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NORIKO HASEBE
Institute of Nature and Environmental Technology, Kanazawa University, Kanazawa, Ishikawa 920-1192, JAPAN

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. 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 (Hyodo, 1984; Sakai et al., 1997). 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 (Kashiwaya et al., 2001) 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. Here several methodologies applicable to lake sediments, which, in many cases, are Quaternary weathered sedimentary rocks, are introduced.

II. Tephra chronology

Widespread tephra by explosive volcanic eruptions play a role as an isochron layer and often found within lake sediments.

Ａ) Age determination of a tephra layer: the correlation to the known wide spread tephra
A rich accumulation of knowledge on tephro- & volcano- stratigraphies is available in countries such as Japan (Figs 1 and 2). When a tephra layer is found from lake sediments recovered form such countries, you could correlate the tephra to well known widespread tephra. The important points in correlation are:

１, The area where the tephra layer (lake sediment) is obtained.
２, Approximate age
３, Mineral and chemical composition of the tephra

To characterise tephra layers, volcanic glasses are the material you focused on. Wash tephra to remove adherent mud (or clay). Remaining sandy fraction contains volcanic glasses. Put them on a slide glass to form a thin section. A kind of resin, which hardens when exposed to sunlight, is easy to handle as the mounting material of them. The shape of volcanic glasses varies depending on its chemistry, physics of eruption, and so on, and is a good indicator to distinguish volcanic glasses from different origins. A refractive index reflects chemical composition of the glass and also useful to identify the glass. As well as volcanic glass characteristics, rare earth element composition and mineral composition especially in terms of accessory minerals also help the identification of volcanic glasses.

B) When a tephra layer is failed to correlate known widespread tephra.
When an obtained tephra layer is correlated to none of known widespread tephra, you can date them by radiometric dating methods. There are many good textbooks for introduction of dating methodologies (e.g. Principles of Isotope Geology by Faure, 1986). Following is the brief introduction of methodologies applicable to tephra from lake sediments.

K-Ar dating
The K-Ar dating can be applied to volcanic glasses when following criteria are satisfied: (1) a sample is fresh without weathering, (2) more than two grams of a sample are obtained, and (3) an expected age is older than ~100,000 years. A sample should be composed of pure volcanic glasses without any contaminant. It divided into two aliquots: one is for Ar40 isotope measurement and the other is for potassium measurement. We need a mass spectrometer to measure amount of Ar40. To assess the contribution from atmospheric Ar40 contamination, the peak comparison method is better than the spike method because the peak comparison method enable to correct possible isotope fractionation factor for atmospheric composition. On the other hand, the spike method has an advantage in its better precision than the peak comparison method. The potassium concentration is often measured by a flame photometer after dissolution of the sample using general chemical procedure. The alternative approach for K measurement use nuclear reactor irradiation. The irradiation turns 39K to 39Ar. Therefore, to date a sample, we can measure the ratio of 40/39 Ar using the same mass spectrometer. Advantage of this method is that the K (in fact 39Ar) and Ar 40 are measured in the same fraction. On the other hand, disadvantage is that isotope fractionation factor in atmospheric Ar contamination is impossible to estimate because of interference Ar isotopes arisen by irradiation. Volcanic glasses from lake sediments are most likely weathered. Therefore, laser ablation Ar/Ar dating, which could date fresh small spots selectively, could be useful.

Fission Track Dating
When volcanic glass contains significant amount of uranium, samples older than ~100,000 years could be dated by the fission track method. After mounting volcanic glasses in resin, samples should be polished to expose significant internal surface and then etched by the hydrofluoric acid to reveal fission tracks which intersect the observed surface. These tracks are visible under the microscope. By combining the number of fission tracks and uranium concentration of a sample, we can calculate the age of a sample. However, tracks within glasses are less stable compared to those in minerals such as zircon and apatite, therefore, we need to estimate the amount of track annealing (healing). One method is "plateau dating", in which, samples are irradiated and heated to observe thermal sensitivity of tracks. The other method uses the size of track diameters to know the amount of track annealing. Due to less understanding the physics of glass track annealing characteristics and difficulty to obtain significant amount of data sufficient for statistical treatment, glass fission track dating is not used commonly in these days. The widespread tephra occasionally contains uranium-bearing mineral such as zircon and apatite. Fission tracks in these minerals are stable at ambient temperature, therefore we can use calculated ages without any correction necessary for glass fission track dating. Etchant for zircon is eutectic liquid of alkali (NaOH: KOH = 1:1 in mole) and that for apatite is dilute nitric acid (e.g. 0.6%). The measurement of uranium content is conventionally done through neutron irradiations at nuclear reactors. Recent progress in micro-chemical analyses, however, might open a new way to calculate and calibrate fission track ages using uranium content obtained other methodologies (e.g. LA-ICP-MS).

