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The multiple chronological techniques applied to the Lake Suigetsu SG06 sediment core, central Japan

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BOREAS



Staff, R. A., Nakagawa, T., Schlolaut, G., Marshall, M. H., Brauer, A., Lamb, H. F., Bronk Ramsey, C., Bryant, C. L., Brock, F., Kitagawa, H., van der Plicht, J., Payne, R. L., Smith, V. C., Mark, D. F., MacLeod, A., Blockley, S. P. E., Schwenninger, J.-L., Tarasov, P. E., Haraguchi, T., Gotanda K., Yonenobu, H., Yokoyama, Y. & Suigetsu 2006 Project Members. 2013 (April): The multiple chronological techniques applied to the Lake Suigetsu SG06 sediment core, central Japan. *Boreas*, Vol. 42, pp. 259–266. 10.1111/j.1502-3885.2012.00278.x. ISSN 0300-9483.

The varved sediment of Lake Suigetsu (central Japan) provides a valuable opportunity to obtain high-resolution, multi-proxy palaeoenvironmental data across the last glacial/interglacial cycle. In order to maximize the potential of this archive, a well-constrained chronology is required. This paper outlines the multiple geochronological techniques being applied – namely varve counting, radiocarbon dating, tephrochronology (including argon–argon dating) and optically stimulated luminescence (OSL) – and the approaches by which these techniques are being integrated to form a single, coherent, robust chronology. Importantly, we also describe here the linkage of the floating Lake Suigetsu (SG06) varve chronology and the absolute (IntCal09 tree-ring) time scale, as derived using radiocarbon data from the uppermost (non-varved) portion of the core. This tie-point, defined as a distinct (flood) marker horizon in SG06 (event layer B-07–08 at 1397.4 cm composite depth), is thus derived to be 11 255 to 11 222 IntCal09 cal. years BP (68.2% probability range).

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The partially varved sediment profile of Lake Suigetsu (Honshu Island, central Japan; 35°35'N, 135°53'E; Fig. 1) offers a rich archive of high-resolution palaeoenvironmental data spanning the last glacial/interglacial cycle, as demonstrated by the recent acceptance of the site as an auxiliary stratotype for the onset of the Holocene Epoch (Walker *et al.* 2009). The

site was first brought to the attention of the Quaternary science community through the work of Kitagawa and colleagues (Takemura *et al.* 1994; Fukusawa 1995; Kitagawa *et al.* 1995; Yasuda *et al.* 2004), providing both a terrestrially based atmospheric radiocarbon calibration data set (Kitagawa & van der Plicht 1998a, b, 2000) and a high-resolution palaeoenvironmental data

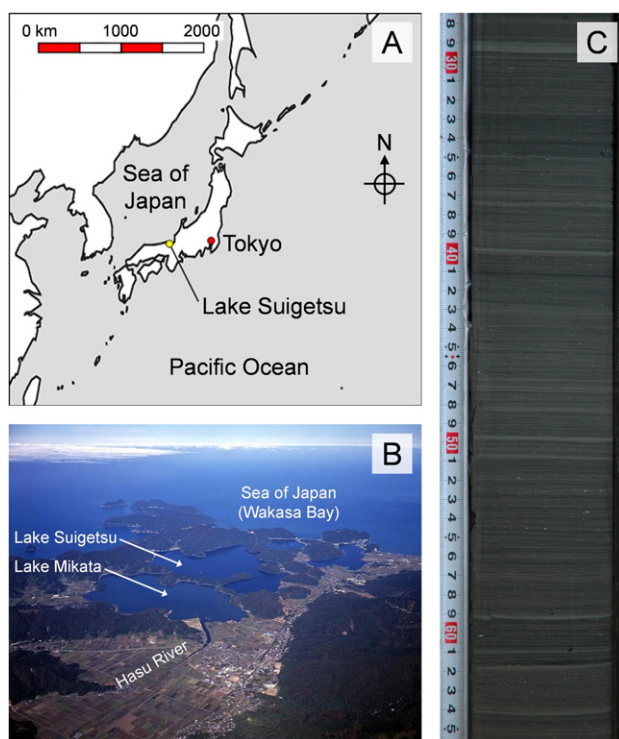


Fig. 1. A. Location of Lake Suigetsu, Honshu Island, central Japan ($35^{\circ}35'N$, $135^{\circ}53'E$). B. Hydrological situation of Lake Suigetsu, close to the Sea of Japan coast at Wakasa Bay. Most of the water and sediment reaching Suigetsu enters via Lake Mikata from the Hasu River. C. Portion of the SG06 sediment core (section C-16, composite depth 37.40 to 37.77 m), demonstrating the annual lamination (varves) present through much of the sediment profile. This figure is available in colour at <http://www.boreas.dk>.

set across the last glacial to interglacial transition (LGIT; Nakagawa *et al.* 2003, 2005, 2006) derived from a ~75-m-long sediment core ('SG93').

