SG06, a fully continuous and varved sediment core from Lake Suigetsu, Japan: stratigraphy and potential for improving the radiocarbon calibration model and understanding of late Quaternary climate changes


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A B S T R A C T

The high potential of the varved sediments of Lake Suigetsu, central Japan, to provide a purely terrestrial radiocarbon calibration model and a chronology of palaeoclimatic changes has been widely recognised for the last two decades. However, this potential has not been fully realised since the only available long sediment core from the lake (“SG93”) was extracted from a single bore hole and was therefore interrupted by gaps of unknown duration between successive core sections. In the summer of 2006, a new sediment core (“SG06”) was recovered from the lake. Four separate boreholes were drilled and the parallel sets of cores recovered were found to overlap completely, without gaps between segments. This new record provides the ability to test existing atmospheric radiocarbon calibration models, as well as to assess the scale of inter-regional leads and lags in palaeoclimatic changes over the last Glacial–Interglacial cycle. Multi-disciplinary analyses from SG06 are still ongoing, but a reliable description of the sedimentary sequence needs to be provided to the wider science community before major outputs from the project are released, thereby allowing fully-informed critical evaluation of all subsequent releases of data based on the SG06 record. In this paper, we report key lithostratigraphic information concerning the SG06 sediment core, highlighting changes in the clarity of annual laminations (varves) with depth, and possible implications for the mechanism of the climate change. We also discuss the potential of the SG06 record to meet the fundamental goals of the INQUA-INTIMATE project.

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BP, combined with data from various marine sources from 12,550 to 50,000 cal BP. Year 0 is defined as 1950 AD.

$^{14}$C BP: Radiocarbon age calculated by convention (Stuiver and Polach, 1977) using the ‘Libby half-life’ of 5568 ± 30 years (Anderson and Libby, 1951). Year 0 is defined as 1950 AD.

cal BP: Conceptual absolute age scale defined as ‘1950 minus yr AD’ or ‘1949 plus yr BC’.

SPECMAP BP: Age inferred by correlating to a marine core, the age of which has been determined by matching $\delta^{18}$O curve to the SPECMAP model (Imbrie et al., 1984).

Note: In this paper, we do not use the ‘$b2k’ notation (defined as before 2000 AD: Andersen et al., 2006; Svensson et al., 2006).

2. Introduction

Establishing leads and lags of past climate changes is one of the major focuses of today’s Quaternary science. It gives almost direct information about triggers and responses to the climate change, which is crucial to the better prediction of our likely future. INQUA-INTIMATE is an international project striving to correlate ice core, marine, and terrestrial records using independent chronologies in an attempt to reveal the relative timing of Lateglacial to early Holocene (80,000–8000 cal BP) abrupt climate changes between different regions and different environments (Lowe et al., 2008; Blockley et al., 2012).

Lake Suigetsu, central Japan, is one of the most suitable study sites to meet the INQUA-INTIMATE aims. The lake has been known to the Quaternary science community for the last two decades for its annually-laminated (varved) sediment record that spans the last c. 70 kyr. Four short sediment cores (‘SG1-4’) were obtained from the centre of Lake Suigetsu by Yasuda and co-workers (Takekura et al., 1994; Kitagawa et al., 1995; Yasuda et al., 2004) using piston-corers in 1991 (SG1-2, less than 4 m) and 1993 (SG3-4, c. 16 m). A longer, 75 m core (‘SG93’, also referred to as simply “SG” in previous studies) was also obtained by the same group in 1993, and reached the base of the sediment profile (Takekura et al., 1994; Kitagawa et al., 1995). These researchers were the very first to demonstrate the occurrence of varved sediment in Japan, which triggered a series of research projects based on analysis of the SG93 core. Most notably, Kitagawa and van der Plicht (1998a,b, 2000) established a high-precision independent chronology for the core through counting of the annual layers (varves). Combining this with >300 radiocarbon determinations measured on terrestrial plant macrofossil remains (mostly comprising leaves and small twigs), these authors generated a radiocarbon age calibration model stretching back to the radiocarbon detection limit (c. 50 kyr cal BP). This study was an early attempt to extend the radiocarbon calibration model beyond the tree-ring limit (11,400 cal BP at that time; Kromer and Becker, 1993), and even now remains the only purely terrestrial radiocarbon calibration dataset that: (i) is free from ‘dead carbon fraction’ correction (unavoidable with speleothem data, e.g. Beck et al., 2001); and (ii) extends back to the radiocarbon detection limit.

