Radiometric Dating of Lake Sediments : A Reaview

Proceedings: International Symposium of the Kanazawa University 21st-Century COE Program Vol. 1 (2003)
Edited by Naoto KAMATA

Radiometric Dating of Lake Sediments: A Review

Noriko HASEBE AND Kenji KASHIWAYA
Institute of Nature and Environmental Technology, Kanazawa University, Kanazawa, Ishikawa 920-1192, JAPAN

Abstract - Lake sediments yield records of information about climatic and tectonic conditions in the past with local to global scales. Dating of sediments is the first step to extract quantitative information from the record. The magneto- and bio- stratigraphy is always a powerful tool. An orbital tuning of successive data on physical and chemical properties of sediments also could provide timescale. Radiometric dating techniques can provide stand-alone numerical values, though each methodology could be applied to restricted samples and time-spans. This paper reviews several radiometric dating methodologies which could be applied to lake sediments, addressing advantages and requirements of each methodology.

I. Introduction

Lake sediments yield records of information about climatic and tectonic conditions in the past with local to global scales depending on geomorphological circumstances of lakes where sediments were recovered. Sediment supply could be from catchement area where geology, topography, precipitation would be main factors to control some of sediments' characteristics. Or, when erosion is minor in surrounding area, aerosol deposition would be dominant and provide global scale information.

Dating of sediments is the first step to extract quantitative historical information from the record. Biostratigraphy is a powerful tool if we could extract age-diagnostic fossils from sediments. However, unlike from the situation of ocean sediments, lives in lakes sometimes evolve in their own ways because of their isolation and might not give us an evident clue to decide depositional ages. Magneto-stratigraphy is always effective to collect significant data especially for fine grained samples [1, 2]. To avoid wrong matching of the normal-reverse magnetic stripe, several age pins to point the record on the right timescale would be necessary. An orbital tuning of successive data on physical and chemical properties of sediments also provides timescale successfully [3]. Again, several ages obtained by different means are highly important to achieve reliable tuning.

Radiometric dating techniques can provide stand-alone numerical values, though each methodology could be applied to very restricted samples and time-spans. This paper reviews several radiometric dating methodologies which could be applied to lake sediments. Addressing advantages and requirements of each methodology would be helpful to figure out an ideal combination of applied techniques to investigate sediments from a particular lake of a given nature. Fig. 1 shows radiometric dating techniques often applied to lake sediments. Following is the detail of each methodology.

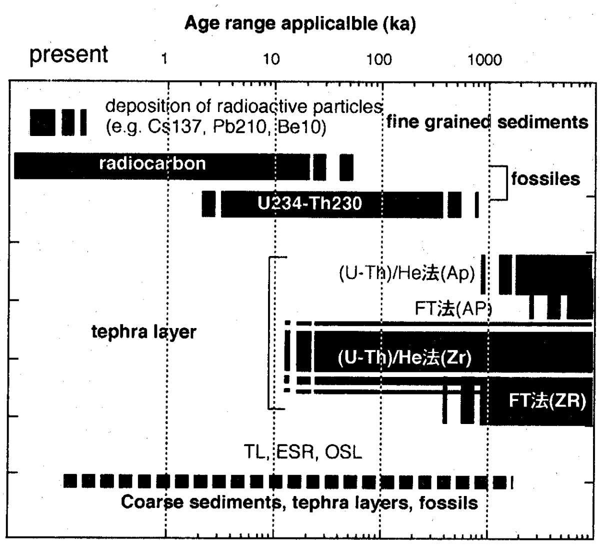

Fig. 1. Age range applicable by each methdology.

II. Cosmogenic Nuclide Dating

A. ^{14}Carbon (Radiocarbon) method

^{14}C (radiocarbon) dating is the most successful method applied to organic material from lake sediments. ^{14}C, produced by the $^{14}N(n, p)^{14}C$ reaction in the upper atmosphere, exists by certain amount in the biosphere and incorporated to living organisms with more or less the same amount through the continuous exchange of carbon between their body and circumstance (atmosphere, sea, lake, etc). When the organism stopped to exchange carbon, in the other word, died, the amount of radiocarbon in the organism start to decrease according to the decay rate of radiocarbon. Ages are calculated by measuring the amount of ^{14}C against total carbon by using accelerated mass spectrometer (AMS) or by observing decay process through counting the beta particle emission. The half-life is 5730 years [4], (5568 years known as Libby's value is commonly used in scientific reports) therefore this method is suitable for samples younger than ~ 50 kyrs. The amount of a sample necessary could be reduced down to ~ mg order in use of the AMS. The question about the ^{14}C production rate in the atmosphere, which has worried scientists for a long time, is recently answered by comparing radiocarbon ages against dendro-chronology and ionium ages, and calibration line between calculated radiocarbon age and true historical age is available [5]. Because the radiocarbon ages not necessarily represent the time of deposition of the lake sediment, the interpretation of data needs extra caution regarding the geological occurrence of fossil organisms.

