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INTEGRATION OF THE OLD AND NEW LAKE SUIGETSU (JAPAN) TERRESTRIAL RADIOCARBON CALIBRATION DATA SETS

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ABSTRACT. The varved sediment profile of Lake Suigetsu, central Japan, offers an ideal opportunity from which to derive a terrestrial record of atmospheric radiocarbon across the entire range of the ^{14}C dating method. Previous work by Kitagawa and van der Plicht (1998a,b, 2000) provided such a data set; however, problems with the varve-based age scale of their SG93 sediment core precluded the use of this data set for ^{14}C calibration purposes. Lake Suigetsu was re-cored in summer 2006, with the retrieval of overlapping sediment cores from 4 parallel boreholes enabling complete recovery of the sediment profile for the present "Suigetsu Varves 2006" project (Nakagawa et al. 2012). Over 550 ^{14}C determinations have been obtained from terrestrial plant macrofossils picked from the latter SG06 composite sediment core, which, coupled with the core's independent varve chronology, provides the only non-reservoir-corrected ^{14}C calibration data set across the ^{14}C dating range.

Here, physical matching of archive U-channel sediment from SG93 to the continuous SG06 sediment profile is presented. We show the excellent agreement between the respective projects' ^{14}C data sets, allowing the integration of 243 ^{14}C determinations from the original SG93 project into a composite Lake Suigetsu ^{14}C calibration data set comprising 808 individual ^{14}C determinations, spanning the last 52,800 cal yr.

INTRODUCTION

Calibration of radiocarbon data is achieved through comparison of measured ^{14}C determinations with those of samples of known calendar age. Such calibration data sets have been derived from a range of natural paleoenvironmental archives, providing records of atmospheric ^{14}C concentration (Δ^{14}C) through time. For inclusion in the internationally ratified ^{14}C calibration curve (IntCal13, Reimer et al., this issue), such records must also provide a reliable, independent means of deriving calendar age, against which the ^{14}C determinations can be directly compared. For the last 12,550 cal yr, dendro-

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chronologically dated tree-ring data are used for this purpose (IntCal09, Reimer et al. 2009). However, this leaves approximately three quarters of the ^{14}C timescale to be calibrated via alternative marine records, which incorporate additional uncertainties relating to the temporally and spatially variable "marine reservoir effect" (Suess 1955; Mangerud 1972; Stuiver et al. 1986; Reimer and Reimer 2001). Similarly, speleothem data (demonstrated most extensively by Hoffmann et al. 2010 and Southon et al. 2012) require correction (for the dead carbon fraction [DCF] from geologically old carbonate), which, like the marine correction, incorporates additional uncertainties.

Ideally, the ^{14}C calibration curve would be composed of reservoir-free, terrestrial ^{14}C data across the entire range of the method. However, archives that provide such a data set are scarce. In 1998, Kitagawa and van der Plicht (1998a,b, 2000) published the first such record, composed of ^{14}C measurements of terrestrial macrofossils extracted from the varved sediment profile of Lake Suigetsu, Honshu Island, central Japan (35°35′N, 135°53′E). However, problems with the varve-based calendar age scale of their "SG93" sediment core precluded the widespread adoption of this data set for calibration purposes. These problems resulted primarily from gaps between successively drilled sections of the core, but were also due to uncertainties in the varve counting itself (van der Plicht et al. 2004; Staff et al. 2010). Therefore, Lake Suigetsu was re-cored in 2006, with the retrieval of 4 parallel, overlapping sediment cores this time enabling complete recovery of the sedimentary sequence and the subsequent construction of the new "SG06" composite sediment profile (Nakagawa et al. 2012). Over 550 ^{14}C determinations have been obtained from terrestrial plant macrofossils picked from SG06, which have been coupled with the core's improved, independent varve chronology (produced through the integration of 2 complementary counting techniques; Marshall et al. 2012; Schlolaut et al. 2012) to provide what is still the only non-reservoir-corrected ^{14}C calibration data set across the entire ^{14}C dating range (Bronk Ramsey et al. 2012).