TL, ESR, OSL dating method
Minerals which do not contain radioactive element (e.g., quartz) also can store radiation damage from surrounding radioactive element such as ^{40}K and uranium series elements. The radiation damage is detected by methods such

as thermoluminescence (TL), electron spin resonance (ESR), and optical stimulated luminescence (OSL). These methods have advantages that the techniques could be applied variety of samples. Applicable age range is from modern to Miocene depending on signals to be detected. Sample preparation is relatively easy compare to above two methodologies. The disadvantage of the techniques lies in difficulty in estimating the amount of annual dose.

C）Tephrochronology of the Lake Baikal region

The lake Baikal is the tectonically formed within the rift. Therefore, we can observe volcanic activity of a rift in surrounding regions. These volcanoes, however, are mostly basaltic, unable to expect explosive eruption. One exception is the Udokan volcanic field, north of Baikal rift, where the trachytic ignimbrite are distributed. Considering the wind direction of the region, though, the supply of tephra into the lake Baikal is ambiguous. Sediments around ~2000 BP and 8000 BP would be worth to watch closely in terms of tephrochronology.

D）The tephrochronology of other lakes

The sediment of the lake Biwa, Japan, contains many tephra layers contributing age determination of sediments. There are several successful reports from lakes in New Zealand（Shane et al., 2002） and eastern side of North America (Neglini et al., 2000), where volcanoes are active（fig. 4&5）.

III. Dating by sedimentary radioactivity

Measurement of radioactivity from Cs137, Be10, and uranium series radioactive elements deposited with sediments are widely used to date lake sediments. The detail is described in the previous sections.

IV. Dating of fossils

Some of fossils found from lake sediments can be dated by radiometric dating methods.

A）Radiocarbon (^{14}C) dating of organic fossils

When organic fossils such as plants are found in lake sediments, radiocarbon dating method, which uses the decay of ^{14}C content against total carbon, can be applied to date the time elapsed since the stop of their activity (death). An age range applicable is less than 50,000 years. The technique used to rely on beta decay detection by liquid scintillation counter. Sample preparation for the purpose of carbon accumulation was time consuming. Recent developments on accelerator mass spectrometry, however, enable the measurement of carbon isotopes separated from other molecular or compounds of similar mass, resulting in the dating of small amount of samples. To date fossils, we need to investigate the occurrences of them carefully to avoid the dating of recycled fossils. Detailed and massive analysis of the sediments from Lake Suigetsu, Japan, using radiocarbon dating techniques provide information about C14 concentration variation through history as well as chronological understanding about environmental evolution of the region.（Fig. 6）

B）Calcareous fossil- ionium method

Calcareous fossils are often found from ocean sediments and U- series dating method is successfully applied. For sediment from lakes, however, there is little report of dating calcareous fossils. Future investigation could extend the knowledge of this field.