However, problems with the varve-based calendar age scale of the SG93 record limited the impact of these studies (van der Plicht *et al.* 2004; Nakagawa *et al.* 2012). A statistical re-analysis of the SG93 data set demonstrated that gaps between successively drilled sections of the SG93 sediment core were the main cause of the errors in this SG93 varve year age scale, with uncertainties in the varve counting representing a minor, secondary cause (Staff *et al.* 2010). (This statistical exercise compared the Suigetsu data with marine data for the older part of the radiocarbon time scale (Hughen *et al.* 2006), which was not available for such a comparison in 1998.)

As a result of these issues, Lake Suigetsu was re-cored in summer 2006, with the retrieval of overlapping sediment cores from four parallel boreholes enabling complete recovery of the sediment profile for the present 'Suigetsu Varves 2006' project (Nakagawa *et al.* 2012). Through the matching of distinctive marker horizons, a composite core ('SG06') of 73.19 m length was produced, providing a fully continuous

record of sediment accumulation spanning the time period back to Marine Isotope Stage 6. The Suigetsu Varves 2006 project has two over-arching aims: (i) to provide high- and ultra-high-resolution, quantitatively reconstructed palaeoenvironmental data for the East Asian monsoon region across the entirety of the last glacial/interglacial cycle; and (ii) to establish a purely terrestrial radiocarbon calibration data set across the complete radiocarbon dating range (approximately the last 60 000 years). Both of these project aims require an accurate and precise 'absolute age' chronology if they are to be successfully achieved. This paper presents the multiple geochronological approaches being undertaken towards this end, and discusses the ways in which these approaches are being integrated into a single, coherent chronology.

Geochronological methods

Varve counting

Varve counting of SG06 is being undertaken by two complementary methods. The first is a more traditional approach, applying manual counting of laminae from thin sections under a high-powered optical microscope (Schlollaut *et al.* in press). The second is a novel application of X-ray fluorescence (XRF) and X-radiography, measuring geochemical variation through the sediment profile at 60- μ m resolution (i.e. >10 measurements per year on average) using an ItraxTM core scanner (Croudace *et al.* 2006; Francus *et al.* 2009), and subsequently identifying the annual layers through manual interpretation (Marshall *et al.* in press).

As with any such incremental layer counting technique (including ice-core and tree-ring chronologies), there is a possibility of there being indistinguishable seasonal layers (producing an under-count compared with the theoretical 'true' age scale), or of intra-annual layers being present (producing an over-count). By combining both thin-section and XRF/X-radiographic counting, such problems have been reduced for SG06, as geochemical signals may still be evident in sections where the visual identification of the annual signal is less obvious. Conversely, visually identifiable laminations may occur in sections where the geochemical signal is unclear. In addition, the comparison of overlapping core sections from parallel boreholes facilitates the counting of seasonal layers where they are horizontally less continuous or less well preserved.

Unfortunately, the preservation of the annual layering at Suigetsu is not perfect (Nakagawa *et al.* 2012), and it has been necessary to use interpolation to achieve the 'complete' SG06 varve chronology. The interpolation method derived for SG06 is automated, thus reducing subjective bias (Schlollaut *et al.* in press).

The data from both counting methods (thin-section analysis and XRF/X-radiography) are interpolated before being integrated into a single, combined varve chronology (Marshall *et al.* in press). Uncertainty estimates from the dual techniques are combined, giving a conservative combined cumulative counting uncertainty envelope. As with other incremental layer counting methods, this cumulative counting uncertainty increases significantly with age. (Additional geochronological techniques to further constrain this cumulative uncertainty are discussed further below.) However, relative chronological information remains high throughout the varved interval, varying between individual sections according to differences in lamina preservation.