Although the varve-based age scale of SG93 has been demonstrated to be compromised, the ~250 ^{14}C determinations from the core remain sound. Therefore, if the 2 sediment cores could be reliably linked, a higher-resolution combined ^{14}C calibration data set could be provided. Here, a physical comparison between the SG93 and SG06 sediment cores is described, enabling such an integration of the respective ^{14}C data sets to be achieved (as has been recently published by Bronk Ramsey et al. 2012).

METHODS

As with the construction of the composite SG06 sediment profile from the 4 contributing, parallel cores (Nakagawa et al. 2012), archive U-channel sediment from most of the SG93 core sections from which ^{14}C measurements had been previously obtained ("SG93-11" to "SG93-14" and "SG93-20" to "SG93-36") were fitted to the SG06 sediment profile through direct matching of distinct marker horizons (tephras, flood layers, turbidite layers, and other distinct sedimentological structures) between the respective cores. Additional robust matching was made for the intervening SG93 core sections ("SG93-15" to "SG93-19") by microfacies analysis of archive SG93 thin sections using light microscopy. Such thin sections were not available for the other SG93 core sections, however.

The original stratigraphic description of SG93 by H Kitagawa (unpublished) included the depths of distinct marker layers (recorded at 5-mm precision). These layers were, where possible, identified in the archive SG93 sediment and used, along with the visual correlations to SG06 described above, to build a conversion model through which interpolated SG06 composite depth equivalents could be derived for all original SG93 ^{14}C samples. Since the depths of the SG93 distinct marker horizons, as well as the depths from which the SG93 ^{14}C samples were taken, were recorded close to the time of the original coring, subsequent expansion/contraction of the archive core material (during the intervening years in storage) is not a problem for the generation of this depth conversion model. Likewise, depth control in SG06 is at 1-mm precision (Nakagawa et al. 2012), as defined by digital photographs of the freshly exposed core section surface taken immediately after extraction from the lake (thereby minimizing subsequent color changes through oxidization and any post-extraction/storage-related expansion/contraction of the sediment).

RESULTS AND DISCUSSION

Most SG93 core sections could be matched without difficulty to SG06 through purely visual means, despite the fact that the SG93 sediment had oxidized and therefore lost much of its visible lamination. Only a handful of SG93 core sections were more difficult to place. Figure 1 shows 2 examples of this physical matching process between the respective SG93 and SG06 sediment cores, using both the archive SG93 U-channel material (Figure 1a) and the archive SG93 thin sections (Figure 1b). Table 1 gives the equivalent SG06 composite depths thus derived for the top and bottom of the 26 individual SG93 core sections.

The span of missing sediment between successive SG93 core sections is obtained through subtracting the equivalent SG06 composite core depth of the bottom of a given SG93 core section from that of the top of the underlying section (Table 2). The age span of this gap is given in the varve count and ^{14}C model-derived age scale of Bronk Ramsey et al. (2012; see also Staff et al. 2013; given in $SG06_{2012}$ yr).

