^{14}C DATING OF TERRESTRIAL MOSS IN TERN LAKE DEPOSITS, ANTARCTICA

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ABSTRACT. Accurate radiocarbon ages were obtained from terrestrial moss from two drill holes in Tern Lake deposits, Antarctica, using liquid scintillation counting (LSC) and accelerator mass spectrometry (AMS). The results show that the lake deposits have been accumulating since the end of the last glacial epoch *ca.* 12,600 cal BP at the rate of 0.13–1.1 mm a^{-1}. We discuss the validity of ^{14}C ages of Antarctic lake deposits, with respect to the latitude effect of ^{14}C productivity, the reservoir effect, the environment effect and the hard-water effect.

INTRODUCTION

Tern Lake (62°13′14″S, 58°57′38″W) is near the Great Wall Station of China at Fildes Peninsula, King George Island, Antarctica (Fig. 1). It is 8800 m^2 in area and 5 m deep, with slightly saline water. Being frozen for more than six months of the year, the area is characteristic of an arid glacial environment with little chemical weathering. The lake deposits are composed mainly of rock fragments, clayey and fine sand and pebbles introduced by melting flows and wind from the surroundings (Li, Zheng and Liu 1992). A better understanding of the sedimentation process, particularly from a chronological approach, will provide valuable information for tracing the ancient environment and climatic variation in the area.

Two drill holes (core A and core B) were made in the lake by Prof. Xiaobo Chen of the Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, during China's fifth Antarctic expedition (January 1988–March 1989). Another drill hole (core C) was made by Professor Baoyin Yuan of the Geology Institute, Chinese Academy of Sciences, during China's ninth Antarctic expedition (April–July 1993). Complete sets of core samples were obtained from the holes, which reached to the basement rock at depths of 7.76 m (core A), 7.45 m (core B) and 3.94 m (core C). Terrestrial moss from lake deposits is an ideal material for radiocarbon dating. It gives more precise ages than can be obtained on bulk sediment. Therefore, this method has become quite common in lake studies (Lotter 1991; Hajdas 1993). Fildes Peninsula is a major colony of terrestrial moss in Antarctica, but moss fragments and authigenic carbonates occur only in very small amounts. Besides the traditional radiometric method, the accelerator mass spectrometry (AMS) technique has been used for ^{14}C measurements in this work.

SAMPLE DESCRIPTION AND ^{14}C ANALYSIS

The Samples

Moss samples from cores A and C were used in this study. Figure 2 shows the profiles of the deposit. Core A measures 7.76 m in length, consisting mainly of sediments, except for the basement rock (0.31 m long) at its lower end. Altogether, 130 pieces of specimens were taken from core A, among which 5 pieces (A1-A5) are rocks and 125 pieces (A6–A130) are sediments sampled at every 6 cm of the hole. ^{10}Be and susceptibility measurements were made on the sediments. A few pieces of animal shell relics were recognized in A42, A46, A47, A48, A54 and A55. Terrestrial moss occurs as

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clay-wrapped spherules in A62 (503–510 cm), A45 (573–575 cm) and A43 (580–585 cm). The moss is 23 mg in A62 and 12 mg in A45; only a few fragments were seen in A43. Core C measures 3.94 m in length, consisting dominantly of sediments, except for the basement rock (0.98 m long) at its lower end. Altogether, 46 pieces of specimens were taken from core C, among which 2 pieces (C1,C2) are rocks and 44 pieces (C3-C46) are sediments, sampled at every 10 cm in the upper portion of the hole and every 5 cm in the depth range 1.4–2.96 m. In comparison, some samples of modern moss from Antarctica have been collected. All moss discussed here is *Drepanocladus uncinatus*.