Supported by the exceptionally high-precision chronology of the SG93 core, Nakagawa et al. (2003, 2005, 2006) conducted high-resolution (average analytical interval = 14.86 yrs) pollen analysis and pollen-based quantitative climate reconstruction through the deglacial interval to the early Holocene section of the core (15,701 to 10,217 SG93 yr BP). They claimed that if the respective Lake Suigetsu, Greenland and Cariaco Basin chronologies were correct, then Lateglacial events in Japan were not synchronous with those of circum N. Atlantic regions such as Greenland (Alley et al., 1993; Björck et al., 1998) and the tropical Cariaco basin (Hughen et al., 1996, 1998, 2000).

Despite the potentially huge importance of these studies, Lake Suigetsu did not attain acceptance as a reference site for either radiocarbon calibration or the anchoring of the Lateglacial event stratigraphy. Subsequent radiocarbon calibration datasets obtained from marine sediment (Hughen et al., 1998), corals (Fairbanks et al., 2005) and cave speleothems (Beck et al., 2001) were adopted by IntCal, although all of these datasets relied on assumptions about radiocarbon reservoir age. The ensemble of available data nevertheless strongly implied that the absolute age range assigned to the SG93 core was significantly underestimated (e.g. van der Plicht et al., 2004).

There are three potential explanations for the apparently “too-young” SG93 varve chronology: (i) undercounting of the number of varves in SG93; (ii) over-counting of annual bandings in all other sites; and (iii) discontinuities within the SG93 core. Unreliable correction of the carbon reservoir effects in all other sites could explain short-term (annual to millennial) differences in the structure of $^{14}$C age scatter between the SG93 and other datasets. However, such an explanation would seem unlikely for the longer-term deviation between SG93 $^{14}$C ages and those obtained from other sites, since there is no feasible mechanism that could allow carbon reservoir ages to become progressively greater further back in time. It is mainly for this reason that the SG93 dataset has never become formally incorporated into the IntCal calibration model (Stuiver et al., 1998; Reimer et al., 2004, 2009).

Perceived problems with the independently derived age scale also had serious implications for the assessment of the timing of Lateglacial events. If it is indeed unreliable, then the temporal offset proposed by Nakagawa et al. (2003, 2005) could simply be an artefact of an erroneous age model. Specifically, when an event in SG93 is claimed to post-date those of other regions (e.g. the Younger Dryas-equivalent cold reversal), this could affect the fact that the SG93 varve chronology tends to be younger than the age models derived for other reference sites.

Recently, Staff et al. (2010) performed a statistical re-analysis of the SG93 data, calibrating the data to the IntCal04 (Reimer et al., 2004) and Cariaco Basin (Hughen et al., 2006) datasets, and concluded that the previously unquantified age gaps between successively drilled SG93 core segments constituted the more likely cause for discrepancy between the SG93 record and other radiocarbon age models. Such a finding was considered encouraging since it implied that the Lake Suigetsu sediment record offered the potential to achieve the aims set in preceding studies, providing that a fully continuous sediment core could be obtained.

In summer 2006, a research team funded by the UK Natural Environment Research Council (NERC) conducted a new sediment coring exercise at Lake Suigetsu, reaching the base of the sedimentary profile (73.19 m below the lake bottom). Cores were recovered from four parallel boreholes with fully overlapping core segments, leaving no room for chronological gaps in the entire sequence. The aim of this paper is to provide detailed litho-stratigraphic information for the new “SG06” sediment core, which will underpin all future studies of the sequence. Special emphasis is given to the potential of the SG06 core to contribute to the overall objectives of the INQUA-INTIMATE project (Blockley et al., 2012).