B. Other cosmogenic nuclide method
C.

Other cosmogenic nuclides such as ^{36}Cl, ^{26}Al, and ^{10}Be also have a potential to provide depositional ages supported by recent advances in micro-analysis mainly using the AMS. The combination of ^{26}Al and ^{10}Be measurements often applied to understanding of geomorphological evolution by estimating exposure duration of surface rocks [6, 7]. The ^{36}Cl measurement is applied to ice cores and ^{36}Cl contents profiles are compared against cosmogenic nuclear production rate to give successive ages of cores [8]. These methodologies have been rarely applied to lake sediments so far, because of the lack of precise understanding on how those elements behave within soils. However, their half-lives of $\sim 10^5$ to $\sim 10^6$ years orders suggest their great potential to be applied to lake sediments.

III. Cs 137

Human activity produced and scattered a lot of artificial radioactive elements mainly by nuclear bomb testing. The peak of those events is at ~1963, therefore some of those elements are enriched in sediments deposited at that time, giving an age mark on sediments. Among those elements, ^{137}Cs has a half life of 30 years and is detectable by means of γ-ray detection. If half-life is too short, most of target atoms were already decayed to another element and undetectable. If half-life is too long, few atom would decay during observation and γ-ray emission would not be detected, impossible to estimate the amount of radioactive isotope. The ^{137}Cs measurement was applied to many lake sediment cores and successfully pointed the age of 1963. The elements which have longer half lives difficult to detect by γ-ray detection (e.g., ^{135}Cs) could be measured by chemical analyses. Recent development of ICP-MS or AMS could provide alternative approach to measure several artificial elements.

IV. U series

Uranium decay series is the source of many techniques to obtain radiometric ages. Among them, ^{210}Pb method, Ionium dating method, fission track (FT) method, and (U-TH)/He method are introduced.

A. ^{210}Pb method

^{210}Pb is one of daughter products of ^{238}U decay chain. When an uranium atom decayed to Rn, a noble gas, it would easily escape to atmosphere. Then, it would further decay to metal element which could not stay in the air any more and might deposit in a lake. The age of sediments would be calculated from the amount of ^{210}Pb, a daughter of radioactive radon, by means of γ-ray detection. ^{210}Pb has a half life of 22 years, therefore capable of age determination back to 200 years. The age calculation is not straight forward because initial amount of ^{210}Pb is difficult to estimate and turbulence of sediment might occur after deposition mostly caused biologically (e.g. worm activity). Given a certain assumption or model to apply, however, the methodology can often provide reliable age framework [9]. The amount of sample necessary depends on concentration of ^{210}Pb and background level of γ-emission detector. Finer sediments, which imply less material supply from the catchment area, often provide better results.

B. Ionium dating (U disequilibrium method)

Ionium dating focuses a part of uranium decay chain: decay from ^{234}U to ^{230}Th. Because of the solubility difference between uranium and thorium, we could expect little amount of Th in lake water, therefore in sediments on the lake bottom or in orgasms which develop their body from lake water. When time passed since deposition, part of ^{234}U decays to ^{30}Th and the ratio of these isotopes provide a depositional age. The amount of both isotopes would be determined by α-emission detection or mass spectrometer. An amount of sample necessary varies depending on techniques adopted. Both techniques needs chemical pre-treatment of samples to avoid signal interfere from other elements. The suitable age range applied is <100 k years concerning half life of ^{230}Th decay (80 kyrs) to subsequent daughter elements. Carbonate fossils are most successful material for this method , though most of the results are from coral reef [10] not from the lake sediments.

Uranium disequilibrium method is a stricter version of the Ionium dating [e.g., 11]. It considers ^{234}U addition to the target system by the decay of ^{238}U, ^{230}Th decrease as a consequence of further decays, and a possible initial incorporation of ^{230}Th into the target system. The method would be applied by measuring precise ratio of each isotope against stable element (mostly ^{232}Th).

C. FT method

Spontaneous fission of ^{238}U also provides depositional ages of sediments where there are tephra layers in lake sediments. When a spontaneous fission occurs, fissioned fragments travel within an uranium bearing mineral or glass and leave a track. By counting a number of such tracks and measuring ^{238}U concentration of target material, an age of tephra can be delivered. The decay constant of this decay style is very low, therefore suitable to samples older than 0.5 Ma. For material with lower uranium content, this limit become older. Amount of samples also depends on uranium content of the dated material. Generally, more than 100 grains of uranium bearing mineral (or glass) would be necessary.