テフラ名 (記号)	年代 (ka) (測定方法)	噴火・堆積 様式と順序	全テフラ量 (みかけ, km³)	本質テフラ粒の特性 火山ガラス, n	斑晶
白頭山苫小牧 (B-Tm)	0.8〜0.9 (A, C)	pfa, pfl, pfa, pfl	50	pm, bw 1.511-1.522	af, (am, cpx) af 1.521-1.525
鬼界アカホヤ (K-Ah)	6.3 (C)	pfa, pfl, afa (coign.)	>170	bw, pm 1.508-1.516	opx, cpx opx 1.708-1.713
鬱陵隠岐 (U-Oki)	9.3 (C)	pfa, pfl	>10	pm 1.518-1.524	bi, am, cpx af 1.522-1.524 ho 1.726-1.740
姶良 Tn (AT)	21(〜25) (C)	pfa, pfl (pp), pfl, afa(coign.)	>450	bw, pm 1.498-1.501	opx, cpx, (ho ; qt) opx 1.728-1.734
クッチャロ庶路 (Kc-Sr)	30〜32 (C)	afa, pfl, afa (coign. ?)	100	pm, bw 1.502-1.505	opx, cpx opx 1.707-1.710
支笏第 1 (Spfa-1, Spfl)	31〜34 (C)	pfa, pfl	200	pm, bw 1.500-1.505	opx, ho, (cpx) ; qt opx 1.729-1.735 ho 1.688-1.691
大山倉吉 (DKP)	43〜55 (U, ST)	pfl, pfa	>20	pm 1.508-1.514	ho, opx, (bi) opx 1.702-1.708 ho 1.673-1.680
阿蘇 4 (Aso-4)	70(〜90) (ST, FT など)	pfl, afa(coign.)	>600	bw, pm 1.506-1.510	ho, opx, cpx opx 1.699-1.701 ho 1.685-1.691
鬼界葛原 (K-Tz)	75(〜95) (ST, TL)	afa(pp), pfl, afa(coign.)	150?	bw, pm 1.494-1.500	opx, cpx ; qt opx 1.705-1.709
御岳第 1 (On-Pm1)	80(〜95) (FT, KA)	pfa	50	pm, (bw) 1.500-1.503	ho, bi, (opx) opx 1.706-1.711 ho 1.681-1.690
三瓶木次 (SK)	80(〜100) (ST)	pfa	20	pm 1.494-1.498	bi ; qt
阿多 (Ata)	85(〜105) (ST)	afa(pp), pfa, pfl, afa(coign.)	>300	bw, pm 1.508-1.512	opx, cpx, (ho) opx 1.704-1.708
洞爺 (Toya)	90〜120 (FT, ST)	afa(pp), pfl, afa (coign.)	>150	pm, bw 1.494-1.498	(opx, cpx, ho ; qt) opx 1.711-1.761 ho 1.674-1.684
阿蘇 3 (Aso-3)	105〜125 (FT, ST)	pfa, pfl, sfl, afa (coign.)	>150	pm, bw 1.512-1.540	opx, cpx opx 1.702-1.705
クッチャロ羽幌 (Kc-Hb)	100〜130 (FT, ST)	afa・pfa, pfl, afa (coign.)	>150	bw, pm 1.502-1.506	opx, cpx opx 1.705-1.710
阿多鳥浜 (Ata-Th)	230〜250 (ST)	pfa, pfl, afa (coign.)	>100	bw, pm 1.498-1.500	ho, opx, bi ; qt opx 1.714-1.718 ho 1.670-1.674
加久藤 (Kkt)	300〜320 (FT, ST)	pfl(coign.)	>100	bw, pm 1.500-1.502	opx, cpx, (ho) opx 1.718-1.725

Table The list of widespread tephra supplied by the mega eruptions in and around Japan Island in the past 300 kyrs

Dating method一A：Archeological remanent，C：Radiocarbon，U：Uranium series dating method，ST：Stratigraphical estimate based on radiometric ages, FT：Fission track method, TL：Thermoluminesence, KA：K-Ar method

Eruption-deposition style—(from bottom to top) pfa：pumice fall deposit, pfl：pyroclastic flow deposit, afa：ash fall deposit, sfl：scoria flow deposit，pp：Plinian style steam eruption ash，coign：ash fall deposit accompanied by large scale pyroclastic flow, afa･pfa represents alternating eruption. Parenthesis indicates small amount of existence.