3. Site description

Lake Suigetsu (35°35’N, 135°53’E, 0 m above present sea level (a.p.s.l.)), is a tectonic lake located proximal to the Sea of Japan coast, Honshu Island, central Japan, and is situated on the western side of the active Mikata fault (Fig. 1). The lake is 34 m deep, and covers an area of c. 4.3 km² with a diameter of c. 2 km in both N–S and E–W directions. Both SG03 (35°34’51”N, 135°53’7”E) and SG06 (35°35’08”N, 135°52’57”E) cores were recovered from the depocentre of the lake. The SG06 coring point is about 250 m offset to the north (Fig. 1). Lake Suigetsu is naturally protected from winds by surrounding hills (max 400 m), as well as from river influx by the
neighbouring Lake Mikata. The Hasu River is the only significant water supply into Lake Suigetsu, but the hydrology of the lake system (Fig. 1C) is such that water from the river first flows into Lake Mikata, which is connected to Lake Suigetsu only by a very shallow (max c. 4 m) and narrow (c. 45 m) channel, and therefore any high-energy hydrological events (such as floods) cannot disturb the sediments deposited at the bottom of Lake Suigetsu.

The regional climate around Lake Suigetsu is typically characterised by both summer and winter monsoons. In summer, Japan receives predominantly south-easterly winds and humidity from the Pacific Ocean, whereas in winter the dominant north-westerly winds come from Siberia (Fig. 2). It should be noted that the winter monsoon in Japan, unlike in China, does not bring about dry conditions to the archipelago; the wind over the relatively warm surface water of the Sea of Japan picks up much moisture and eventually provides heavy winter precipitation to Japan, particularly along the western side of the country, including the Lake Suigetsu region. Present day climatic data recorded at the Tsuruga meteorological observatory (35°39′00″ N, 136°03′54″ E, 16 m a.p.s.l.), about 15 km ENE of Lake Suigetsu, is as in Table 1.

Because of the strong seasonality, different types of material are deposited at the lake bottom throughout the different seasons. This original sedimentary structure, with seasonally alternating material, is well preserved in Lake Suigetsu because of the abiotic and very stable conditions at the lake bottom, and is recognised as varves when observed in the sediment core section (Marshall et al., in prep. will report technical details, results, implications, precision and accuracy of varve counting using ultra-high resolution XRF and X-radiographic data; Schlolaut et al., in prep. will also report technical details, results, implications, precision and accuracy of varve counting using thin-section microscopy).

4. Coring, logging and storage methods

Sediment coring was conducted from 03 July to 11 August 2006 using a hydro-pressure thin-walled piston sampler installed on a floating platform (Fig. 3). The inner diameter of the sampling tube was 7.8 cm. There was no need to use a smaller diameter corer for recovery of bottom sediments because, unlike other commonly-used percussion systems (e.g. Mingram et al., 2006), the hydro-pressure sampler does not undergo significant power loss as it penetrates into deeper horizons. Some core sections were magnetically oriented using newly developed in-situ magnetic field sensors or, more simply, a mark on the drilling rod. Sediment core sections were extracted from their sampling tubes within a few days (at the latest) of recovery from the lake. A mechanical piston was used for extraction, which inevitably meant that the top c. 5 cm of each core section was compressed and/or disturbed. No significant disturbances caused by the piston were observed beyond 5 cm from the top of each core segment. Extracted cores were immediately split into two half cylinders and a ‘quasi-real scale’ digital photograph was taken of the freshly exposed core section surface, before any colour changes through oxidisation could occur (observable within a minute of exposure to the air). In order to compensate for this problem: (i) a colour chart was always placed alongside the sediment in each photograph; and (ii) surface colour was instrumentally measured using a Konica Minolta CM-2002 Colourimeter at every 10 cm from the top of each core segment (Fig. 4). Where available, layers with clearly identifiable characteristics (including tephra layers, clay layers, laminae with characteristic colouration, etc.) were chosen at c. 10–20 cm intervals and assigned numbers (Fig. 5). The positions
of these numbered laminae were defined at 1 mm precision using the scale in the digital photographs.