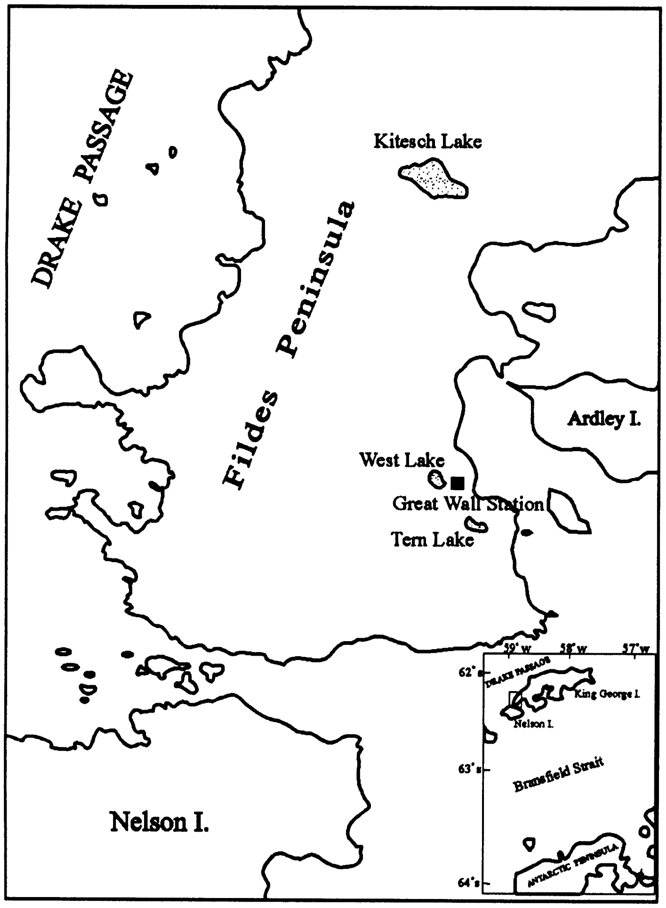

Fig. 1. Schematic map showing the geographical setting of Tern Lake in the Fildes Peninsula. The square in the inset map is Fildes Peninsula.

^{14}C Measurement

^{14}C-AMS analyses were made on A62 and A45. First, the samples were cleaned for 10 min in a supersonic batch before drying in a vacuum freeze dryer for 24 h. Five mg of the dried moss was loaded with CuO into a silica ampule, which was then sealed under a vacuum and subjected to 950°C for 2 h to convert all the moss into CO_2. The CO_2 in ampule was then transferred to a sample preparer with a vacuum of up to 10^{-3}–10^{-4} Pa, in which the CO_2 was reduced to elemental carbon by reacting with high-purity hydrogen in the presence of 425-mesh cobalt powder as a reducer at 625°C for 9 h. Targets specifically used for ^{14}C-AMS measurement were prepared by pressing the carbon-mixed cobalt powder in a copper mold at a pressure of 5 t cm^{-2}. The area of graphite on the target surface is *ca.* 10 mm^2. The ^{14}C measurements were carried out using the Zürich ETH/PSI AMS system. All the measurements were repeated at least twice to achieve an accuracy within 1–2% (Suter *et al.* 1984).

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The traditional decay counting method has been used in ^{14}C measurements of the samples from core C and modern moss from Antarctica. After converting moss into C_6H_6, ^{14}C measurements were carried out using Quantulus 1220™ ultra low-level liquid scintillation spectrometer at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences. The accuracy is within 2–4%.

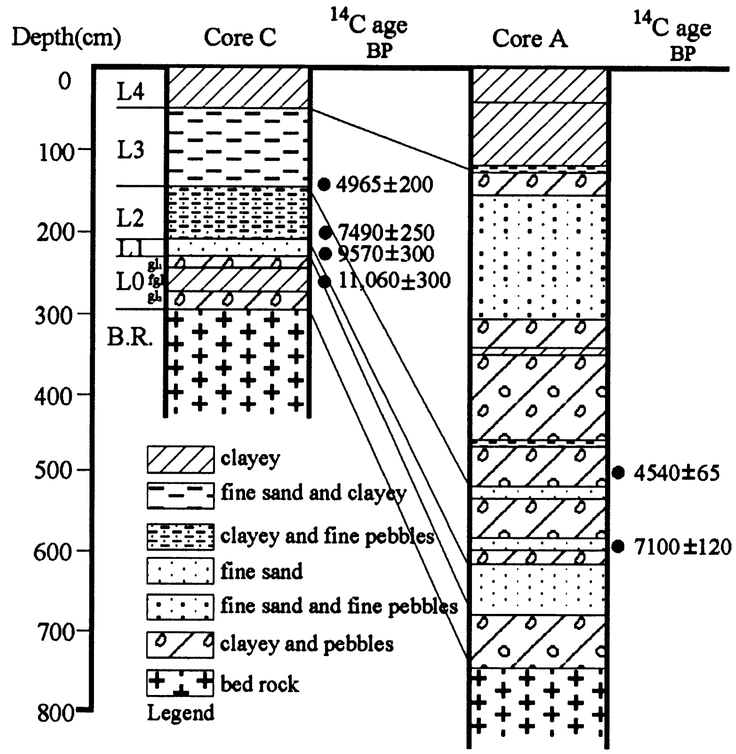

Fig. 2. Profiles of Tern Lake deposit

Results and discussion

^{14}C Ages of Lake Deposits

Table 1 presents the results of ^{14}C dating and tree-ring corrections. A 4% correction was made on the $^{14}C/^{12}C$ ratio of A45 in view of apparent isotopic fractionation.