The gaps between core sections are all <20 cm, with the exception of that between sections SG93-28 and SG93-29, which was a “known problem” to the original authors (Kitagawa and van der Plicht 1998a,b, 2000), who included 300 yr for the 17 cm of missing sediment estimated. The mean sediment loss between the 26 SG93 core sections was found to be 8.11 cm (95.4 $SG06_{2012}$ yr), representing a total loss of 202.8 cm of sediment and approximately 2386 ($SG06_{2012}$) yr. This is slightly greater than the “not larger than 2000 varve years” attributed by van der Plicht et al. (2004) to the potential cumulative calendar age uncertainties arising from “the possible miscounting of varves and/or hiatuses in the varve sequences” (assessed through comparison of the SG93 ^{14}C data set with those of other long ^{14}C calibration records published at that time). In actuality, it appears that the SG93 varve chronology included a slight over-count compared to the combined varve count and ^{14}C model-derived $SG06_{2012}$ chronology of Bronk Ramsey et al. (2012); between the top of SG93 core section SG93-13 and the bottom of SG93 core section SG93-34, 29,102 SG93 vyr were counted, compared to 28,625 $SG06_{2012}$ yr (for the retrieved SG93 sediment, i.e. 31,011 total $SG06_{2012}$ yr minus the 2386 yr of missing sediment from the inter-core section gaps). This is presumably the result of the inclusion of a certain proportion of intra-annual laminations present within the Suigetsu record (see Schlolaut et al. 2012), and represents an over-count of 1.67% (cf. the “< 1.5% counting error” estimated by Kitagawa and van der Plicht 1998b based upon duplicated counts of selected SG93 core sections and parallel subsections from specific core depths).

Using the revised core depth/varve age information derived for these SG93 core sections (now lacking the sedimentary gaps that had previously been included, but unrecognized), the SG93 ^{14}C data are demonstrated to be in excellent agreement with those from the SG06 study (Figure 2). Through integrating the 2 cores’ data sets, the 565 ^{14}C determinations from the Suigetsu Varves 2006 project are bolstered by 243 SG93 ^{14}C data points. This significantly enhances the resolution of the combined Lake Suigetsu calibration data set, with 808 individual ^{14}C determinations spanning the last 52,800 cal yr, as recently published by Bronk Ramsey et al. (2012).