D. U-Th/He method

The U-Th/He method can be applied to the same material with that FT method is applied to. This method measures number of α particles (He atoms) emitted from ^{238}U, ^{235}U, and ^{232}Th through decaying to the stable daughter of ^{206}Pb, ^{207}Pb and ^{208}Pb respectively. By heating the material measured, He atoms stored in material are extracted and measured by means of mass spectrometer. Because every decay scheme produces several He atoms, the age range applied would be > 10 kyrs, which is much younger than the age limit by the FT method. Because He is highly mobile noble gas, ages by this method sometimes are much younger than expected and long been interpreted as unreliable and untrustworthy. Recent understanding of the He diffusion behaviour, however, promises its potential as a Quaternary dating technique [12]. Although there is no example of this mehtod to be applied to lake sediments yet, the method has the great potential.

V. TL, ESR and OSL methods

Mineral crystals often preserve defects in them. Those defects trap particles radiated from surrounding materials which may include natural radioactive elements such as ^{40}K and uranium series elements. A mineral exposed to surrounding material longer yield more trapped particles. Therefore the signal intensity which represent amount of trapped particles can represent an age provided the annual dose of surrounding material. There are three techniques to detect signals, TL (thermoluminescence), ESR (electron spin resonance) and OSL (optical stimulated luminescence) methods. Those methodologies have high potential to date sediments because they can date quarts and feldspar, which are most common minerals in sediments. However difficulties to estimate annual dose prevent wide spread of this methodology. Age range datable varies depending of annual dose and initial amount of defects. Old samples would not be suitable because defects could be saturated with trapped particles. There are several successful examples of dating lake sediments (e.g. [13]).

References

[1] M. Hyodo, "Possibility of reconstruction of the past geomagnetic field from homogeneous sediments," *Journal of Geomagnetism and Geoelectricity* Vol. 36, pp. 45-62, 1984.

[2] H. Sakai et al, "Paleomagnetic Study with 14C Dating Analysis on Three Short Cores from Lake Baikal, "*Bulletin of the Nagoya University, Furukawa Museum* Vol. 13, pp. 11-22, 1997.

[3] K. Kashiwaya, S. Ochiai, H. Sakai , T. Kawai, "Orbit-related long-term climate cycles revealed in a 12-myr continental record from Lake Baikal," *Nature* Vol. 410, pp. 71-74, 2001.

[4] H. Godwin, "Half-life of radiocarbon", *Nature* Vol. 195, pp. 984, 1962.

[5] H. Kitagawa, J. van der Plicht, "Atmospheric radio-carbon calibration to 45000 yr B.P.:late glacial fluctuations and cosmogenic isotope production," *Science* Vol. 279, pp. 1187-1190, 1998.

[6] K. Nishiizumi et al, "Cosmic ray produced 10 Be and 26 Al in Antarctic rocks: exposure and erosion history," *Earth and Planetary Science Letters* Vol. 104, pp. 440-454, 1991.

[7] A. M. Heimsath, W. E. Dietrich, K. Nishiizumi, R. C. Finkel, "Cosmogenic nuclides, topography, and the spatial variation of soil depth", *Geomorph* Vol. 27, pp. 151-172, 1999.

[8] G. Wagner et al, "Chlorine-36 evidence for the Mono Lake event in the Summit GRIP ice core, " *Earth and Planetary Science Letters* Vol. 181, pp. 1-6, 2000.

[9] E. L. Mecray, J. W. King, P. G. Appleby, A. S. Hunt, "Historical trace metal accumulation in the sediments of an urbanized region of the Lake Champlain watershed, Burlington, Vermont," *Water, Air and Soil Pollution* Vol. 125, pp. 201-230, 2001.

[10] A. Omura, Y. Ota, "Recent Progress on Coral Reef Terrace Study in Japan," *The Quaternary Research* Vol. 38, pp. 228-236, 1999.

[11] P. Shane, O. B. Lian, P. Augustinus, R. Chisari, H. Heijni, "Tephrostratigraphy and geochronology of a ca. 120 ka terrestrial record at Lake Poukawa, North Island, New Zealand," *Global and Planetary Change* Vol. 33, pp. 221-242, 2002.

[12] K. A. Farley, B. P. Kohn, B. Pillans, "The effects of secular disequilibrium on (U-Th)/He systematics and dating of Quaternary volcanic zircon and apatite," *Earth and Planetary Science Letters* Vol. 201, pp. 117-125, 2002.

[13] R. M. Negrini et al., "A paleoclimate record for the past 250,000 years from Summer Lake, Oregon, USA: I. Chronology and magnetic proxies for lake level," *Journal of Paleolimnology* Vol. 24, pp. 125-149, 2000