Radiocarbon dating

Terrestrial plant macrofossils contained within the Lake Suigetsu sediment profile provide a direct record (i.e. without the need for reservoir correction) of atmospheric radiocarbon (^{14}C) concentration across the entire ^{14}C dating range (c. 0 to 60 000 cal. a BP). The reliability of these samples was demonstrated by Staff *et al.* (2011), who compared 182 radiocarbon determinations from the upper (largely non-varved) 15 m of the SG06 sediment core with the IntCal09 (international consensus) ^{14}C calibration curve (Reimer *et al.* 2009). Across this time interval (i.e. the last ~12 000 cal. years), the IntCal curve is composed of similarly reliable terrestrial data (from mid-latitude northern hemisphere tree rings), also free of any requirement for reservoir correction. The primary conclusion of Staff *et al.* (2011) is that the ^{14}C data from the Lake Suigetsu plant macrofossils do provide a reliable archive of past changes in atmospheric radiocarbon concentration ($\Delta^{14}\text{C}$). This in turn demonstrates that the Lake Suigetsu sediment profile is indeed continuous over the last 12 000 cal. years (i.e. it does not include lengthy age gaps, namely those exceeding a handful of years), which supports the conclusions drawn from thin-section observation (Schlolut *et al.* in press). If this were not the case, the use of the site for palaeoenvironmental reconstruction would be severely impaired owing to the resulting difficulties in deriving the core chronology.

A secondary conclusion drawn by Staff *et al.* (2011) is that, by extrapolation, the Lake Suigetsu sediment profile is also suitable for providing a continuation to the purely terrestrial radiocarbon calibration curve across the preceding time period, back to 60 000 cal. a BP. Data currently (or soon to be) included within the IntCal curve (Reimer *et al.* 2009, in prep.) are obtained from corrected marine or speleothem data. Whereas both of these sources require assumptions about the necessary marine reservoir or dead carbon fraction corrections, Lake Suigetsu provides the opportunity to

achieve a more reliable terrestrial data set free from these additional uncertainties.

The Lake Suigetsu ^{14}C data set extended into the pre-tree-ring time period, reaching back to the present limit of the radiocarbon dating technique, is the subject of a paper by Bronk Ramsey *et al.* (in prep.). This complete SG06 ^{14}C data set consists of >600 ^{14}C determinations, which are divided approximately equally (to demonstrate additional quality control) between the Oxford Radiocarbon Accelerator Unit (ORAU) and the NERC Radiocarbon Facility–Environment (NRCF-E), East Kilbride. These samples were divided as regularly as possible down the sediment core, with ~10% direct inter-laboratory duplication of (sufficiently large) samples (Staff *et al.* 2011). Although the full SG06 varve chronology is yet (at the time of submission) to be completed, Bronk Ramsey *et al.* (in prep.) have, nevertheless, been able to compare the Suigetsu data with alternative, marine-derived ^{14}C calibration data. In this way, evidence is provided for the significant variability of the site-specific marine reservoir corrections that have necessarily been assumed and applied to these marine data sets. Such findings do not undermine the present IntCal consensus data set, which is always a ‘work-in-progress’, incorporating the most up-to-date data available, but demonstrate the importance of having a complementary, ‘wholly terrestrial’ data set throughout the entire ^{14}C period, and the additional information that can be derived from the alternative data sets when both marine and terrestrial data can be reliably combined.

Incorporation of the SG93 data set

Although the varve-based age scale of the previous project’s SG93 sediment core has been demonstrated to be incomplete, the ~300 ^{14}C determinations of plant macrofossils obtained from the core remain sound. Physical comparison has now been successfully undertaken between the fully continuous SG06 sediment profile and archive U-channel sediment from most SG93 core sections (‘SG11’ to ‘SG14’ and ‘SG20’ to ‘SG36’) from which ^{14}C measurements had been previously obtained by Kitagawa & van der Plicht (1998a, b, 2000). This was achieved through the direct matching of major event horizons between the respective cores in exactly the same way as between the four cores contributing to the composite SG06 profile (Nakagawa *et al.* 2012). Additional robust matching was made for the intervening SG93 core sections ‘SG15’ to ‘SG19’ using microscopic marker horizons from archive thin-sections of this core. Using the revised core depth/varve age information for these SG93 data (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 data from the SG06 study. Thus, the ~600 radiocarbon determinations

from the present study can be bolstered by these original SG93 ^{14}C data to produce a significantly enhanced resolution of data points in the final Lake Suigetsu calibration data set (i.e. ~900 individual radiocarbon determinations spanning the last *c.* 60 000 cal. years).