Volcanic glass pm：pumice glass, bw：bubble glass, ”n” represents refractive index,

Phenocryst一af：alkali feldspar, am：amphibole, ho：hornblende, cpx：clinopyroxene, opx：orthopyroxene, bi：biotite, qt：quarts

From Machida and Arai “Atlas of tephra in and around Japan”

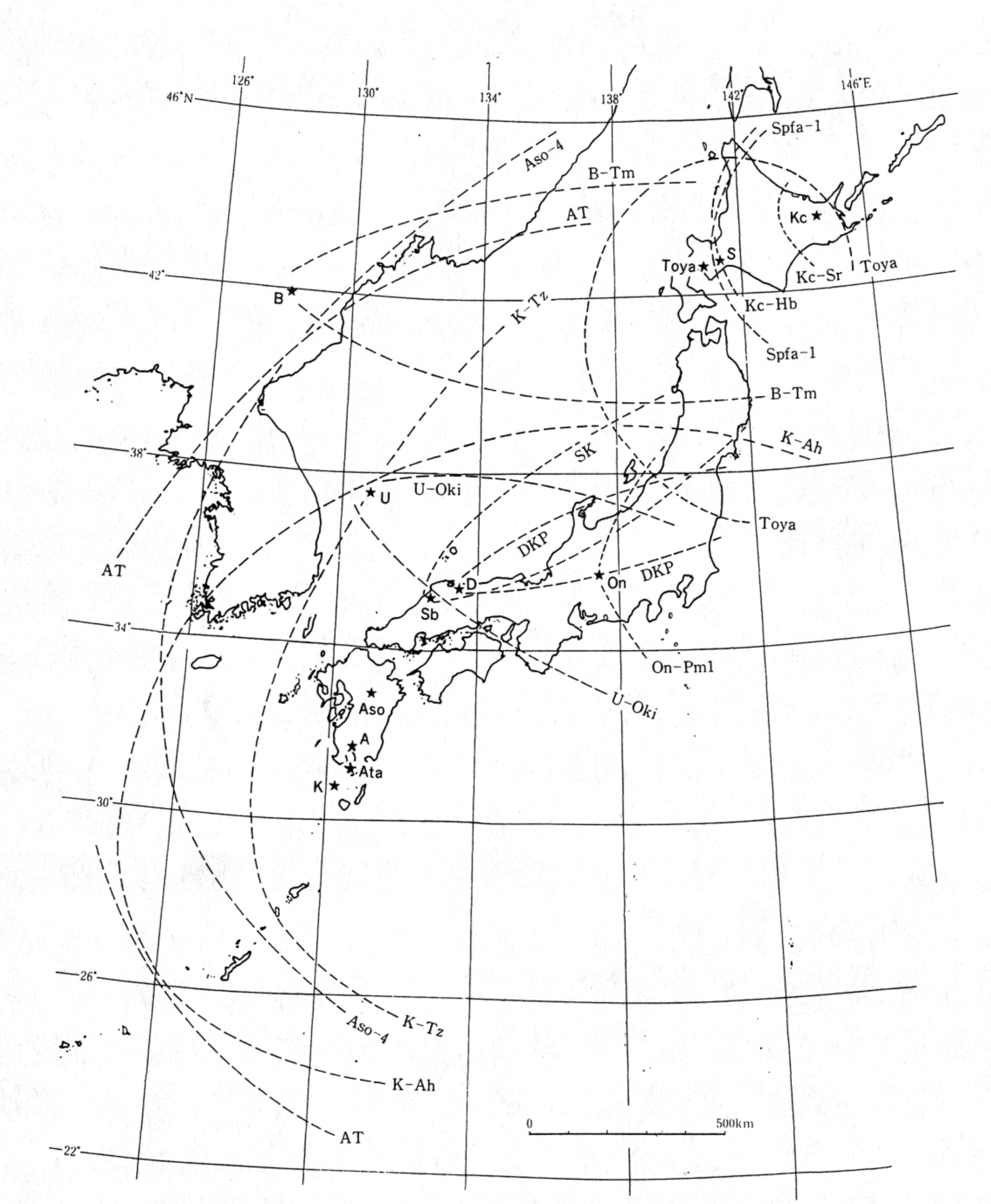

Fig. 1 Distribution of the late Quaternary wide spread tephra around Japan

Dotted lines indicate the distribution margin where the tephra is visible at the locality. See the table to identify the tephra abbreviation. Origin of tephra (volcano or caldera), Kc: Kucharo, S: Shikotsu, Toya: Toya, On: Ontake, D: Daisen, Sb: Sanbei, Aso: Aso, A: Aira, Ata: Ata, K: Kikai, B: Bekduesan, U: Ururundo