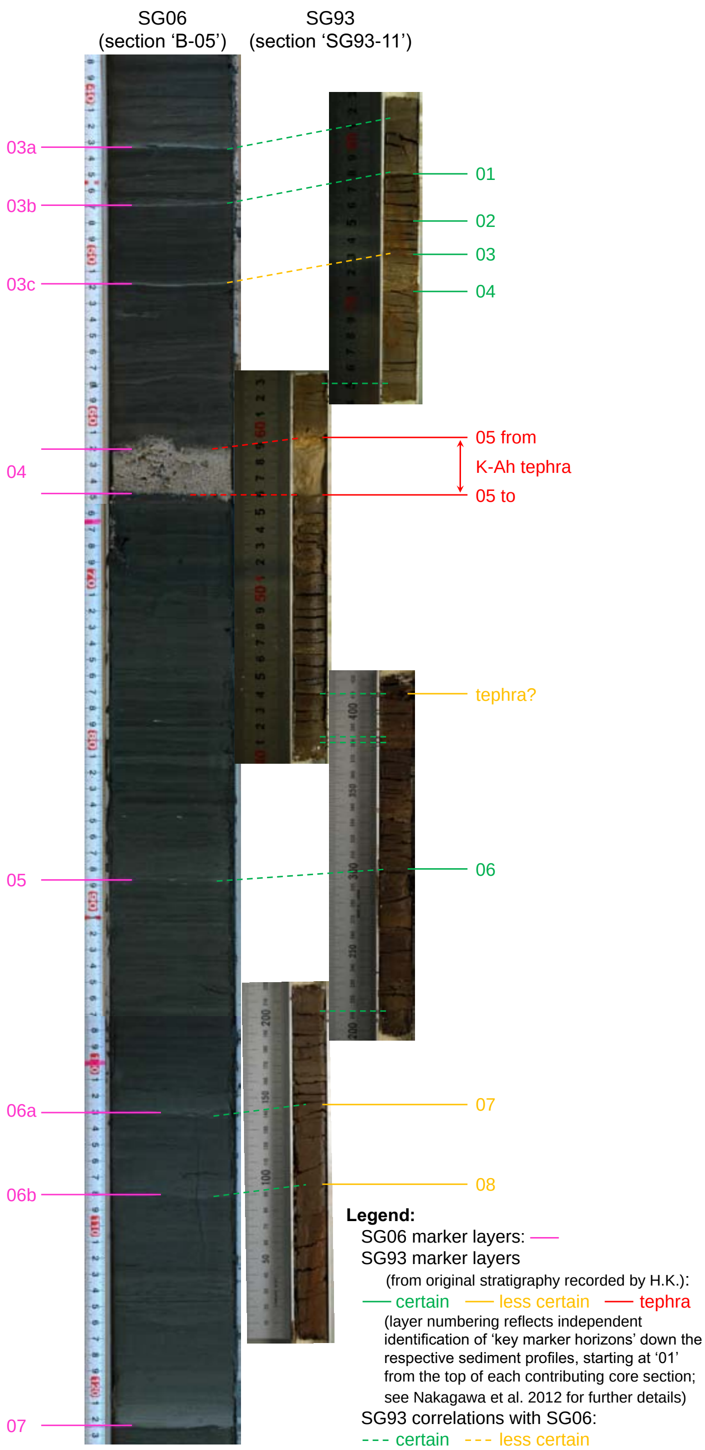

Figure 1a Example matching of an archive SG93 U-channel core section (here, section "SG93-11") on to the fully continuous SG06 composite core (here, section "B-05"). The online version of this figure is presented in full color.