A minor caveat should be made, however, namely that the ^{14}C data from SG93 were not all from terrestrial plant macrofossils. Seven measurements were obtained from insect fragments (Kitagawa & van der Plicht 2000), which should be removed from the finalized Lake Suigetsu ^{14}C calibration data set as the synthesis of ^{14}C via the trophic pathway into these organisms is not as direct (from the atmosphere) as for photosynthesizing terrestrial plants.

Tephrostratigraphy and $^{40}\text{Ar}/^{39}\text{Ar}$ dating

Lake Suigetsu is located in a volcanically active area, and numerous tephra layers, representing the fallout from distinct volcanic centres and eruptions, are present throughout the sediment profile. Through chemical analysis, these tephra layers can be matched to tephra deposits in other distal sediment records, or to proximal material from the source volcanoes themselves. These tephra layers provide a series of isochronous markers, which may be widely dispersed. Using the continuous sediment profile of SG06, and the excellent chronological precision enabled, it is anticipated that Suigetsu will eventually provide a regional tephrostratigraphic type-site akin to the partially varved Lago Grande di Monticchio record for the central Mediterranean (Wulf *et al.* 2004, 2008).

There are 30 distinct visible tephra layers present within the SG06 sediment core. These are supplemented by cryptotephra layers that, although too fine to form visible layers, can be identified by microscopic means. Preliminary cryptotephra analysis of a short section (~5 m) of SG06 suggests that, on average, the visible tephra layers within the Lake Suigetsu cores will be augmented by about two cryptotephra layers per metre.

In addition to the relative chronological information provided by tephrostratigraphy, certain tephtras (those that are alkali-rich) can be radiometrically dated via the argon–argon ($^{40}\text{Ar}/^{39}\text{Ar}$) technique. Unfortunately, tephtras from Japanese source volcanoes are low in potassium-rich sanidine (the desired mineral phase for dating at the younger end of the Geological Time Scale), and cannot be reliably $^{40}\text{Ar}/^{39}\text{Ar}$ -dated. However, occasional tephtras from Korean source volcanoes found within SG06 do contain sanidine to $^{40}\text{Ar}/^{39}\text{Ar}$ dating, and one such eruption, the ‘SG06-1288 tephra’ (at 1286.1 to 1288.0 cm composite depth; Nakagawa *et al.* 2012), has already been successfully $^{40}\text{Ar}/^{39}\text{Ar}$ -dated (Smith *et al.* 2011). Because the crystals within the distal tephra deposits are too fine-grained for $^{40}\text{Ar}/^{39}\text{Ar}$ dating, geochemical correlation with proximal erupted material is first required, and it is these

proximal deposits that the $^{40}\text{Ar}/^{39}\text{Ar}$ measurements are obtained from. In this way, the SG06-1288 tephra (equivalent to the regionally widespread ‘U-Oki’ tephra) has been ascribed to the ‘U4’ unit of Ulleungdo stratovolcano, South Korea (~500 km WNW of Lake Suigetsu) and $^{40}\text{Ar}/^{39}\text{Ar}$ -dated to $10\,000 \pm 300$ a BP.

Optically stimulated luminescence

Pilot optically stimulated luminescence (OSL) measurements ($n=11$) have already been obtained from SG06, and it is hoped that a more extensive data set can be produced in the near future. These measurements, although focused primarily on the depths below countable varves, would contain a certain subset overlapping with the ^{14}C and varve chronologies to demonstrate a proof of method. Whereas $^{40}\text{Ar}/^{39}\text{Ar}$ measurements are relatively precise, but sporadically distributed down-core owing to the limited number of suitable, Korean tephra layers present, individual OSL measurements are less precise, but can potentially be taken throughout the SG06 core profile (with airborne particles suitable for OSL dating arriving from China during the annual winter monsoon).

Integration of chronological methods

The multiple, independent geochronological methods applied to the SG06 sediment core can be integrated to provide more robust chronological control for the palaeoenvironmental data obtained from the Lake Suigetsu sediments. Figure 2 provides a schematic representation of this integration into a coherent, combined chronology.