Sediment cores were obtained from 4 separate boreholes (A, B, C and D), all within 20 m horizontal distance from each other, with the core sections fully overlapping such that material from any given Lake Suigetsu sedimentary horizon would be represented by at least one of the individual sediment cores. This overlapping of cores was simultaneously monitored using the core section images, which was particularly necessary since the lake level was oscillating from day to day by several tens of centimetres reflecting the changeable weather of the Japanese summer monsoon season. After taking comprehensive core photographs and subsequent subsampling by ‘double-L (LL) channel’ (Fig. 6 – a.k.a. ‘Nakagawa channel’) (Nakagawa, 2007) for later multi-proxy analysis, cores were wrapped with moist flower foam (Oasis™) (avoiding direct contact with the core material) using plastic (Saran) film to avoid desiccation. The wrapped cores were transported to cold storage (+4 °C) near the lake as soon as possible. For logistical reasons, however, some core sections had to stay in ambient temperatures (between 20 and 40 °C) for a few days prior to storage. Cores were finally shipped using a cold container (+4 °C) to their permanent cold storage site (+4 °C) at the University of Newcastle, UK.

5. Stratigraphy of the SG06 core

5.1. General rule for coding and depth control

Core segments are coded according to bore hole (A, B, C, and D) (Fig. 7) and numbers given to the successive core segments within each bore hole (01 at the top of the sediment profile). Boreholes A, B, C, and D yielded 46, 47, 21, and 4 core segments, respectively. Position within each segment is defined by the distance from each core segment top, which in turn is defined by the scale in the digital photographs of the core. Laminae with strong character/visibility are labelled by number starting from 01 at the top. For example, lamina A-20-05e in Fig. 5 can also be expressed as A-20-75.1 cm. Sometimes lamina labels were added later in order to facilitate more precise correlation. Such additional laminae are identified with Greek alphabet codes (α, β, etc.).

5.2. Construction of the composite section

A composite master section was generated by connecting middle parts of the core segments, bound by labelled lamina both above and below (except for the first and the last sections, namely A-01 and B-47 cores, for obvious reasons). The top 5 cm of cores were avoided from the master section wherever possible, because of compression or disturbance of the core being likely, as mentioned in Section 4. The “composite depth”, a depth scale assigned to the composite master section, was defined simply as the combined lengths of the segments in the master section. Segment lengths were defined by the scale in the digital core images. Composite depth of the segments that are not in the master section was determined by correlation to the master section. Fig. 7 plots all of the core section images arranged

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Table 1

<table>
<thead>
<tr>
<th>Climate indices observed at Tsuruga, the nearest meteorological observatory to Lake Suigetsu (Japan Meteorological Agency, 1998a,b). Values were averaged for the 30 year period from 1961 to 1990.</th>
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<tbody>
<tr>
<td>Mean annual temperature</td>
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<td>Mean temperature of the warmest month</td>
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<td>Mean temperature of the coldest month</td>
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<tr>
<td>Annual precipitation</td>
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<tr>
<td>Precipitation from April to September</td>
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<td>Precipitation from October to March</td>
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Fig. 2. Atmospheric circulation around Japan. A: summer, B: winter (modified after Porter and An, 1995).
against the composite depth scale thus generated. Correlation between neighbouring cores was principally established through visual matching of the lamination pattern, using especially those characteristic event horizons observed. Correlation points used to define composite master section are indicated by red horizontal lines in Fig. 7. We consider that there is no correlation error for the top c. 46 m and bottom c. 10 m of the SG06 core, where sediments are rich in fine structure such as varves. The section from c. 46 m to c. 63.5 m is more problematic because the sediment does not have much obvious structure, apart from large scale (of the order $10^2$–$10^3$ cm) colour changes and occasional tephra layers. Visual correlation was nevertheless undertaken for this section using small-scale core photographs (Fig. 8), but the correlation of this part of the SG06 core potentially includes some error. All uncertain correlations are indicated in Fig. 7 by dotted red horizontal lines connecting parallel cores. Our correlation model has had no revisions on the composite master section and only very minor adjustments for parallel sections over the 4 years since coring. However, we are always aware of the potential for our current correlation model (version: 24th August 2009) to be updated once we have generated more high-resolution analytical data from the overlapping cores, since ‘wiggle matching’ of proxy curves might enable correlation at much higher precision than comparison of the optical images.

A note must also be made on core section A-14, which is severely disturbed and does not properly bridge between the neighbouring B-13 and B-14 core sections. However, because the B-13 core contains the undisturbed top of the very thick AT-tephra layer (Machida and Arai, 2003; Miyairi et al., 2004) and the B-14 core contains the undisturbed bottom of the same tephra event, we consider that all missing material between the B-13 and B-14 cores is the middle part of the AT-tephra. In other words, the core is stratigraphically discontinuous here but there is no missing “period” represented by the regular deposition pattern of clay and organic material. In order to define the composite depth beyond the AT-tephra, we arbitrarily assumed a 24 cm loss of material between the B-13 and B-14 cores.