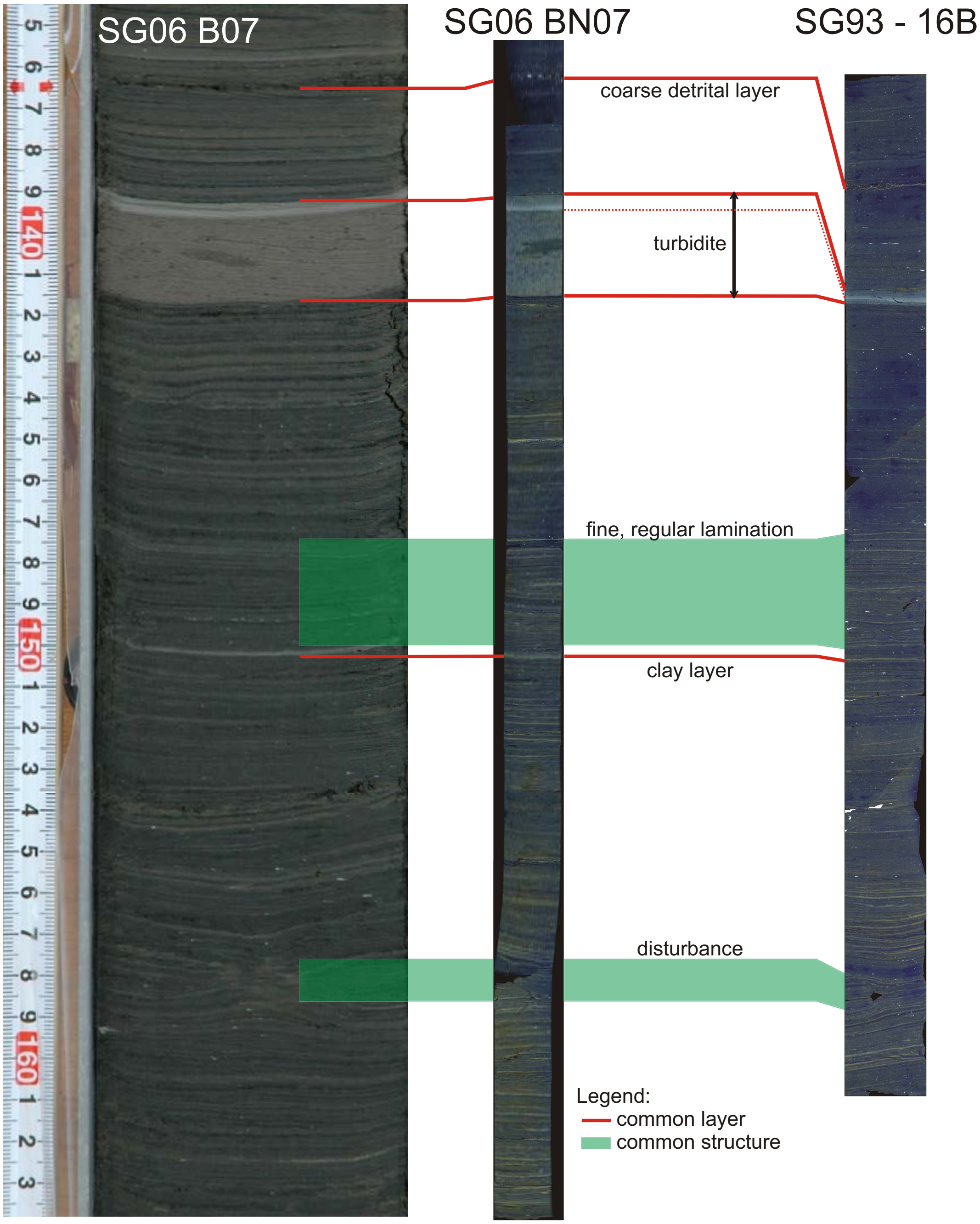

Figure 1b Example matching of an archive SG93 thin section (here, section “SG93-16-B”) on to the fully continuous SG06 composite core (here, section “B-07”). The thin-section scans of both core sections (SG06 core section B-07, center, and SG93 core section SG93-16-B, right-hand side) are shown in polarized light against the original SG06 core photograph (core section B-07, left-hand side). The online version of this figure is presented in full color.

Table 1 Equivalent SG06 composite depth (August 2009 version; Nakagawa et al. 2012) and varve count and ^{14}C model-derived calendar age scale (given in "$SG06_{2012}$ yr BP"; Bronk Ramsey et al. 2012; Staff et al. 2013) for the 26 SG93 core sections (SG93-11 to SG93-36) from which ^{14}C determinations were obtained by Kitagawa and van der Plicht (1998a,b, 2000).

SG93 core section		Original SG93 depth (cm)	Original SG93 vyr BP	SG06 composite depth (cm)	Revised $SG06_{2012}$ yr BP
SG93-11	Top	895.0	n/a	945.0	7023 ± 31
	Bottom	987.0	n/a	1029.6	7950 ± 23
SG93-12	Top	987.0	n/a	1037.8	8018 ± 21
	Bottom	1045.0	n/a	1091.8	8479 ± 23
SG93-13	Top	1042.0	8828	1095.0	8512 ± 25
	Bottom	1133.0	9520	1182.2	9347 ± 18
SG93-14	Top	1133.0	9520	1193.2	9431 ± 16
	Bottom	1225.0	10,213	1280.7	10,172 ± 21
SG93-15	Top	1225.0	10,213	1285.1	10,210 ± 20
	Bottom	1317.0	10,880	1374.2	11,016 ± 19