The primary age scale of SG06 is provided by the combined varve counting method. However, this varve age scale provides only a ‘floating’ data set, as the annual lamination pattern is not sufficiently well preserved throughout the Holocene to enable an ‘absolute’ varve chronology (i.e. one that continues through to the present day). Accordingly, the varve chronology must be ‘tied’ to the absolute age scale via some alternative means. To do this, the ^{14}C data from SG06 were modelled against the IntCal09 calibration curve using Bayesian wiggle-matching techniques (Bronk Ramsey 2008, 2009). The data for this modelling process lie comfortably within the tree-ring portion of IntCal09 (i.e. younger than 12 550 cal. a BP), and thus only the ‘wholly reliable’ (tree-ring-derived) portion of IntCal09 is used for this wiggle-match. This produces an SG06 varve year chronology (as tied to IntCal) that remains ‘wholly terrestrial’ – free from any marine reservoir assumptions that would be incorporated if the earlier portion of IntCal were included in the modelling process. Although the entire SG06 ^{14}C data set across this ~12 000-year period (comprising 182 ^{14}C determinations from 15 m of SG06 core) is utilized for this

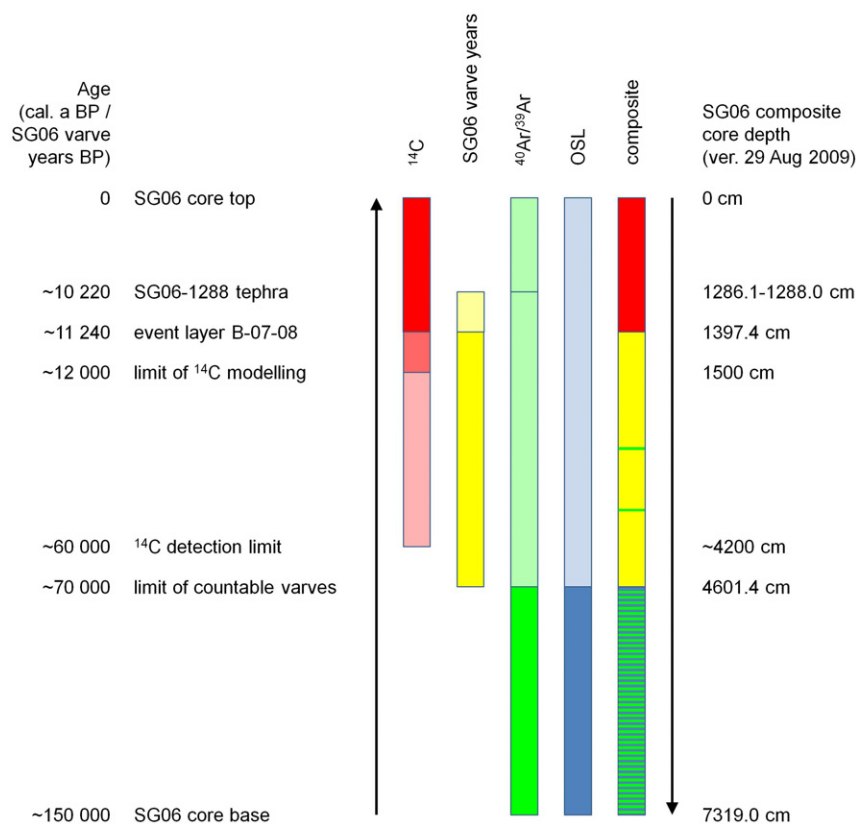


Fig. 2. Schematic representation of the integration of the independent geochronological methods applied to SG06 into a coherent, combined chronology. (Darker colouring represents the geochronological techniques directly forming the composite core chronology, whereas lighter colouring represents the supporting techniques.) ^{14}C data (red) modelled against IntCal09 (Reimer *et al.* 2009) provide the chronology for the most recent ~11 240 years, with additional modelled ^{14}C data back to c. 12 000 cal. a BP being used to generate the tie-point of the varve chronology (~11 240 to ~70 000 SG06 varve years BP/cal. a BP; yellow) to the absolute time scale. $^{40}\text{Ar}/^{39}\text{Ar}$ (green) and OSL (blue) measurements will provide additional constraints to the varve chronology, and will provide the sole chronological data beyond the lower limit of varve preservation. ^{14}C measurements beyond the IntCal09 tree-ring limit are being used for the generation of the terrestrial calibration curve, but are also being used, at present (Bronk Ramsey *et al.* in prep.), to ensure that the 'overall tilt' (long-term trend) of the ^{14}C calibration data does not deviate significantly from other, independently radiometrically dated ^{14}C calibration data sets (Hoffmann *et al.* 2010; Southon *et al.* 2012). To optimize independence from these reservoir-affected data sets, shorter-term variability is not being used to 'correct' the SG06 time scale (see Bronk Ramsey *et al.* in prep.). This figure is available in colour at <http://www.boreas.dk>.