From Machida and Arai “Atlas of tephra in and around Japan”

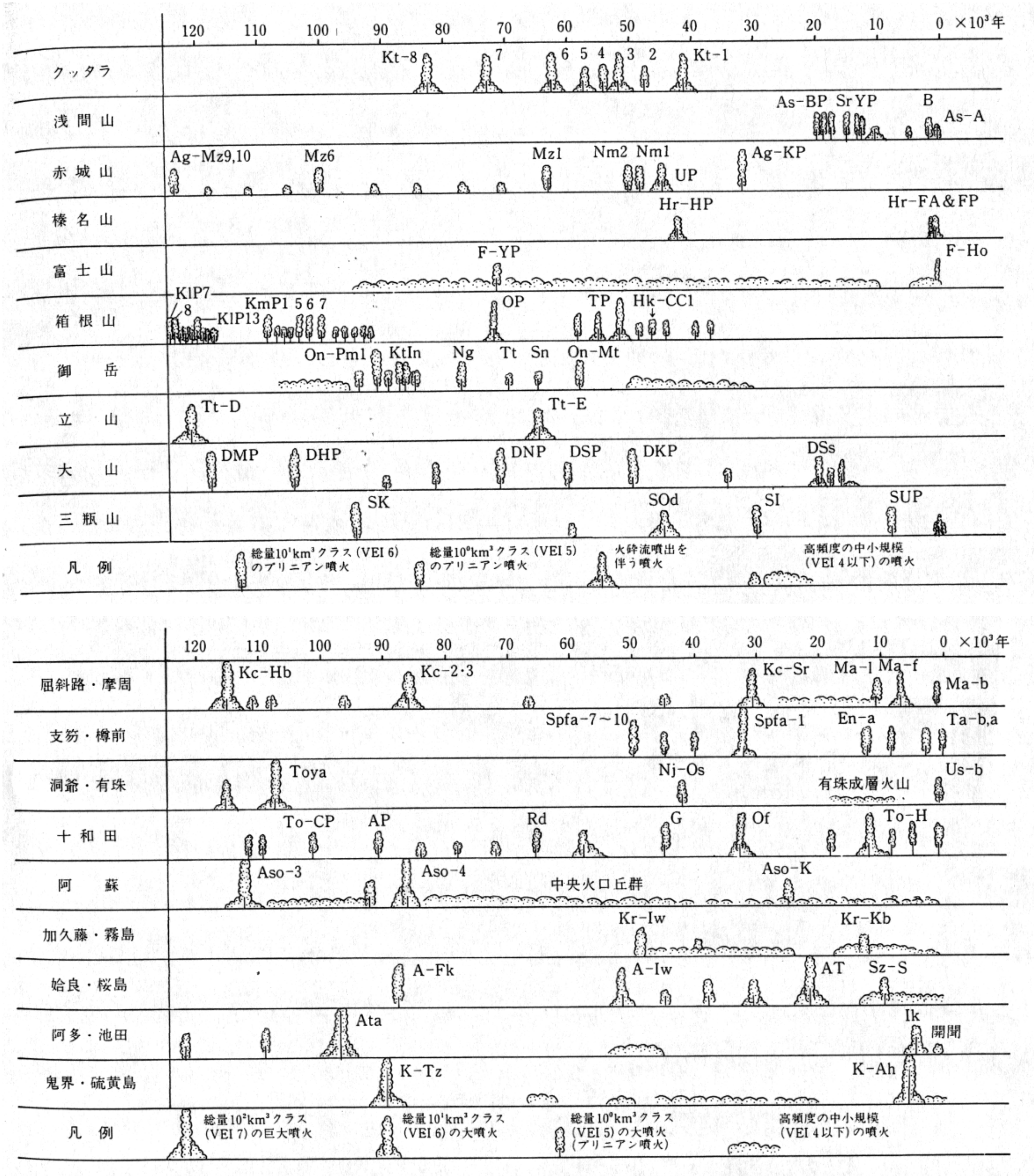

Fig. 2 The history of mega-eruption in late Quaternary (past 125kyrs). Upper figure; 10^0-10^1km^3 scale, Lower figure; 10^1-10^2km^3 scale.