SG93-16	Top	1317.0	10,880	1393.4	11,203 ± 13
	Bottom	1408.0	11,789	1474.2	11,971 ± 45
SG93-17	Top	1408.0	11,789	1490.6	12,138 ± 45
	Bottom	1498.0	12,864	1579.0	13,043 ± 33
SG93-18	Top	1498.0	12,864	1580.6	13,062 ± 33
	Bottom	1589.0	14,267	1672.4	14,249 ± 48
SG93-19	Top	1589.0	14,267	1681.1	14,362 ± 52
	Bottom	1680.0	15,713	1765.1	15,703 ± 55
SG93-20	Top	1680.0	15,713	1769.0	15,782 ± 54
	Bottom	1771.0	17,166	1853.5	17,626 ± 56
SG93-21	Top	1771.0	17,166	1858.2	17,717 ± 55
	Bottom	1855.0	18,572	1947.3	19,185 ± 52
SG93-22	Top	1855.0	18,572	1950.8	19,236 ± 52
	Bottom	1939.0	19,992	2036.9	20,800 ± 52
SG93-23	Top	1939.0	19,992	2035.3	20,774 ± 52
	Bottom	2028.0	21,566	2120.9	22,131 ± 39
SG93-24	Top	2028.0	21,566	2123.9	22,180 ± 36
	Bottom	2119.0	23,088	2219.1	23,708 ± 53
SG93-25	Top	2119.0	23,088	2217.9	23,686 ± 53
	Bottom	2210.0	24,630	2316.4	25,230 ± 62
SG93-26	Top	2210.0	24,630	2327.7	25,419 ± 60
	Bottom	2301.0	26,162	2427.2	27,619 ± 93
SG93-27	Top	2301.0	26,162	2429.5	27,619 ± 93
	Bottom	2393.0	27,601	2526.8	28,747 ± 97
SG93-28	Top	2393.0	27,601	2530.5	28,801 ± 98
	Bottom	2477.0	28,938	2609.0	29,903 ± 95
SG93-29	Top	2494.0	29,238	2643.5	30,009 ± 94
	Bottom	2586.0	30,521	2729.8	31,385 ± 104
SG93-30	Top	2586.0	30,521	2740.1	31,611 ± 103
	Bottom	2678.0	32,040	2830.9	33,493 ± 104
SG93-31	Top	2678.0	32,040	2833.3	33,544 ± 104
	Bottom	2770.0	33,470	2918.1	35,286 ± 82

