^{210}Pb dating of the Miaoergou ice core from the eastern Tien Shan, China

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ABSTRACT. In 2005, two ice cores with lengths of 58.7 and 57.6 m respectively to bedrock were recovered from the Miaoergou flat-topped glacier (43°03′19″ N, 94°19′21″ E; 4512 m a.s.l.), eastern Tien Shan. ^{210}Pb dating of one of the ice cores (57.6 m) was performed, and an age of AD 1851 ± 6 at a depth of 35.2 m w.e. was determined. For the period AD 1851–2005, a mean annual net accumulation of 229 ± 7 mm w.e. a^{-1} was calculated. At the nearby oasis city of Hami (~80 km from the Miaoergou flat-topped glacier) the annual precipitation rate is 38 mm w.e. a^{-1}, hence glacial meltwater is a major water supply for local residents. The surface activity concentration of ^{210}Pb$_{ex}$ was found to be ~400 mBq kg^{-1}, which is higher than observed at other continental sites such as Belukha, Russia, and Tsambagarav, Mongolia, which have surface activity concentrations of 280 mBq kg^{-1}. The ^{210}Pb dating agrees well with the chronological sequence deduced from the annual-layer counting resulting from the seasonalities of δ^{18}O and trace metals for the period AD 1953–2005, and β-activity horizons resulting from atmospheric nuclear testing during the period AD 1962–63. We conclude that ^{210}Pb analysis is a suitable method for obtaining a continuous dating of the Miaoergou ice core for ~160 years, which can also be applied to other ice cores recovered from the mountains of western China.

KEYWORDS: accumulation, glacier chemistry, ice chronology/dating, ice core

INTRODUCTION

Mid- or low-latitude glaciers represent a natural archive, well suited for studying past environmental and climatic conditions (Hou and others, 2003; Kang and others, 2003; Barbante and others, 2004; Yang and others, 2006; Wang and others, 2010; Xu and others, 2010; Shen and others, 2012; Wu and others, 2013). Accurate dating is an essential prerequisite for the correct interpretation of paleoclimatic information from ice-core records. For the time period covered by ice cores, ranging from decades to thousands of years, many different ice-core dating methods have been used, including profile characteristics (e.g. seasonal variation of particles; conductivity characteristics; stable isotopes and major ions contained in the core) (Oeschger and Langway, 1989; Alley and others, 1997; Petit and others, 1999; EPICA Community Members, 2004; NorthGRIP Members, 2004; Svensson and others, 2005). The assignment of reference layers to known sources (β-activity peak from nuclear bomb debris, volcanic ash horizons, etc.) (Legrand and Delmas, 1987; Cole-Dai and others, 2000), as well as radioisotope dating and glacier flow models, have also been used (Johnsen and others, 1972; Raisbeck and Yiou, 1985; Raisbeck and others, 1987; Ciais and others, 1994). More than 20 dating indicators have been applied to the Greenland ice sheet GISP2 and GRIP ice cores (Dansgaard and others, 1993; Meese and others, 1997). The choice of the most appropriate dating method depends on the timescale and accuracy requirements. Multi-proxy annual-layer counting is the most accurate dating method (Alley and others, 1997). Reference horizons are usually used to verify and cross-check the annual-layer counting dating (Pourchet and others, 1983; Eichler and others, 2000; Liu and others, 2011).