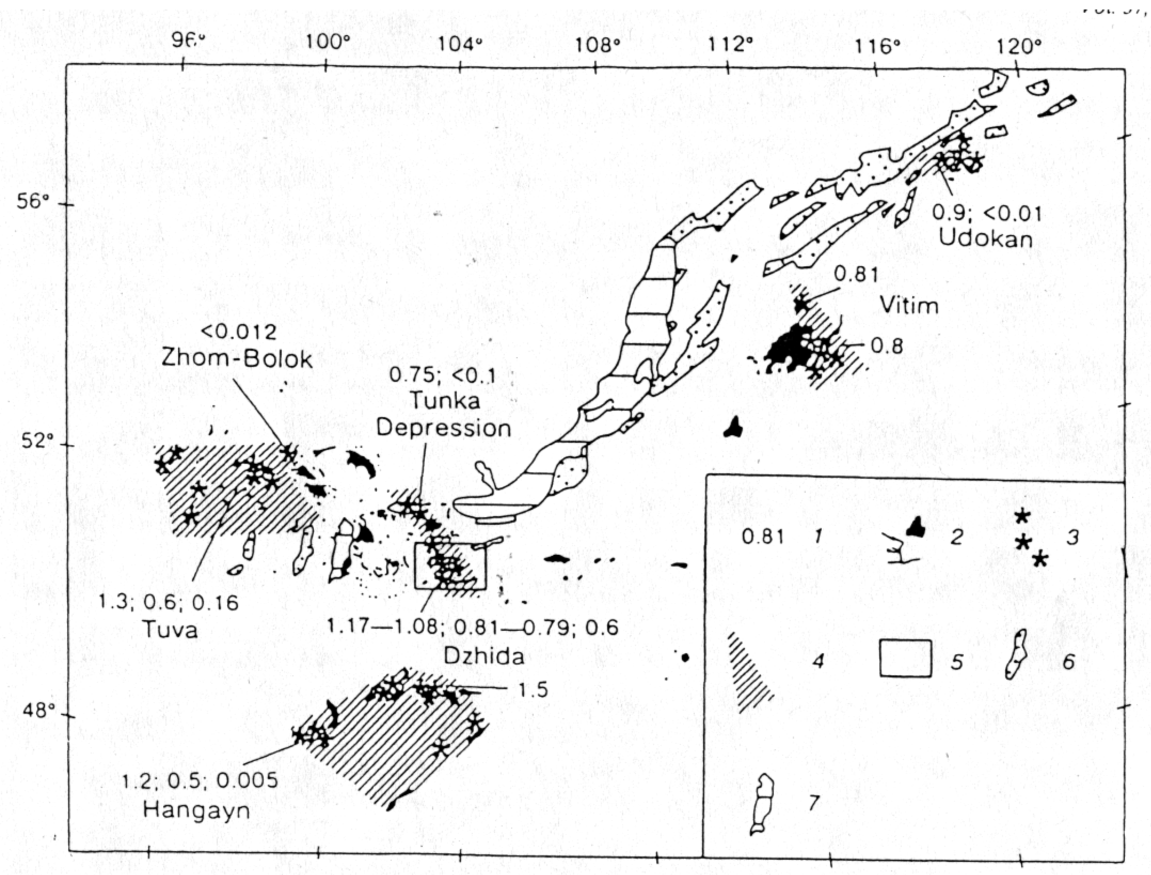

Figure 3 Quaternary volcanic activity around the lake Baikal

1:numerical ages, 2:Cenozoic volcanic rift,

3:Quaternary and Pliocene volcanoes, 4:Quaternary volcanic area,

5:Detailed research area within Dzhida district, 6:valleys without lakes,

7:Valleys with lakes

From Rasskazov et al. (1996)