Table 1 Equivalent SG06 composite depth (August 2009 version; Nakagawa et al. 2012) and varve count and ^{14}C model-derived calendar age scale (given in "SG06$_{2012}$ yr BP"; Bronk Ramsey et al. 2012; Staff et al. 2013) for the 26 SG93 core sections (SG93-11 to SG93-36) from which ^{14}C determinations were obtained by Kitagawa and van der Plicht (1998a,b, 2000). *(Continued)*

SG93 core section		Original SG93 depth (cm)	Original SG93 vyr BP	SG06 composite depth (cm)	Revised SG06$_{2012}$ yr BP
SG93-32	Top	2770.0	33,470	2930.1	35,504 ± 81
	Bottom	2862.0	34,946	3015.3	36,964 ± 87
SG93-33	Top	2862.0	34,946	3027.0	37,150 ± 86
	Bottom	2953.0	36,402	3123.5	38,441 ± 89
SG93-34	Top	2953.0	36,402	3134.0	38,586 ± 90
	Bottom	3045.0	37,930	3203.1	39,523 ± 98
SG93-35	Top	3045.0	n/a	3217.8	39,744 ± 99
	Bottom	3136.0	n/a	3297.6	40,840 ± 79
SG93-36	Top	3136.0	n/a	3302.0	40,901 ± 78
	Bottom	3227.0	n/a	3385.1	42,098 ± 84

Table 2 The length (in cm), and equivalent temporal durations (in SG06$_{2012}$ yr; Bronk Ramsey et al. 2012; Staff et al. 2013), derived for the missing sediment between successive sections of the SG93 sediment core.

SG93 inter-core section gap	Length of missing sediment (cm)	Age span of missing sediment (SG06$_{2012}$ yr)	SG93 inter-core section gap	Length of missing sediment (cm)	Age span of missing sediment (SG06$_{2012}$ yr)
SG93-11 to SG93-12	8.2	68	SG93-24 to SG93-25	–1.2[a]	–22
SG93-12 to SG93-13	3.2	33	SG93-25 to SG93-26	11.3	188
SG93-13 to SG93-14	11.0	84	SG93-26 to SG93-27	2.3	0[b]
SG93-14 to SG93-15	4.4	37	SG93-27 to SG93-28	3.7	54
SG93-15 to SG93-16	19.2	187	SG93-28 to SG93-29	34.5[c]	106
SG93-16 to SG93-17	16.4	167	SG93-29 to SG93-30	10.3	227
SG93-17 to SG93-18	1.6	19	SG93-30 to SG93-31	2.4	51
SG93-18 to SG93-19	8.7	113	SG93-31 to SG93-32	12.0	218
SG93-19 to SG93-20	3.9	79	SG93-32 to SG93-33	11.7	186
SG93-20 to SG93-21	4.7	91	SG93-33 to SG93-34	10.5	144
SG93-21 to SG93-22	3.5	51	SG93-34 to SG93-35	14.7	221
SG93-22 to SG93-23	–1.6[a]	–26	SG93-35 to SG93-36	4.4	60
SG93-23 to SG93-24	3.0	50			