The time range accessible using radioactive isotope ^{210}Pb dating is ~150 years and is determined by the 22.3 year half-life of ^{210}Pb, a product of the natural ^{238}U decay series (Gäggeler and others, 1983; Knüsel and others 2003; Olivier and others, 2003). ^{238}U is the most abundant isotope of uranium, a primordial radioactive element in nature. ^{238}U is ubiquitous in nature at an average level of ~5 ppm in soil. The half-life of ^{238}U is 4.6×10^9 years. ^{238}U decays after several intermediate nuclides into ^{222}Rn which has a half-life of 3.8 days. As a noble gas, radon emanates from the Earth's surface into the atmosphere where it decays via the very short-lived intermediate nuclides ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po (all having half-lives shorter than 30 min) into ^{210}Pb. ^{210}Pb has a half-life of 22.3 years and decays into its daughter ^{210}Bi with a half-life of 5 days, which itself decays into a 'granddaughter' ^{210}Po with a half-life of 138.4 days. This means that after several half-lives of ^{210}Po, i.e. ~1 year, the activity concentrations of all three nuclides, i.e. of ^{210}Pb, ^{210}Bi and ^{210}Po, are equal (secular equilibrium). With the emission of an alpha particle, ^{210}Po finally decays into the stable ^{206}Pb, the end product of the ^{238}U decay series (Benoit and Hemond, 1987). Hence, the activity concentration of ^{210}Pb can be measured by analyzing either ^{210}Pb itself or ^{210}Bi or ^{210}Po after several half-lives of these progenies. Since detection of α-particles from the decay of ^{210}Po is very sensitive and nuclide-specific, in contrast to β-particles emitted by ^{210}Pb or ^{210}Bi, it is advisable to

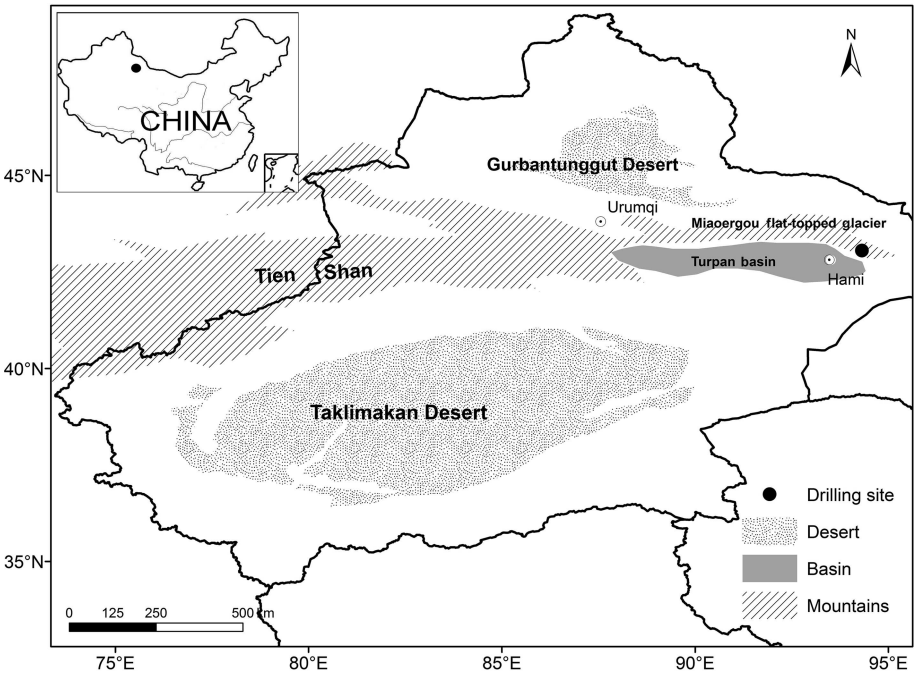

Fig. 1. Location of the Miaoergou flat-topped glacier in the eastern Tien Shan, China. The black dot shows the position of the drilling site (43°03′19″ N, 94°19′21″ E; 4512 m a.s.l.).

determine the activity concentration of ^{210}Pb in ice cores by analyzing the ^{210}Po activity.

The first attempts to date ice layers using the ^{210}Pb method were made by Goldberg (1963). Later, Krishnaswamy and Lal (1971) and Koide and others (1972) made an exploratory study of ^{210}Pb dating on lake waves and the gulf sediments. Gäggeler and others (1983) proved for the first time that the ^{210}Pb dating method was a useful tool for dating cold high-altitude alpine glaciers. This approach has since been used to date a number of ice cores (e.g. from Illimani, Bolivia (Knüsel and others, 2003); Cerro Tapado (Ginot and others, 2006) and Monte San Valentin, Chile (Vimeux and others, 2008)). However, until now there has been no reported ^{210}Pb dating of ice cores from the Tibetan Plateau and surrounding regions. In this study, we used ^{210}Pb to date the Miaoergou ice core drilled from the eastern Tien Shan, China.