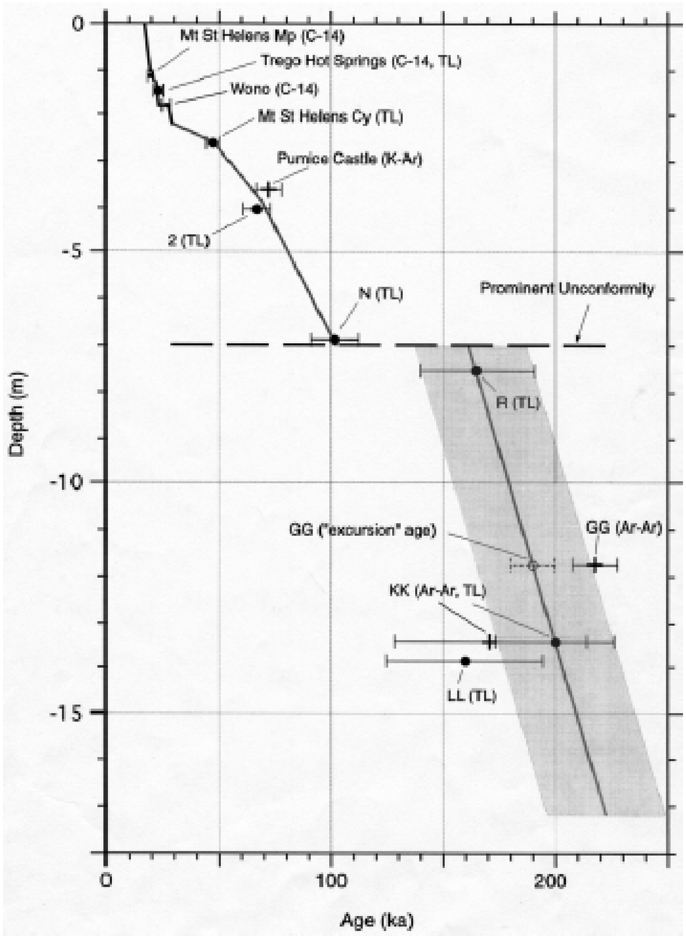

Figure 4 Successive example of lake sediment dating from the Summer Lake USA (Negrini et al., 2000 より)