Validity of ^{14}C Ages of Antarctic Lake Deposits

The ^{14}C age of a sedimentary deposit corresponds to the time when the sedimentary carbon was removed from the atmosphere carbon exchange reservoir, *i.e.*, when the organic matter was buried. It is well known that the ^{14}C method is based on the assumption that ^{14}C is homogeneously distributed between the various carbon reservoirs and that the initial ^{14}C concentration of the sample can be represented by the present-day ^{14}C concentration in the atmosphere. Considering the geographic uniqueness of Antarctica, a special mention is in order here about the validity of ^{14}C dating on Antarctic samples by taking into account the various effects on ^{14}C distribution on the lake.

The Latitude Effect

^{14}C is produced in the atmosphere at a constant rate through the cosmic-ray reaction ^{14}N (n,p) ^{14}C; its modern production rates can be found from measured neutron intensity in the atmosphere. ^{14}C pro-

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TABLE 1. ^{14}C Ages of Terrestrial Moss from Tern Lake Deposits, Antarctica

Field no.	Lab no.	Depth (cm)	^{14}C age (yr BP)	Tree-ring corrected age (cal BP)
Core A				
A45	GC91096	573–575	7100 ± 120	~7930
A62	GC91097	503–510	4540 ± 65	~5180
Core C				
C5	GC94052	277–282	11,060 ± 300	~12,000
C12	GC94053	233–244	9570 ± 300	~10,500
C17	GC94055	212–217	7490 ± 250	~8290
C27	GC94054	167–172	4965 ± 200	~5700

ductivity (expressed as ^{14}C numbers s^{-1}) in the present-day atmosphere is a function of latitude and elevation (in terms of atmospheric mass depth, g cm^{-2}). The ^{14}C productivity is two times higher at high latitudes (>60°) than at sea level (Equator) (1003 g cm^{-2}) and this factor may be increased to 8–10 at an elevation equivalent to 100 g cm^{-2} (Lal and Peter 1967). A $\Delta^{14}C$ value of 220‰ of modern moss at King George Island, Antarctica has been obtained. As reported in literature, the $\Delta^{14}C$ value of nuclear explosions in the 1960s has decayed to 170‰. By comparing these two values, a $\Delta^{14}C$ variation of 50‰ can be inferred for the Antarctic region. This latitude effect may result in a ^{14}C age 400 yr younger than it should be.

The Reservoir Effect

As indicated by nuclear test ^{14}C-tracing, the atmosphere-seawater exchange of CO_2 is rather slow around the Antarctic in the southern oceans. Reservoir effects like this are also reflected to a varying extent by the gas-sea exchange rate of CO_2 and deep sea circulation between seas with and without floating ice (Siegenthaler 1989). But all of these effects can be safely neglected in the terrestrial moss from which our results were obtained.

The Environmental Effect

Antarctica is nearly completely covered by thick snow and ice throughout the year. ^{14}C may be produced *in situ* as the oxygen nuclei in the ice reacts with cosmic rays. The absorption mean free path for cosmic radiation particles in ice has been estimated to be 1.7 m. This indicates that *in-situ* produced ^{14}C must be involved in the top cover of ice to a depth of 2–3 m. As can be imagined, such *in-situ* ^{14}C will be carried into lakes by either wind or meltwater. On the other hand, ancient atmospheric ^{14}C may have been trapped in ice during snow accumulation in the geologic past (Lal and Jull 1990).

Generally, ^{14}C trapped from ancient air will give an older ^{14}C age, whereas the *in-situ* ^{14}C will have the opposite effect. Although the two effects offset each other to some extent, further studies are needed before a more exact estimation can be made of the overall effect of these environmental factors on ^{14}C dating.