wiggle-match, the precise point at which the SG06 varve chronology is connected to the IntCal09 tree-ring chronology is defined by one of the many distinct marker horizons in SG06 (i.e. characteristic layers used for correlating overlapping core sections, such as tephtras, flood layers and turbidites; Nakagawa *et al.* 2012) – event layer B-07–08 at 1397.4 cm composite depth (Fig. 3A). The choice of B-07–08 as the tie-point to the IntCal time scale was made on the grounds that: (i) an obvious stratigraphic (marker) horizon was needed; (ii) the tie-point needed to be sufficiently far from the ends of the modelled time interval to reduce uncertainty in the wiggle-match modelling; and (iii) B-07–08 coincides with a portion of the ^{14}C calibration curve with a steep gradient (Fig. 3B), resulting in more tightly constrained calibrated (unmodelled) ^{14}C data of measurements adjacent to the event that, in turn, produce more tightly constrained modelled ages from this section of the core. Accordingly, the modelled age

of B-07–08 in SG06 is between 11 255 and 11 222 cal. a BP at the 68.2% probability range (between 11 275 and 11 209 cal. a BP at the 95.4% probability range), which can be approximated to a normal distribution with $\mu=11\,241$ cal. a BP and $\sigma=17$ (Fig. 3C). (The Bayesian modelling for this wiggle-match was undertaken using OxCAL ver. 4 (Bronk Ramsey 2008, 2009), with the same model coding as that presented by Staff *et al.* (2011), but including an additional 'Date' query function at the position of the B-07–08 marker horizon, 1397.4 cm composite depth.) An additional benefit of linking the Suigetsu varve chronology to the IntCal09 tree-ring time scale in this way is that it eliminates the cumulative varve count error that would necessarily have been incorporated from the counting of the most recent 11 millennia (had it been possible to have performed continuous counting from the present). This then allows much higher precision and accuracy of ^{14}C age calibration using the Suigetsu data set.

