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Research paper

An automated method for varve interpolation and its application to the Late Glacial chronology from Lake Suigetsu, Japan

Gordon Schlolaut [a,*], Michael H. Marshall [b], Achim Brauer [a], Takeshi Nakagawa [c], Henry F. Lamb [b], Richard A. Staff [d], Christopher Bronk Ramsey [d], Charlotte L. Bryant [e], Fiona Brock [d], Annette Kossler [f], Pavel E. Tarasov [f], Yusuke Yokoyama [g,h], Ryuji Tada [g], Tsuyoshi Haraguchi [i] Suigetsu 2006 project members[1]

[a] *Section 5.2: Climate Dynamics and Landscape Evolution, German Research Centre for Geosciences (GFZ), Telegrafenberg, 14473 Potsdam, Germany*
[b] *Institute of Geography and Earth Sciences, Aberystwyth University, SY23 3DB, UK*
[c] *Department of Geography, University of Newcastle, Newcastle-upon-Tyne NE1 7RU, UK*
[d] *Oxford Radiocarbon Accelerator Unit (ORAU), Research Laboratory for Archaeology and the History of Art (RLAHA), University of Oxford, Dyson Perrins Building, South Parks Road, Oxford OX1 3QY, UK*
[e] *NERC Radiocarbon Facility - Environment (NRCF-E), Scottish Enterprise Technology Park, Rankine Avenue, East Kilbride G75 0QF, UK*
[f] *Institute of Geological Sciences, Palaeontology, Freie Universität Berlin, Malteserstrasse 74-100, Building D, 12249 Berlin, Germany*
[g] *Department of Earth and Planetary Sciences, Faculty of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033, Japan*
[h] *Ocean Research Institute, University of Tokyo, 1-15-1 Minami-dai, Nakano-ku, Tokyo 164-8639, Japan*
[i] *Department of Geosciences, Osaka City University, Sugimoto 3-3-138, Sumiyoshi, Osaka 558-8585, Japan*

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A B S T R A C T

The Lake Suigetsu sediment has been recognised for its potential to create a wholly terrestrial (i.e. non-reservoir-corrected) ^{14}C calibration dataset, as it exhibits annual laminations (varves) for much of its depth and is rich in terrestrial leaf fossils, providing a record of atmospheric radiocarbon. Microscopic analysis revealed that the varve record is curtailed due to the incomplete formation or preservation of annual laminae, necessitating interpolation. The program for varve interpolation presented here analyses the seasonal layer distribution and automatically derives a sedimentation rate estimate, which is the basis for interpolation, and applies it to complement the original varve count. As the interpolation is automated it largely avoids subjectivity, which manual interpolation approaches often suffer from. Application to the Late Glacial chronology from Lake Suigetsu demonstrates the implementation and the limits of the method. To evaluate the reliability of the technique, the interpolation result is compared with the ^{14}C chronology from Lake Suigetsu, calibrated with the tree-ring derived section of the IntCal09 calibration curve. The comparison shows that the accuracy of the interpolation result is well within the 68.2% probability range of the calibrated ^{14}C dates and that it is therefore suitable for calibration beyond the present tree-ring limit.

1. Introduction

Varved (annually laminated) sediments are palaeoenvironmental archives that at the same time allow the construction of high precision age models, potentially down to a seasonal resolution (Brauer et al., 1999). However, a common problem is the occurrence of incompletely varved sections. Changes in the depositional environment may interrupt varve formation or result in partially indistinct records (Zolitschka et al., 2000), which therefore require interpolation. Commonly, interpolation is carried out manually, using sedimentation rate estimates from neighbouring, well varved sections. The main error source of this conventional interpolation approach is that sedimentation rates in compromised intervals (i.e. intervals with an incompletely developed varve record) and well varved intervals can be different. Also, the conventional interpolation cannot be applied to sediment profiles that do not show well varved intervals. The new approach presented here is based on an automated analysis of frequency distributions of seasonal layers from the compromised interval itself and therefore avoids this main problem associated with conventional varve interpolation. Moreover, since the interpolation

* Corresponding author. Tel.: +49 331 288 1355; fax: +49 331 288 1302.
E-mail address: gosch@gfz-potsdam.de (G. Schlolaut).
[1] For full details see: www.suigetsu.org.

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method is computer based and automated it enables the reliable reproduction of a result, which is difficult to achieve when the interpolation is carried out manually. This novel approach is applied to the Lake Suigetsu sediment from the Last Glacial-Interglacial Transition (LGIT) (Table 1), which is an example of such an incompletely developed varve record.

The Suigetsu varves were first analysed by Kitagawa and van der Plicht (1998a, b, 2000), using a sediment core recovered in 1993 (SG93). They showed that, besides being annually laminated for much of its depth, the sediment also provides one of the most comprehensive atmospheric radiocarbon records, as it is rich in terrestrial leaf fossils. This makes it suitable for extending the atmospheric radiocarbon calibration model beyond the present IntCal tree-ring limit (12.55 ka cal BP (Reimer et al., 2009)) to >50 ka cal BP. However, the SG93 data significantly diverged from alternative, marine-based calibration datasets, due to gaps in the sediment profile and varve counting uncertainties (van der Plicht et al., 2004; Staff et al., 2010).