Indirect evidence that supports the robustness of our correlation model is the trend in departure of the composite depth from that of the raw drilling depth. Due to the porous and elastic nature of sediment and the high over-loaded pressure, sediment cores generally expand once they are exposed to atmospheric pressure. Because of this, as well as the fact that the composite depth of the sediment profile is defined as the combined segment length between correlation points measured by the scale in the optical core images (i.e. under atmospheric pressure), composite depth tends to become increasingly greater than the original drilling depth (which is defined as in-situ distance from the lake bottom). The departure of composite depth from drilling depth in the SG06 core increases gradually and quasi-homogeneously (Fig. 9). This strongly supports our hypothesis of there being no major correlation error throughout the entirety of the sequence. The diagram shows a plateau between 46 and 63.5 m. Because this plateau includes segments that are correlated by clear marker layers such as tephra (e.g. C-19 and A-28 correlated at 4962.6 cm composite depth).
5.3. Varved sediment

Because a large part of the SG06 core is finely laminated and thus has sub-millimetre scale structure, it is not realistic to make a full conventional description of the core. Instead, we produced an objective index to quantify the visibility of fine lamination (the “Lamination visibility index”, LVI) and substituted this into a more conventional description (Fig. 10A). The LVI was defined as the standard deviation of the core image greyscale for the vertically adjacent 30 pixels (~5.1 mm) [with greyscale values having been averaged across the horizontally neighbouring 30 pixels before calculating the index]. Because the standard deviation is not correlated to the absolute level of the original greyscale value, the index has the capacity to cancel out the effect of the changing natural light levels and to extract information on the variability of sediment colouration with depth.

As can be seen in Fig. 10D, sediments with LVI values around 1 and 2 have virtually no structure (i.e. impossible to establish a chronology by counting varves). Sediments with LVI values around 3 are more structured: some sections are not yet clearly varved but show a high LVI value due to the presence of material with very differing greyscale values; others are finely laminated but do not show very high LVI values because the varves consist of materials with less differing greyscale values. Varves are generally very clearly visible for the sediments with LVI values around 4 or higher (Fig. 10D).

For the composite core section representing the time period between the IntCal09 tree-ring limit and radiocarbon detection limit (12,550–50,000 IntCal09 BP — see Section 5.5 for the preliminary chronology of the SG06 core), the LVI value typically oscillates around 4, indicating the generally well varved nature of the core for this section. However, the LVI values change over very short intervals and there are still a considerable number of fragmented sections with LVI values lower than 3 within this time period. The frequency of the 30 pixel window showing LVI values lower than 3 for this particular section was 37%, whilst the frequency of windows demonstrating an LVI value greater than 3.5 for the same section was 51%. These facts in combination imply that it is possible to establish a varve chronology for the SG06 core, but that at places this needs to be supplemented with an interpolation method to compensate for missing varves (Schlolaut et al., in prep.). Combined uncertainties of counting and interpolation were estimated using the core section overlapping with the tree-ring part of the IntCal09 calibration model. The sedimentation rate of this section was calculated by two independent methods: varve counting/interpolation and 14C wiggle matching. Within this section the interpolated varve model lies well within the 2-sigma (95.4%) probability range of the calibrated age (Schlolaut et al., in prep.; Marshall et al., in prep.). However, in some deeper core sections where LVI values are reduced, the varve counting uncertainty is likely to be greater (Schlolaut et al., in prep.; Marshall et al., in prep.).