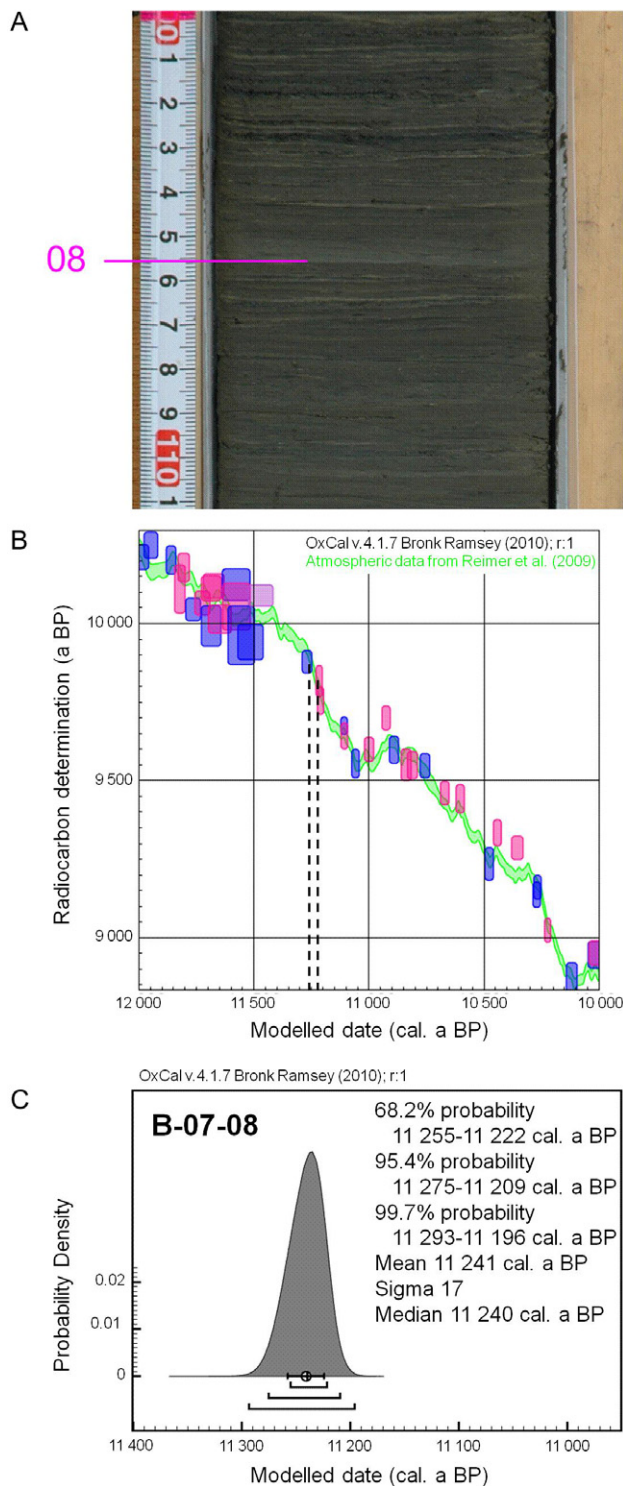


Fig. 3. A. Event layer B-07-08 within the varved SG06 sediment core (at 1397.4 cm composite depth). B. The placement of B-07-08 (dotted black lines) on the IntCal09 ^{14}C calibration curve (Reimer *et al.* 2009; green) using SG06 ^{14}C determinations obtained from the Oxford Radiocarbon Accelerator Unit (ORAU; blue data points) and the NERC Radiocarbon Facility-Environment (NRCF-E), East Kilbride (magenta data points). Combined data points produced from samples duplicated between the two laboratories are shown in purple. C. The posterior probability density function generated for event layer B-07-08 in SG06, which provides the tie-point between the floating SG06 varve chronology and the 'absolute' IntCal09 tree-ring time scale. This figure is available in colour at <http://www.boreas.dk>.

is that, while the integration of the ^{14}C data sets of the two projects is 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-year resolution; Kitagawa & van der Plicht 1998b) is not as precise as that for the SG06 samples (taken at millimetre precision; Staff *et al.* 2011). Furthermore, the correlation between SG93 and SG06 has greater uncertainty away from the 'key correlation horizons' (which exist at intervals of ~5 cm 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 are not ideal for the high-precision linkage to the decadal resolved IntCal09 tree-ring data set.

As described above, the SG06-1288 tephra has been $^{40}\text{Ar}/^{39}\text{Ar}$ -dated by Smith *et al.* (2011) to $10\,000 \pm 300$ a BP. This age is statistically indistinguishable at 1σ uncertainty from the ^{14}C -derived modelled age of this event in SG06 of between 10 231 and 10 202 cal. a BP at the 68.2% probability range (between 10 255 and 10 177 cal. a BP at the 95.4% probability range; Staff *et al.* 2011). Thus, an independent verification is provided for the accuracy of the ^{14}C chronology obtained for the uppermost SG06 sediment sections, and, vice versa, the modelled ^{14}C data support the $^{40}\text{Ar}/^{39}\text{Ar}$ date, demonstrating the reliability of the measurements even close to the younger limit of the $^{40}\text{Ar}/^{39}\text{Ar}$ method.

Above the upper limit of countable varves, further radiocarbon data, modelled against the IntCal09 calibration curve, provide the chronology for the uppermost core section, which is required to investigate the specific palaeoenvironmental aims of the Suigetsu Varves 2006 project (including investigation of Holocene climatic variability and Holocene geohazard recurrence intervals; Saito-Kato *et al.* in prep.).