β-activity measurements and annual-layer counting are two of the main approaches used in mountain ice-core dating. β-activity dating is based on the identification of late 1950s and early 1960s radioactive debris from nuclear weapons testing around the world, with a peak activity in the Northern Hemisphere around AD 1962–63. Annual-layer counting can be used to determine ice-core age by studying physical and chemical indicators of species that exhibit seasonal changes in the ice-core record. Examples are δ^{18}O or chemical species that exhibit seasonal variability (e.g. ammonia from agricultural activity). As ice cores are subjected to annual-layer thinning with increasing depth, the method can only determine the age of the upper part of the ice core, i.e. is limited to a relatively short period. The ^{210}Pb dating method yields a continuous age–depth relationship for up to two centuries and has been widely used in recent years (Knüsel and others, 2003; Cecil and others, 2004; Ginot and others, 2006; Vimeux and others, 2008).

Some assumptions have to be made for successful application of the ^{210}Pb dating method. The amount of supported ^{210}Pb coming from the ^{238}U content in mineral dust contained in the ice should be constant and the mean ^{210}Pb activity in precipitation should have remained constant during the dating period (CF:CS model assumption, where CF stands for constant rate of supply and CS for constant activity concentration in precipitation (Appleby, 2001). Moreover, there should be no significant transport of ^{210}Pb by percolating meltwater. During the warm season, in daytime the air temperature may rise above 0°C. However, the formed meltwater will refreeze during the night (Shumskiy, 1964) or due to the negative temperatures inside the ice (Liu and others, 2006). The night temperature decreased from –2.92°C at 1 m to –7.62°C at 8 m depth and gradually increased to –6.25°C from 8 to 20 m depth (Song and others, 2011). We therefore conclude that the melting process has little impact on the ^{210}Pb dating.

MATERIALS AND METHODS

Ice-core sampling

The Miaoergou flat-topped glacier covers an area of ~3.45 km^2. Its altitude from the summit to the ice tongue ranges from 4512 to 3840 m, and the equilibrium-line altitude is ~4100 m a.s.l. (LIGG, 1986). In 2005, two ice cores to bedrock (58.7 and 57.6 m length for cores 1 and 2, respectively) were recovered from a dome on Miaoergou glacier (43°03′19″ N, 94°19′21″ E; 4512 m a.s.l.) (Liu and others, 2011; Fig. 1). The low borehole temperature at the drilling site (–7.2°C at 10 m depth and –8.2°C at the bottom) is beneficial for the preservation of ice-core records (Liu and others, 2009). The ice cores were transported frozen to the State Key Laboratory of Cryospheric Sciences, Lanzhou, China, for processing. A first study of trace elements contained in core 2 was performed down to 17 m (14 m w.e.) (Liu and others, 2011). Besides some heavy metals, the bomb peak assigned to the period AD 1962–63 was also found at ~12.5 m depth (11 m w.e.) by total β-counting of ^{90}Sr and ^{90}Y in the ice samples (Liu and others, 2011). This yielded an

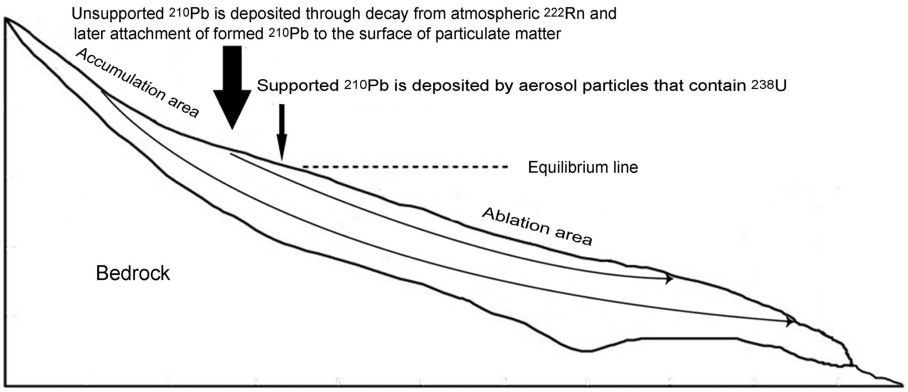

Fig. 2. Sketch of a glacier profile showing the main sources of ^{210}Pb. The ^{210}Pb activity of glacier sediments has two components: a supported component deriving from the ^{238}U (equal to the ^{226}Ra) decay, and an unsupported (or excess) component deriving from the atmospheric fallout of ^{210}Pb (marked as $^{210}Pb_{ex}$).