Oscillation of the LVI value seems to exhibit millennial scale structure. There are 19 distinct peaks in the smoothed LVI curve between the K-Ah tephra (dated at c. 7300 cal BP, Machida and Arai, 2003) and the radiocarbon detection limit, with possibly further 2 (or more) less distinct peaks over the same section (black and white triangles, respectively, in Fig. 10A). The typical time interval between these peaks is roughly estimated to be in the region of 2.0–2.3 kyr. Whether or not these oscillations are related to the known millennial scale climate changes during the glacial period (such as Dansgaard-Oeschger (D-O) events) needs to be further investigated using other palaeoclimatic proxies. If such a relationship were to be demonstrated, however, this might imply: (i) a more fundamental causal mechanism external to the global climate system; and (ii) East Asia responded more sensitively to such a mechanism than the N. Atlantic regions, since: (a) the observed “cycle” in the LVI is persistent throughout both the glacial period and the Holocene; and (b) the amplitude of the LVI oscillation does not seem to become smaller even during the period when a D-O cycle is not well pronounced (such as the period between the Last Glacial Maximum and the onset of GI-1e (Dansgaard et al., 1993; Björck et al., 1998)).

As noted above, the sediment between 4601.4 cm and 6375.2 cm composite depth (ver. 24 Aug. 2009) is not laminated. This section corresponds to unit ‘SG-IV’ of the SG93 core stratigraphy which represents the period when the lake was not deep enough to maintain an anibiotic bottom water environment (Takeamura et al., 1994). Sediments below 6375.2 cm down to the core bottom are composed of alternations of peat, massive inorganic clay layers, and occasionally finely laminated organic clays. This is a counterpart of unit ‘SG-V’ in the SG93 core, which represents alternating fluvial and shallow water environments that occurred after the initial tectonic formation of the basin.

5.4. Event layers

The varved sediment of the SG06 core is occasionally intercalated by thick layers lacking such fine structure. These are
classified into two empirical types: (i) a relatively light-coloured massive clay layer, directly overlying the regularly-deposited varved sediment (Fig. 11A); and (ii) a very similar clay layer, but generally much thicker and accompanied by an underlying dark-coloured and slightly coarser layer (Fig. 11B). It is hypothesised that the clay layers of the former type were formed by large flood events. These layers lack coarse material, which would normally underlie clay layers derived from flood events affecting lake sites,
but this can be explained because the coarser materials carried by the Hasu River (the only significant water source into the multiple lake system) would be deposited within Lake Mikata and hence would not reach Lake Suigetsu. Only fine clay that can remain in suspension for a longer time could subsequently be deposited in Lake Suigetsu. The thicker event layers with coarser material towards the bottom and finer material towards the top are interpreted as small-scale turbidites, i.e. thick layers formed by reworking of the deposits from the basin wall, which contain both fine grain-sized clay and coarser particles transported from slopes around the lake by surface runoff. The most likely cause to trigger such turbidites is earthquakes. According to the most preliminary age-depth model based on tephra ages, the turbidite layers seem to have been formed every 2.8 kyr on average (min-max: 1.2–5.3 kyr) (Fig. 10B). This may represent the typical activity frequency of major displacement of the Mikata fault (Fig. 1) (cf Kawakami et al., 1996).

5.5. Tephrostratigraphy and preliminary chronology

A total of 30 visible tephra layers were recognised within the entire SG06 core sequence, 11 of which are being identified using mineral composition, shard morphology, and shard refractive indices (more robust identification by glass chemistry is being carried out; Smith and Blockley, personal communication). The distribution of these visible tephra layers, as well as their ages according to the existing literature, are summarised in Fig. 10C. The age of the SG06 core bottom is yet to be determined, but is subject to further investigation. If the sediment accumulation rate is assumed to have been constant between the core bottom and the Aso-4 tephra layer (composite depth c. 4960 cm), then the age of the core bottom may be as old as 200 ka. Even if the sedimentation rate below the Ata tephra (composite depth c. 5350 cm) was twice as high as the overlying section, the estimated age for the core bottom would still be around 150 ka. Low resolution fossil pollen assemblage data from the core bottom is dominated by boreal conifer trees and herbs, indicating generally cold climate (Nakagawa, unpublished data). Based on these facts, we provisionally conclude that the base of the SG06 core is older than marine isotope stage (MIS) 5 and that sediment deposition in Lake Suigetsu commenced during the MIS 6.