Below B-07-08, the SG06 varve chronology (given in 'SG06_x varve years BP', where 'x' refers to the version of the chronology) commences, using B-07-08 as the tie-point to IntCal09. The total uncertainty of the

It should be noted that, while the incorporation of the SG93 ^{14}C data (outlined above) does improve the resolution of the (pre-Holocene) ^{14}C calibration data set, these data are not included in the Bayesian modelling to anchor the site's floating chronology to the IntCal09 time scale. The rationale behind this approach

SG06₂₀₁₂ varve year age scale at B-07–08 is simply that produced from the ¹⁴C modelling (i.e. +14, –19 years, 68.2% probability range). Below this tie-point (down to the bottom of countable varves at 4601.4 cm composite depth), the cumulative varve interpolation error is combined with the ¹⁴C wiggle-match uncertainty to provide the total SG06 varve year uncertainty envelope. Accordingly, the total chronological uncertainty is +42, –62 years (68.2% probability range) at an approximation to the IntCal09 tree-ring limit, 12 550 SG06₂₀₁₂ varve years BP (1524.8 cm composite depth). This uncertainty inevitably increases down-core to the limit of countable varves at 4601.4 cm composite depth (c. 70 000 cal. a BP; note that at the time of submission, the SG06 varve year chronology had not been finalized for this lower core section).

In the near future, we intend to obtain additional chronological information to constrain the cumulative chronological uncertainty for these lower core depths. Principally, additional tephra layers of Korean origin present within the Lake Suigetsu sediment profile will enable the incorporation of additional ⁴⁰Ar/³⁹Ar measurements that will significantly reduce these uncertainties (from approximately ±3000 years cumulative varve uncertainty at 50 000 cal. a BP, namely 6% at present, to ~1% precision).

Until these additional, high-precision constraints on the Suigetsu varve chronology have been obtained, however, ¹⁴C data beyond the IntCal09 tree-ring limit will be used (Bronk Ramsey *et al.* in prep) to ensure that the ‘overall tilt’ (long-term trend) of the ¹⁴C calibration data does not deviate significantly from other, independently radiometrically (i.e. U-Th) dated ¹⁴C calibration data sets (Hoffmann *et al.* 2010; Southon *et al.* 2012). To optimize independence from these reservoir-affected data sets, shorter-term variability is not being used to ‘correct’ the SG06 time scale (see Bronk Ramsey *et al.* in prep. for further details). This ‘adjusted’ time scale is given in ‘SG06_x years BP’ (cf. ‘SG06_x varve years BP’ in the uncorrected varve chronology), where ‘x’ again refers to the version of the chronology.

Below the lower limit of countable varves, ⁴⁰Ar/³⁹Ar dating will also provide valuable chronological information. Such measurements will be supplemented by OSL measurements, which, although offering less precise data from isolated measurements (noted above), will nevertheless increase chronological precision between the ⁴⁰Ar/³⁹Ar measurements. These OSL determinations can be obtained quasi-continuously throughout the sediment profile, with their chronological precision greatly enhanced through the application of Bayesian modelling.

Non-independent methods of ‘tuning’ the Suigetsu chronology to other records (e.g. ice cores, speleothems and other lacustrine or marine sediment cores) based on their respective palaeoenvironmental signals are

being deliberately avoided in the Suigetsu Varves 2006 project. Such methods would introduce a circular logic when trying to assess any spatio-temporal leads and lags in the global climate system that the palaeoenvironmental project is seeking to address.

Finally, it should be emphasized that using the SG06 core as a correlation target, via ¹⁴C ‘wiggle-match’ modelling for the most recent ~60 000 years, offers an even greater potential than the core’s ‘absolute’ age scale, as this will facilitate the identification of potentially high-resolution leads and lags in the global climate system (i.e. correlation uncertainty is not affected by absolute age uncertainty). Even beyond the ¹⁴C dating range, the presence of visible tephra and cryptotephra provides numerous distinctive chronological markers that, if geochemically linked to alternative palaeoenvironmental records (such as marine sediment cores from the West Pacific region), will enable high-precision relative chronological questions to be addressed.

Conclusions

A precise, accurate chronology for the Lake Suigetsu sediment profile is vital if the considerable potential impact of the site on Quaternary science is to be realized. To this end, the multiple chronological methods applied to the SG06 sediment core provide large, complementary data sets that enable more robust geochronological and palaeoenvironmental hypotheses to be tested than through the application of any single technique. The Suigetsu varves are, at present, unique in providing a direct record of atmospheric radiocarbon that is tied to an independent, annually resolved time scale through to the limit of the ¹⁴C method. The additional wealth of potentially ultra-high-resolution palaeoenvironmental proxy data available from the core makes this one of the most significant global records of palaeoclimatic change over the last glacial/interglacial cycle, and it is therefore anticipated that, over the coming years, Lake Suigetsu will provide a key palaeoclimatic reference site for the East Asian monsoon region.

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