determinations themselves, and do not suggest any systematic bias in the methodology of Kitagawa and van der Plicht.

Whilst the present exercise undoubtedly contains a degree of circularity in the assumptions made, particularly since calibrating the one dataset onto the other should inevitably produce strong correspondence, the fact that the revised age-depth profile for the Suigetsu data (Fig. 5) remains highly linear (albeit with occasional 'steps', where OxCal has identified more significant inter-core section gaps), lends support for this profile being authentic, and therefore for the correspondence to be genuine.

5. Conclusion

The close correlation between the revised Lake Suigetsu dataset (generated herein) and the existing radiocarbon calibration datasets both lends support for the latter, as well as suggesting that the new radiocarbon calibration data being generated from the

Lake Suigetsu sediment profile (Suigetsu 2006 Project Members) will indeed provide an accurate extension to the terrestrial radiocarbon calibration curve, right back to the limits of the method (*circa* 60 ka bp).

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