5.6. Plant macro remains

Lake Suigetsu is located in the mid-latitude temperate zone, and has never been covered by Quaternary ice sheets. Since the lake has always been surrounded by forest even during the Last Glacial Maximum (Gotanda et al., 2002; Gotanda and Yasuda, 2008), tree leaves, twigs, and bark have been constantly falling on to the lake surface throughout the lake’s existence. Some of these eventually sink to the lake bottom and are preserved as fossils in the abiotic and reducing conditions of the varved sediment matrix (Fig. 12). So far a total of 1176 terrestrial plant macro remains have been recovered, at least half of which are large enough for radiocarbon dating by accelerator mass spectrometry (AMS) (Fig. 13) to provide results with sufficient precision to be included in radiocarbon calibration datasets. This is about twice the number of samples dated by Kitagawa and van der Plicht (1998a,b, 2000) from SG93 core. Terrestrial plant macrofossils are not concentrated in any specific intervals but are quasi-uniformly distributed.

Fig. 8. Correlation of non-laminated core segments. A: reliable correlation using tephra. B: uncertain correlation due to lack of fine sedimentary structure. C: The same segment as B in smaller scale which shows larger structure of the core that can be used for low-precision correlation.

Fig. 9. Departure of composite depth from drilling depth, calculated at all numbered laminae in the SG06 sediment core. The general trend of the scatter is very linear, supporting the overall continuity of the core. Data points do not fit perfectly on a single line because of the uncertainty in the drilling depth control (cores were recovered from a floating platform and the water depth changed almost every day reflecting the very changeable weather of the Japanese summer monsoon season). A few outliers represent secondary movement of the core within the sampling tube.
6. Potential contributions for INTIMATE perspectives—coming attractions—

The SG06 sediment core has the potential to make a significant contribution to the overarching aims of INTIMATE (Blockley et al., 2012), covering three principal areas: (i) extension of the terrestrial radiocarbon calibration model; (ii) providing an East Asian regional template of high-resolution palaeoclimate reconstruction, coupled with a high-precision chronology; and (iii) providing intra- and inter-regional tie-points for correlation between SG06 and other study sites. The remainder of this section outlines the multidisciplinary research that is currently being conducted on the SG06 core, also highlighting the potential significance of the expected project outcomes.

6.1. Terrestrial radiocarbon calibration model

One of the principal objectives of the Suigetsu Varves 2006 project is to combine a large number (~600) of terrestrial radiocarbon dates with the continuous and independent varve count chronology of the same core to generate a wholly terrestrial radiocarbon calibration model free from any of the aforementioned carbon reservoir corrections. Because of the improved continuity of the core (as compared to the SG93 study), as well as the more advanced methods of varve counting utilised by the project team (coupled thin-section microscopy and ultra-high resolution X-ray fluorescence (XRF) scanning methodologies, Schlolaut et al., in prep.; Marshall et al., in prep.), the SG06 core is expected to generate a more reliable, fully terrestrial radiocarbon calibration...
model beyond the current IntCal tree-ring limit (12,550 IntCal09 yr BP, Reimer et al., 2009) and back to the radiocarbon detection limit (beyond 50 kyr cal BP). It is also hoped that through comparison of the SG93 and SG06 sedimentary structures, there might be the possibility of combining the SG93 and SG06 radiocarbon datasets, thereby significantly increasing the resolution of the final Suigetsu radiocarbon calibration dataset to c. 900 data points (c. 300 from the SG93 dataset and c. 600 from the present project). The average dating interval within the resulting calibration curve would be c. 83–56 yrs (i.e. either c. 600 or c. 900 data points covering the radiocarbon dating method, 0 to c. 50,000 cal BP). Unlike the current IntCal09 model, the Suigetsu-based calibration model will be entirely free from the assumed corrections for the marine reservoir effect, meaning that: (i) it will provide a more reliable template for assessing the relative inter-regional event timings; and (ii) the departure of the marine calibration model from the Suigetsu terrestrial model will give a more robust indication of variations in the magnitude of marine reservoir effects through time. The differences between the marine and terrestrial radiocarbon calibration models will in turn also provide important information about the response of the marine circulation system to major climate changes, and vice versa. The extended calibration model will also cover some key periods for understanding the origins of humankind, such as extinction of Homo neanderthalensis and the spreading of Homo sapiens from Africa to the rest of the world.