Hard-Water Effect

Lakes in Antarctica, as in other regions in the world, are subject to the so-called "hard-water effect" with respect to ^{14}C dating (Oeschger 1988). Alternating volcanic rocks and widespread calcite are found around Tern Lake (Zheng 1997). Bicarbonates may be formed as water and CO_2 react with carbonate fragments carried into the lake, for example, $CO_2 + H_2O + CaCO_3 \Leftrightarrow Ca^{2+} + 2HCO_3^-$. Carbon in $CaCO_3$ is free of ^{14}C, and is therefore known as "dead carbon". Thus, dilution of the organic carbon

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in aquatic plants by such dead carbon will result in older ^{14}C ages. However, this effect has been avoided in our study because terrestrial rather than aquatic moss was used for ^{14}C dating.

Sedimentation Rate

By comparing the stratigraphic column and ^{14}C age between two profiles, the sedimentary deposit in Tern Lake can be divided into five beds: L0–L4 (Fig. 2). For core A: L4 (0–1.2 m) is composed of clayey sand; L3 (1.2–5.1 m) consists of fine and clayey sand and pebbles; L2 (5.1–6.05 m) clayey and fine sand and rock fragments; L1 (6.05–6.8 m) fine sand; L0 (6.8–7.45 m) clayey sand and pebbles. An average sedimentation rate of 1.1 mm a^{-1} since 4540 BP can be obtained from the ^{14}C age of 4540 ± 65 BP of A62, which is located at a depth of 503–510 cm in the profile. Similarly, a rate of 0.8 mm a^{-1} since 7100 BP is indicated by the ^{14}C age of 7100 ± 120 BP of A45 (573–575 cm). Considering that sample A45 is 68 cm lower than A62 in the profile, and is 2560 yr older, an average rate of 0.3 mm a^{-1} can be inferred for the deposition of L2. For core C: L4 (0–0.48 m) consists of clayey sand; L3 (0.48–1.48m) fine and clayey sand; L2 (1.48–2.13m) clayey sand and fine pebbles; L1 (2.13–2.34 m) fine sand; L0 (2.34–2.96 m) clayey sand and pebbles. The average sedimentation rates can be obtained from the ^{14}C age; they are: 0.35 mm a^{-1} for the upper 1.72 m; 0.18 mm a^{-1} for the depth range 1.72–2.17 m; 0.13 mm a^{-1} for 2.17–2.44 m; and 0.26 mm a^{-1} for 2.44–2.82 m. There are some obvious differences in the sedimentary environments between the two profiles, but the boundary ages between the various beds of the profiles can be estimated based on a comparison of the stratigraphic column and the calibrated ^{14}C age, as is shown in Table 2.

TABLE 2. Estimated Boundary Ages Between Sedimentary Beds in Tern Lake, Antarctica*

Bed	Core C depth (cm)	Core C descriptions	Core A depth (cm)	Core A descriptions	Boundary age (cal BP)
L4	0–48	Clayey sand	0–120	Clayey sand	1500
L3	48–148	Fine & clayey sand	120–510	Fine & clayey sand, fine pebbles	5500
L2	148–213	Clayey sand & fine pebbles	510–605	Clayey & fine sand, rock fragments	7500
L1	213–234	Fine sand	605–680	Fine sand	10,500
L0	234–296	Clayey sand & pebbles	680–745	Clayey sand & pebbles	12,600

*Boundary ages were calculated from the calibrated dates of Table 1 and the sedimentation rates for the various beds.

The lithology of drill core C in Tern Lake (Fig. 2) shows that the upper part (above 234 cm) consists of lacustrine deposits (L1–L4) and the lower part overlying Quaternary basements is due to glacial drifts (L0). The glacial drifts (L0) are composed of the first and second glacial drifts (gl_1 and gl_2) and their intercalations of lacustrine-swamp sediments (fgl) in which abundant relics of submerged vegetation and fossils of foraminifera, marine ostracodes and diatoms were observed. These deposits are considered to be strongly influenced by the marine environment, representing a warm episode during late glaciation (Zheng 1997). The calibrated ^{14}C age of terrestrial moss extracted from the intercalation (fgl) (277–282 cm) of core C is 12,000 cal BP. With the calculated sedimentation rate, the boundary age of the glacial drifts (L0) is then estimated at 12,600 cal BP (Table 2). The above results on lithology and chronology could reflect the history of glacial movements. We could consider that Tern Lake deposits have been accumulating since the end of the last glacial epoch 12,600 yr ago at a rate of 0.13–1.1 mm a^{-1}. It is worth noting that 11,000 BP has been widely accepted as the lower limit of the glacial epoch or the beginning of the Holocene in northern Europe (Lotter *et al.* 1991). However, our