The Suigetsu Varves 2006 project aims to overcome the reported problems of the SG93 project. A new and continuous master profile was constructed (SG06), based on parallel cores from four bore holes, recovered in 2006 (Nakagawa et al., 2012). The varve interpolation program was devised to aid in the construction of an improved calendar age scale for the terrestrial SG06 radiocarbon calibration model. Therefore no information based on the ^{14}C chronology can be used to complement the varve count as the varve chronology must be completely independent.

While this study focuses on the establishment of the new varve interpolation program and the results from microscopic varve counting, a second paper (Marshall et al., 2012) introduces an additional, novel and independent varve counting method utilising µXRF and X-radiography. The comparison of the results from the two methods, their individual strengths and weaknesses and the combination into the final Suigetsu varve chronology are given in Marshall et al. (2012). Hence, the LGIT varve chronology presented here, based on microscopic counting only, does not represent the final SG06 varve chronology.

Table 1
Overview variables, abbreviations and terminology.

Term	Definition
bs	Bin size
pυ	Peak value
$\kappa(p)$	Mode variance window
μ	Mean of Gaussian distribution
σ	Standard deviation of Gaussian distribution
BP	Before present (AD 1950 = 0)
cd	Composite depth (version 24 Aug 2009 (Nakagawa et al., 2012))
CDF	Count distances frequency (plot/distribution)
efd	Event-free depth (thickness of macroscopic, instantaneous deposits is set 0)
LAO	Light amorphous organic (material)
LGIT	Last glacial-interglacial transition
LQS	Section quality selective (count)
SQS	Layer quality selective (count)
SR	Sedimentation rate [mm/a]
sr	Mean annual sediment accumulation [mm] (equals the SR in value)
Section	An arbitrary core interval
Sub-section	A core interval defined by the interpolation program which is interpolated with a mean SR estimate derived from count distances within the sub-section; the core is divided into multiple, overlapping sub-sections
Well varved section	A core interval defined by the user, depending on the quality and continuity of the seasonal laminations
LGIT	The period between the end of the last Glacial and the Holocene onset; synonymous with the terms Late Glacial and Last Termination
LGIT stadial	Climatic equivalent of the Younger Dryas (YD) biozone as defined in Europe (Mangerud et al., 1974; Jessen, 1935)
LGIT interstadial	Climatic equivalent of the Bølling/Allerød (B/A) biozone as defined in Europe (Mangerud et al., 1974; Jessen, 1935)

1.1. Study site

Lake Suigetsu is situated in Fukui prefecture on the west coast of Honshu Island, central Japan. It is part of a tectonic lake system (Mikata Five Lakes) with the active Mikata fault running N–S less than 2 km to the east (Fig. 1). The lake is approximately 2 km in diameter and has a maximum water depth of 34 m (Nakagawa et al., 2005).

In AD 1664 a canal was built connecting Lake Suigetsu with Lake Kugushi (itself already connected to the sea), which resulted in the inflow of salt water into the previously fresh water lake and the subsequent formation of a chemocline between 3 and 8 m water depth, which now separates the lower salt water body and the upper fresh water layer (Masuzawa and Kitano, 1982; Kondo et al., 2009). Due to this artificial change in the hydrology, the majority of the Lake Suigetsu sediment formed under limnological conditions that are only partially comparable to those of the present.

The fresh water, that comprises the upper water body, flows into Lake Suigetsu from Lake Mikata through a shallow sill connecting the two lakes. Lake Mikata is fed by the Hasu river, which constitutes the only major fresh water source to the lake system. In this setting Lake Mikata acts as a natural filter for coarse detrital material from the Hasu river catchment. Therefore the sediment of Lake Suigetsu consists predominantly of autochthonous and authigenic material.

2. Materials and methods

2.1. Varve description and counting

Sediment analysis and varve counting were carried out by thin section microscopy. For thin section preparation the LL-channel sediment sections (Nakagawa et al., 2012) were cut into 10 cm long segments and freeze dried. Afterwards the samples were impregnated with synthetic resin under vacuum. The blocks produced were glued to glass slides with the same resin and then ground and polished down to ≈20 µm (Brauer and Casanova, 2001). A petrographic microscope with magnification from 25× to 400× was used for counting.

An idealised varve with the main seasonal layers is depicted in Fig. 2a. At the base a spring related layer of *Aulacoseira subarctica* and *Aulacoseira ambigua* diatoms occurs, which may also contain some siderite. Following above is a detrital layer, which is dominated by silt-sized quartz and feldspar and contains only few clay minerals. The detrital layers are deposited mainly in spring, but can also form later in the year. In summer a layer of light amorphous organic material (LAO-layer) follows. Above, a layer of *Encyonema* diatoms occurs, either below or within the base of a following siderite layer. Both varve sub-layers, *Encyonema* and siderite, are related to autumn. Above a clay layer follows, which can partially overlap with the siderite layer and forms in autumn to winter. A full description of how the individual varve sub-layers were assigned to the different seasons is given below.

The layers of *Aulacoseira* spp. are often difficult to distinguish as the overall abundance of these diatoms is high. Since *A. subarctica* and *A. ambigua* cover a wide range of environmental conditions in