6.2. Climate changes

Once varve counting has been completed, the SG06 core will provide an almost ideal archive from which to derive terrestrial palaeoenvironmental reconstruction and subsequent inter-regional comparison because: (i) the organic-rich, fine-grained sediment contains a wealth of environmental indicators including pollen, diatoms, biomarkers and other organic compounds, and aeolian dust; (ii) the sediment represents information about mid-latitude terrestrial monsoon regions which cannot be represented by ice cores or marine cores; and (iii) the proxy data will be provided with an independent age scale, thus avoiding the use of climatic signals for correlation purposes, and the consequent circular logic that this frequently entails. This final point is particularly significant for meeting INTIMATE’s aims, because the target time period of INTIMATE, from 60,000 to 8000 cal BP, is represented in the SG06 core by finely laminated sediments for the entirety of this period (from c. 41.5 to c. 10.4 m in composite depth – see Fig. 10A).

Methods of climate reconstruction currently being conducted within the Lake Suigetsu 2006 varved sediment project include the following: pollen analysis and pollen-based quantitative climate reconstruction (Nakagawa et al., 2002, 2003, 2005, 2006, 2008); XRF elemental and major component analyses (Francus et al., 2009; Kido et al., 2006); thin-section microfacies analysis; diatom analysis; biomarker analysis; compound specific stable isotope analysis (Tyler et al., 2010); aeolian dust flux and origin analyses; and microbial DNA analysis.

6.3. Correlation with other study sites

The INTIMATE project ultimately aims to compile all available palaeoclimate information (i.e. ice core, marine and terrestrial records) for the period from 60,000 to 8000 cal. BP, examining the relative timings of climatic events across different regions, and understanding the mechanical/causal links between different components of the climate system. Correlation of proxy records using an independent age scale is a logical approach towards this goal (Lowe et al., 2008). However, having a varve counting and terrestrial radiocarbon dated chronology from SG06 is not enough for this purpose for the following reasons. Firstly, varve counting has unavoidable errors that are cumulative with depth (as is the case with the counting of annual layers within ice cores — see e.g. Rasmussen et al., 2008). This makes it extremely difficult to precisely correlate time scales independently generated by annual layer counting at more than one site. Secondly, the purely terrestrial radiocarbon chronology of Lake Suigetsu does not
allow direct correlation between the SG06 core and marine/ice cores since: (i) marine cores are subject to an unknown marine reservoir effect; and (ii) ice cores do not contain sufficient atmospheric carbon for radiocarbon dating. In order to overcome these problems, we need to explore methods of more direct correlation.

Tephra seems to be the best tool to correlate SG06 with marine cores from regions near to Japan. There are already 14 visible tephra layers representing the period covered by the INQUA-INTIMATE project. Additionally, many more microtephra layers can be expected from the same interval. If we can successfully correlate SG06 with Pacific or Sea of Japan sediment cores, then that would immediately mean that we would be able to assign terrestrial radiocarbon ages to the oxygen marine isotope stages (Paci) and D-O events (Sea of Japan – Tada et al., 1999), respectively.

Correlation between SG06 and ice cores is more problematic. One possibility is to use the D-O event record in the Sea of Japan sediments as a ‘stepping stone’ and correlate them with 18O records from Greenland. This, however, would immediately exclude the possibility of assessing the lead or lag relationship of millennial scale climate changes between Greenland and Monsoon Asia, which is contrary to INTIMATE’s protocol and targets. Greenland and Antarctic ice cores have been successfully correlated using atmospheric methane content and 10Be flux (Blunier et al., 1998; Blunier and Brook, 2001; EPICA community members, 2005). The former is not possible for SG06 simply because lacustrine cores do not contain trapped air bubbles. 10Be might be a possibility as lake sediments do contain 10Be particles. However, its interpretation is not straightforward because in lakes, unlike in ice sheets, 10Be flux represents a mixed signal of cosmic ray intensity and catchment dynamics. Lake Suigetsu and Greenland are too distant from each other for most (if not all) of the tephra layers to reach both sites. Finally, we expect that 14C in Lake Suigetsu can be correlated to 10Be flux reflected in polar ice cores, as both are considered to be direct indicator of variations in cosmic ray intensity. This is supposedly independent of the climate system, and would therefore allow the possibility to determine leads and lags between the SG06 terrestrial climate proxies and the Greenland and Antarctic 18O, D and other isotopic and chemical records, without involving climate as a correlation tool.
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