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研究課題名（和文）An improved radiocarbon calibration dataset from Lake Suigetsu (Japan) by application of an advanced varve interpolation algorithm to an extended Lake Suigetsu varve chronology

研究課題名（英文）An improved radiocarbon calibration dataset from Lake Suigetsu (Japan) by application of an advanced varve interpolation algorithm to an extended Lake Suigetsu varve chronology

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研究成果の概要（和文）：水月湖の年縞（毎年または季節ごとの葉理）計数による年代決定モデルを年縞の下限（コア深度40.4m）にまで拡張し、年縞の下限の正確な深度が初めて高い確度で決定された。不完全な年縞記録を解読するため、年縞を内挿するプログラムの開発を行い、自動化により開発初期から大きく改善した。確率分布適合という新しいアプローチにより様々な堆積物に応用可能となった。
年縞の計数とともに微細堆積相データを高解像度で取得した。これらは最終氷期末期の気候変動や、最終氷期の洪水や台風の高解像度復元といった古環境復元に有用である。
これらのデータは現在、さらなる古環境解析に用いており、年代論に関する論文を準備中である。

研究成果の概要（英文）：The Suigetsu varve chronology (i.e. the age model based on the counting of annual and seasonal laminations) was extended to the varve limit at 40.4 m core depth and the exact depth of the varve limit was reliably determined for the first time.A significantly improved varve interpolation programme was developed. In difference to the first attempt to develop such a tool for incompletely varve records (such as Lake Suigetsu) the programme can now be run fully automated and can be applied to a much wider range of archives due to the new approach of probability distribution fitting.
Alongside varve counting also high resolution microfacies data were collected. These were and are used for palaeo-environmental reconstruction, such as the climate evolution at the end of the last glaciation and high resolution flood/typhoon reconstruction for the last glacial.The data are currently used for further palaeo-environmental analysis and prepared for forthcoming publications on geochronology.

研究分野：palaeo-limnology, palaeo-climatology, chronology

キーワード：Lake Suigetsu　chronology　varves　climate reconstruction　limnology

1．研究開始当初の背景

The research carried out within this project is a follow up to the ‘Suigetsu Varves 2006‘ (SG06) project. The SG06 project aimed to construct a purely atmospheric radiocarbon calibration curve as well as reconstructing past climatic changes from the sediments of Lake Suigetsu. Lake Suigetsu is located in Fukui prefecture directly at the coast of the Sea of Japan. It is part of a tectonic lake system (Mikata-go-ko) and about 2 km in diameter and 34 m deep.

Radiocarbon (14C) dating is the most widely used dating method for samples with an age of up to 50,000 years before present (50 ka BP, with 0 yr BP = AD 1950). But due to variations in 14C production (and other processes), 14C dates must be corrected (i.e. calibrated) to account for these production variations. For that an archive is needed which enables 14C dating as well as an independent method of dating - in case of Suigetsu by the counting of annual laminations (i.e. varves), to determine the real age (calendar age) of a 14C date. Theoretically one perfect calibration dataset could be used for all 14C dated sites, though no calibration dataset is truly perfect. The calibration dataset from Lake Suigetsu produced in the SG06 project is to date the only truly atmospheric calibration dataset in the international consensus calibration dataset (IntCal13) beyond the so called “tree-ring limit”, i.e. beyond 13.9 ka BP.

The SG06 project (as well as a predecessor project (‘SG93’)) also showed the potential and importance this lake can have for palaeo-climatic reconstruction in Japan.

2．研究の目的

While the SG06 project was successful, it also presented new scientific challenges and produced more data than could be analysed in detail. Hence, the objective of this Kakenhi project was to address these issues.