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^{14}C results show that in Fides Peninsula, the Holocene began as early as 12,600 cal BP, which may indicate that the beginning of the Holocene is hemisphere-dependent, happening earlier in Antarctic regions. Comparison of climate records of the Greenland Ice Core and Antarctic Ice Core (Vostok and Byrd ice cores) suggests that near the beginning of the last deglaciation, warming in Antarctica began *ca.* 3000 yr before the onset of the warm Bølling period in Greenland (Sowers and Bender 1995). The above results from Tern Lake may also be related to those by Sowers and Bender (1995). Samples from core C with even higher resolution have been taken for further study.

Conclusion

1. ^{14}C ages were accurately determined on terrestrial moss collected from Tern Lake deposits in the Antarctic. The results indicate that the deposits have been accumulating since the end of the last glacial epoch 12,600 BP at a rate of 0.13–1.1 mm a^{-1}.
2. The validity of ^{14}C ages obtained from Antarctic samples was evaluated regarding the various effects on the worldwide ^{14}C balance, including those related to latitude, the *in-situ* production of ^{14}C, the ancient air trapped in ice, air-sea exchange and deep seawater cycle, *etc*. The reservoir effect and the hard-water effect can be disregarded with confidence since ^{14}C in terrestrial moss was measured in this work.

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References

Hajdas, I., Ivy-Ochs, S. D., Beer, J., Bonani, G., Imboden, D., Lotter, A., Sturm, M. and Suter, M. 1993 AMS radiocarbon dating and varve chronology of Lake Soppensee, 6,000 to 12,000 ^{14}C years. *Climate Dynamics* 9: 107–116.

Lal, D. and Jull, A. J. T. 1990 On determining ice accumulation rates in the past 40,000 years using in situ cosmogenic ^{14}C. *Geophysical Research Letters* 17(9): 1303–1306.

Lal, D. and Peter, B. 1967 Cosmic ray produced radioactivity on the Earth. *In* Fluigges, S., ed., *Handbuch für Physik* 46/2. Berlin, Springer-Verlag: 551–612.

Li, Z., Zheng, X. and Liu, X. 1992 *Volcanic Rocks in the Fierdos Peninsular, King George Island, Western Antarctica.* Beijing, Science Press: 74–100. (in Chinese).

Lotter, A. F. 1991 Absolute dating of the Late-Glacial period in Switzerland using annually laminated sediments. *Quaternary Research* 35: 321–330.

Lotter, A. F., Ammann, B., Beer, J., Hajdas, I. and Sturm, M. 1991 A step towards an absolute time-scale for the Late-Glacial, annually laminated sediments from Soppensee (Switzerland). *In* Bard, E. and Broecker, W., eds., *The Last Deglaciation: Absolute and Radiocarbon Chronologies.* NATO ASI Series: 12. Heidelberg, Springer-Verlag: 45–68.

Oeschger, H. 1988 The global carbon cycle, a part of the earth system. *In* Castagnoli, G. C., ed., *Solar-Terrestrial Relationships and the Earth Environment in the Last Millennia.* Proceedings of the International School of Physics "Enrico Fermi"; course 95. Amsterdam, Elsevier: 329–352.

Siegenthaler, U. 1989 Carbon-14 in the oceans. *In* Fritz, P. and Fontes, J.-C., eds., *Handbook of Environmental Isotope Geochemistry* 3. Amsterdam, Elsevier: 75–137.

Sowers, T. and Bender, M. 1995 Climate records covering the last deglaciation. *Science* 269: 210–214.

Suter, M., Balzer, R., Bonani, G., Hofmann, H., Morenzoni, E., Nessi, M., Wölfli, W., Andree, M., Beer, J. and Oeschger, H. 1984 Precision measurements of ^{14}C in AMS: Some results and prospects. *Nuclear Instruments and Methods* 223(B5): 117–122.

Zheng, H. H. and Huang, B. L. 1997 Antarctic glacial retreats and the records of sea level change in deposits at the North Bank of the Shenzhen Bay, South China. *Chinese Journal of Geochemistry* 16(2): 154–161.

https://doi.org/10.1017/S0033822200018816