[a]Negative differences imply sections of minimal missing material, where expansion of the extracted SG93 core sections is particularly pronounced (up to 3% upon release from the pressure of the overlying sediment and water column, as cited by Nakagawa et al. 2012).
[b]0 missing yr, despite 2.3 cm of missing sediment, because the gap coincides with an instantaneous depositional event layer.
[c]cf. 300 yr inserted by Kitagawa and van der Plicht (1998a,b, 2000) to account for an estimated 17 cm of "known" missing sediment.

It should be noted that 7 of the original measurements from SG93 were obtained from insect fragments (Kitagawa and van der Plicht 2000). These have been excluded from the composite SG93/SG06 data set presented here (and published by Bronk Ramsey et al. 2012), since the synthesis of ^{14}C from the atmosphere via the trophic pathway into these organisms is not as direct as is the case with photosynthesizing terrestrial plants—therefore, not representing the contemporaneous Δ^{14}C as reliably as the (relatively short-lived) plant macrofossil samples dated.

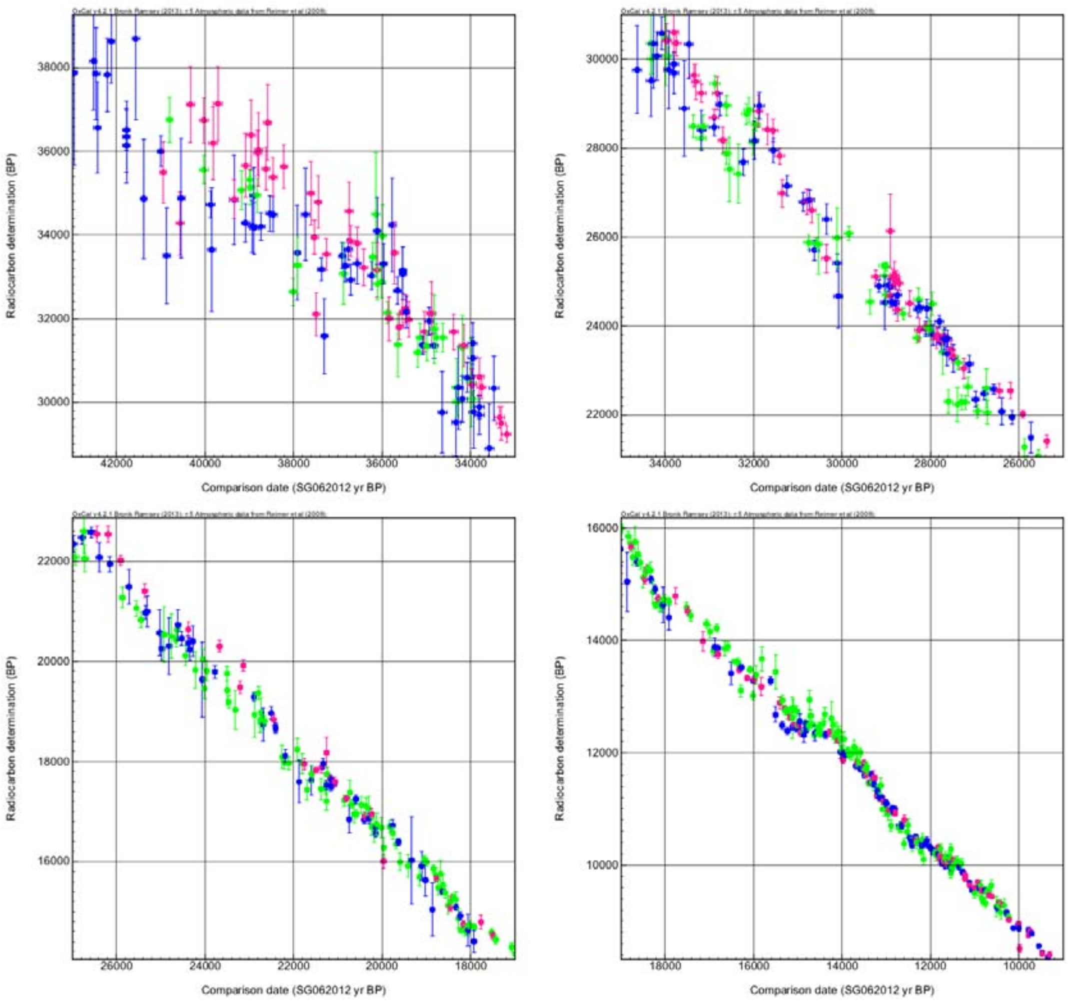

Figure 2 Comparison of SG06 ^{14}C data (produced at Oxford Radiocarbon Accelerator Unit, ORAU, blue data points, and the NERC Radiocarbon Facility-East Kilbride, pink data points) with the revised SG93 data (Centre for Isotope Analysis, University of Groningen, green data points). All data are as presented by Bronk Ramsey et al. (2012). The calibrated age scale is given in $SG06_{2012}$ yr BP (see Bronk Ramsey et al. 2012 and Staff et al. 2013). The online version of this figure is presented in full color.

Also, while the incorporation of the SG93 ^{14}C data does improve the resolution of the (pre-Holocene) composite ^{14}C calibration data set, these data were not included in the Bayesian modeling to anchor the site's floating varve chronology to the IntCal09 timescale (Staff et al. 2013). The rationale behind this approach was that, while the integration of the ^{14}C data sets of the 2 projects is deemed robust, the depth control with which ^{14}C samples were collected from SG93 (i.e. from 3-cm integrated sampling depths for the uppermost 19.3 m of the core, corresponding to 20- to 50-yr temporal resolution; Kitagawa and van der Plicht 1998b), is not as precise as that for the SG06 samples (taken at ~1-mm precision; Staff et al. 2011; Nakagawa et al. 2012). Furthermore, the correlation between SG93 and SG06 has greater uncertainty away from the "key correlation horizons" (which exist at intervals of ~5 to ~30 cm, depending on the stratigraphy of particular core depths and on the differential preservation of the archive SG93 core sections) than does the extremely reliable correlation between the parallel boreholes of SG06 (Nakagawa et al. 2012). Therefore, while the SG93 data contribute additional information for pre-Holocene ^{14}C calibration, they were not considered appropriate for the high-precision linkage to the decadally resolved IntCal09 tree-ring data set (i.e. the SG93 data were not used for the Bayesian ^{14}C modeling applied to tie the floating Suigetsu varve chronology to the "absolute" IntCal09 timescale; as described by Staff et al. 2013).

CONCLUSION

Through visual matching of the SG93 and SG06 Lake Suigetsu sediment cores, the ^{14}C determinations from the respective projects have been combined into a single calibration data set comprising 808 ^{14}C measurements from terrestrial plant macrofossils over 52,800 cal yr. At present, this Lake Suigetsu record provides the only continuous, non-reservoir-corrected data set of atmospheric ^{14}C across the entire range of the ^{14}C dating method, and it contributes a central component of the current version of the international consensus ^{14}C calibration model, IntCal13 (Reimer et al., this issue).

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