A central aim was to improve and extend the Suigetsu varve chronology. Besides varve counting by light microscopy the so called ‘Varve Interpolation Programme’, developed within the SG06 project, was to be improved. Often, varve formation or preservation is imperfect, resulting in less years being counted than actually passed during the formation of a sediment interval. Hence, varve interpolation is necessary and for this common problem the Varve Interpolation Programme (VIP) was developed. While it overcame the issue of incomplete varve formation/preservation for the Suigetsu chronology, it also was difficult to use and at the same time the full potential of the approach used (statistical analysis of count distances to derive sedimentation rate estimates) was not yet unlocked. Since a powerful tool to overcome incompletely varved records benefits research beyond the Suigetsu project, it was aimed to significantly improve the VIP.

The second, equally important aim, of the research was to utilise the available proxy data (such as microfacies information, element measurements, pollen counts and others), as well as newly generated data, for palaeo-environmental reconstruction. Lake Suigetsu is a particularly important archive in East Asia (and unique in Japan) for such a task, as it covers an unusual long time frame uninterrupted and at the same time it can be independently dated by varve counting, which is essential to compare it with other archives in other parts of the world. The analysis interval reaches from 10 to 50 ka BP, thus covering the last deglaciation as well as large parts of the last Glacial. The primary research focus was to characterise the last deglaciation in Japan in detail and to reconstruct typhoon evolution through the Glacial.

3．研究の方法

The primary method applied was thin section microscopy using an optical petrographic microscope. This technique was used to count varves as well as to characterise the sediment. The latter means that all types of layers were measured (position, thickness) and described (components, internal structure). This includes seasonal layers, for example iron carbonate and diatom (i.e. algae) layers, as well as event layers, for example tephras, flood or landslide layers.

The programming of the Varve Interpolation programme was carried out using Matlab software.

As mentioned before, a range of different datasets from the SG06 project were available for (re-)analysis. From these micro X-ray fluorescence (µXRF) data were given a particular focus. These data provide semi-quantitative information on element concentrations (such as iron or

titanium), and were originally measured for an independent approach to varve counting. Yet, these data also are extremely useful for palaeo-environmental reconstruction and µXRF and microfacies data are rather complementary to each other, given that both have sub-annual resolution.

4．研究成果

(1)研究の主な成果

The main published result from this project addresses the northern hemispheric evolution of the ‘Younger Dryas Stadial’ (YDS). After the end of the last Glaciation about 15,000 years ago the northern hemisphere experienced the relatively sudden onset of warm conditions. But about 2000 years later a sudden cold event occurred (the YDS), which lasted for about another 2000 years. While the exact cause(s) for the YDS are not yet fully certain, it is known that the Atlantic Meridional Overturning Circulation (AMOC) weakened significantly during this time, potentially caused by a major inflow of meltwater from the Laurentian Ice Sheet into the North Atlantic. Previously it has been shown that the YDS has a two phase character in Europe and the North Atlantic, caused by a slow recovery of the AMOC and an associated northward shift of the atmospheric polar front. This let to warmer and wetter conditions in Europe. Within this Kakenhi project it was shown for the first time that the YDS also has a two phase character in East Asia. Furthermore, the characteristics between Europe and Japan are inversed. While the second phase of the YDS was warmer in Europe it was colder in Japan – associated with an increase in the strength of the East Asian Winter Monsoon and stronger winds. A likely mechanism behind this climatic dipole is an increased transport of moisture into Asia, caused by the northward shift of the polar front, leading to a stronger snow cover affecting circulation in East Asia.

Furthermore, the Varve Interpolation Programme (VIP) was significantly improved (publication in preparation). The new VIP uses a novel approach in which log-normal distributions are fitted to count distance distributions using a Monte Carlo fitting. This is followed up by iterative optimisation loops. There are numerous advantages compared to the older interpolation method. Firstly, the programme can be run fully automated. Previously it was necessary to manually determine parameters for artificial data generation, which was used for comparison with the real data. While this was an important part of the old programme it also required experience and was hence difficult for new users. Through the full automatisation the programme now provides fully objective and reproducible results and is significantly easier to use. Through the new approach the programme can also be applied to a much wider range of records. Previously an annual sediment accumulation of 1.5 times the mean sedimentation rate (or less) was suggested as ideal; now 2.5 times the mean sedimentation rate can easily be handled. Also the accuracy has been improved. For example the programme can now successfully distinguish fully varved intervals, thus avoiding over-interpolation in such intervals and making manual corrections unnecessary.