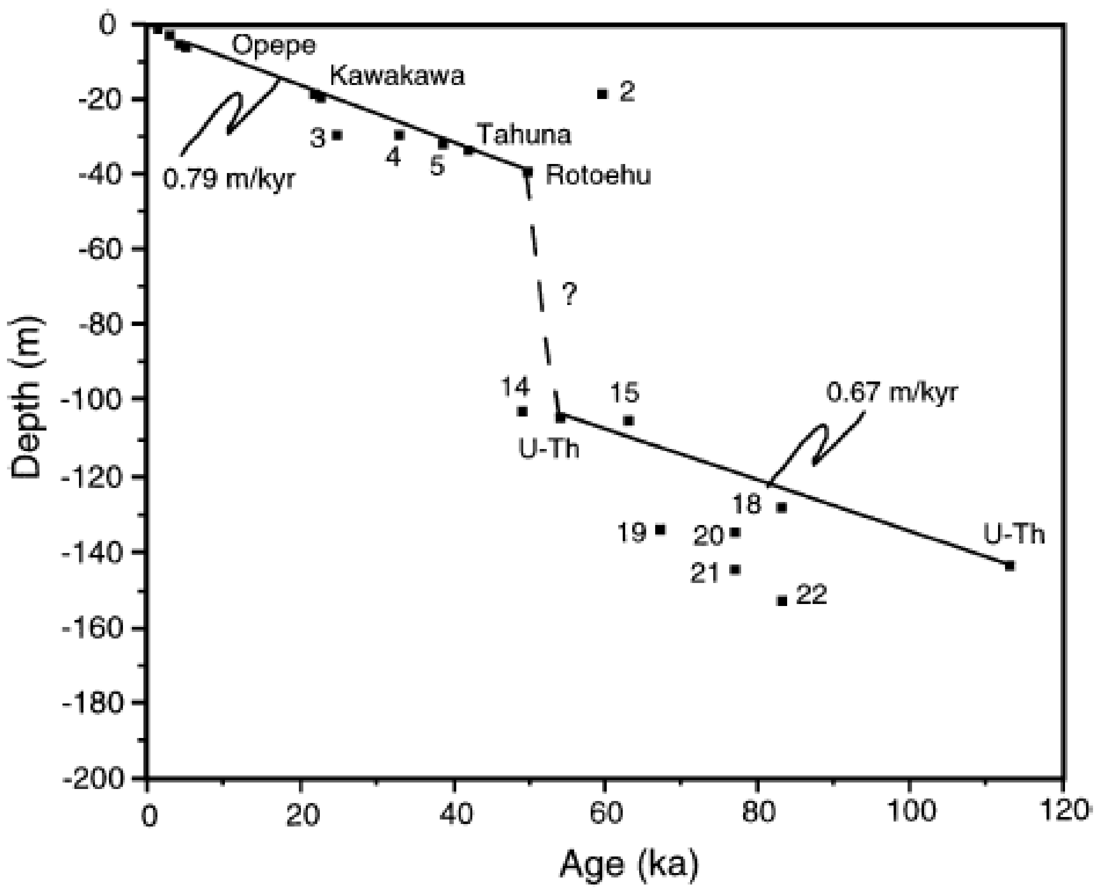

Figure 5 Example of lake sediment dating from the Lake Poukawa, the New Zealand. Ages of Upper 40 m are given by the tephrochronology, and lower are U-Th ages. Figures are OSL ages.（Shane et al., 2002）

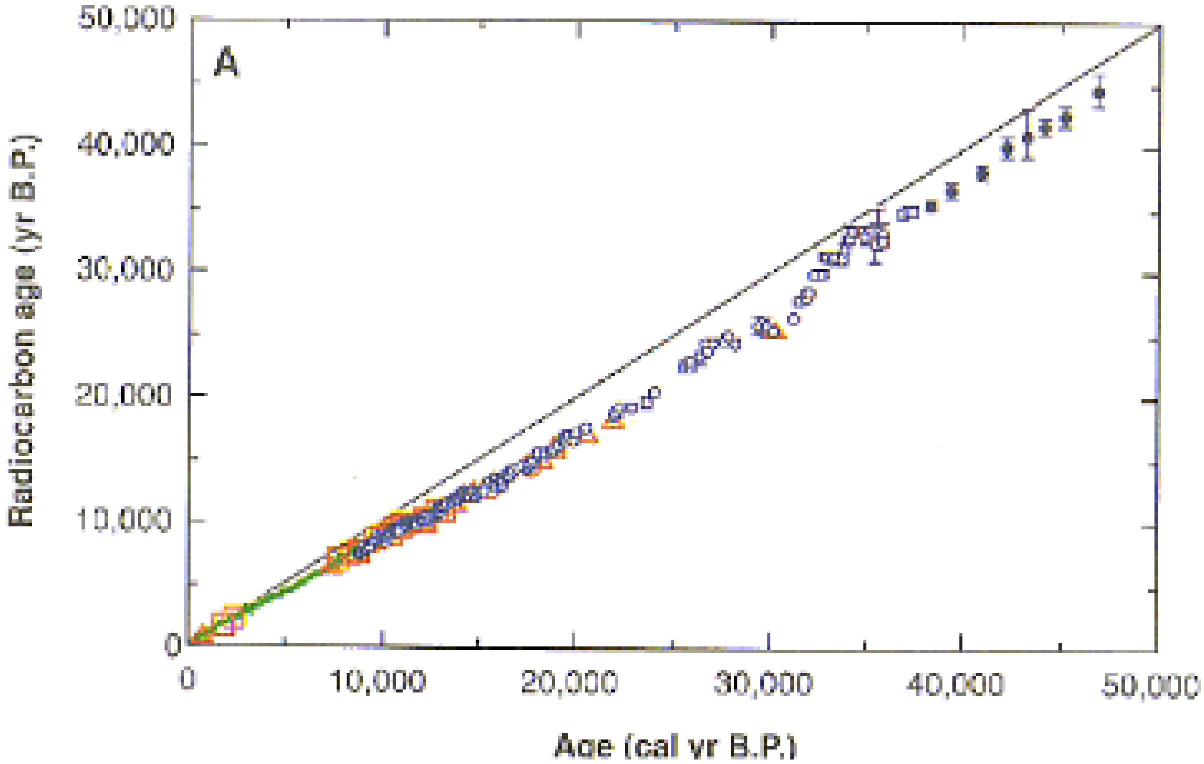

Figure 6 Detailed radiocarbon dating from the Lake Suigetsu, Japan（Kitagawa and van den Plichtm 1998）