Thirdly, the Suigetsu varve chronology was extended to the varve limit, which occurs at about 50 kyr BP. This is younger than previously thought, since laminations in core photographs suggested an annual lamination also in deeper parts of the core. However, microscopic analysis revealed that these laminations are usually not seasonal. Occasional occurring seasonal layers are too infrequent for reliable interpolation. However, it does coincide with the radiocarbon limit and thus does not interfere with the objective of this research project. Publication of these data will be carried out in FY2017.

Fourthly, a high resolution reconstruction of the typhoon frequency from 10 to 50 ka BP was carried out. Using thin section microscopy, flood layers were identified at unprecedented resolution. Based on the varve structure it was determined that typhoons are the primary cause of these flood layers. The produced dataset is the only quantitative (with respect to recurrence) typhoon reconstruction at such resolution and over such a long time frame from Japan and and East Asia. However, the sedimentary analysis revealed multiple influences on the flood layer record. Changes in the catchment of the lake can influence the flood layer formation and impose a local signal on the record. For example, a major landslide at 38 ka BP was followed by a phase of increased flood layer occurrence. Apparently the landslide exposed a large

area of surface which was more easily eroded than ground protected by vegetation. Hence, also weaker precipitation events could wash enough material into the lake to form distinguishable flood layers at the coring location (i.e. at the middle of the lake). Comparable is an increase in the flood layer frequency after the deposition of a massive ash layer, which, too, is easily erodible, increasing the sensitivity of the system. Another example is an interval of low organic productivity, reducing the "dilution" of detrial material and improving flood layer distinguishability. For such reasons it is difficult to treat the dataset as one continuous record. However, avoiding such compromised intervals still enables typhoon reconstruction over thousands of years. Furthermore, by separating different thickness classes, differences in typhoon strength can also be considered, since stronger floods are the primary (though not sole) cause for thicker flood layers. First results presented at the European Geoscience Union annual meeting suggest that two different mechanisms were controlling typhoon frequency and strength, operating at centennial time scales. Variations in solar radiation are the primary suspects to explain these mechanisms.

(2) 得られた成果の国内外における位置づけとインパクト

Results where presented at numerous international conferences in Europe and the USA (see publication list). The publication on the Younger Dryas Stadial also led to a newspaper article on the topic in the 'Nikkei Shinbun' (published on the 23rd of April). According to Altmetric the research paper was picked up by 8 further (online) news outlets.

(3) 今後の展望

As mentioned in the 'main results' section, further publications based on this project are in preparation for FY2017.

Furthermore, the results from Lake Suigetsu have the unique potential to serve as a backbone for palaeo-environmental reconstruction in Japan especially. Other archives can be tied to Suigetsu, for example by tephrochronology or by wiggle-matching of 14C dates, enabling the construction of a linked regional network of sites used for palaeo-environmental analysis, enabling a better understanding of regional variations in past climatic changes.

５．主な発表論文等

〔雑誌論文〕（計１件）

① Gordon Schlolaut, Achim Brauer, Takeshi Nakagawa, Henry F. Lamb, Jonathan J. Tyler, Richard A. Staff, Michael H. Marshall, Christopher Bronk Ramsey, Charlotte L. Bryant, Pavel E. Tarasov, Evidence for a bi-partition of the Younger Dryas Stadial in East Asia associated with inversed climate characteristics compared to Europe, 2017, Nature Scientific Reports 7, 44983; doi: 10.1038/srep44983 査読有

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６．研究組織

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