average net annual accumulation rate of 259 mm w.e. a^{-1}. From annual-layer counting based on heavy-metal concentrations, an age of AD 1953 was deduced at 17 m depth (14 m w.e.), resulting in an average net accumulation rate of 269 mm w.e. a^{-1}. The analysis was stopped at 17 m depth (assigned to AD 1953) due to lack of dating of the deeper part of the core. In this paper, we present a further dating of core 2 using the ^{210}Pb dating method.

Experiment

The ice samples are processed according to the standard method established by Gäggeler and others (2011). Each of the ice samples was cut parallel to the drilling axis in a –18°C cold room at the State Key Laboratory of Cryospheric Sciences. The weight of each sample was ~300 g. Each sample was melted after adding 10 mL conc. HCl, 1 g NH_4OH–HCl per 100 g ice. NH_4OH–HCl served as a reducing agent to ensure polonium stays in an elemental state in the acidified solution. Then 100 µL ^{209}Po tracer was added to the solution to determine the yield of the separation. Spontaneous deposition of Po on an Ag disk (15 mm diameter), which was fixed on a wire and immersed in the liquid, was achieved during ~8 hours at 95°C in 500 mL Erlenmeyer flasks using a magnetic stirrer. Typical chemical and counting yields were ~80%. After drying, the disks were transferred to the University of Bern for α-counting. The samples were positioned in vacuum chambers at a distance of 1 mm from silicon surface barrier detectors (ORTEC, ruggedized, 300 and 450 mm^2) having an α-energy resolution of ~23 keV full width at half-maximum (FWHM) at 5.3 MeV. The yield of ^{209}Po tracer was measured via its 4.9 MeV α-line. Typical counting yields were ~45%.

Age calculation method

The ^{210}Pb activity concentration of glacier ice has two components: a supported component derived from the ^{238}U (equal to the ^{226}Ra) decay rate, and an unsupported (or excess) component derived from the atmospheric fallout of ^{210}Pb (marked as $^{210}Pb_{ex}$). Supported ^{210}Pb is deposited by aerosol particles that contain ^{238}U, while excess ^{210}Pb is deposited through decay from atmospheric ^{222}Rn and later attachment of formed ^{210}Pb to the surface of particulate matter (Fig. 2). The supported ^{210}Pb activity can be determined by measuring the value of the experimental background at ages not accessible by the ^{210}Pb method (Wan, 1997), and the excess ^{210}Pb activity can be determined by subtracting the supported ^{210}Pb activity from the total ^{210}Pb activity concentration (marked as $^{210}Pb_{tot}$) (Appleby and Oldfield, 1983). The age of an ice core can then be calculated applying the decay law to the measured $^{210}Pb_{ex}$ activities along the ice core. As the supported ^{210}Pb values are assumed to be constant along the ice core, the age was calculated using the $^{210}Pb_{ex}$ values applying the CF:CS model. This model assumes a constant rate of deposition, i.e. of annual precipitation rates, and that the activity concentration of ^{210}Pb in precipitation remained constant over time, independent of the amount of precipitation during a given snowfall (Wan, 1997; Xia and Xue, 2004; Zhang and others, 2008, 2012).

RESULTS AND DISCUSSION

The ^{210}Pb activity profile

The record of the $^{210}Pb_{tot}$ activity concentrations measured along the ice core is depicted in Figure 3, which shows an exponential decrease as a function of depth in line with the radioactive decay law. The $^{210}Pb_{tot}$ activity concentrations below 35.2 m w.e. down to bedrock were constant, with a

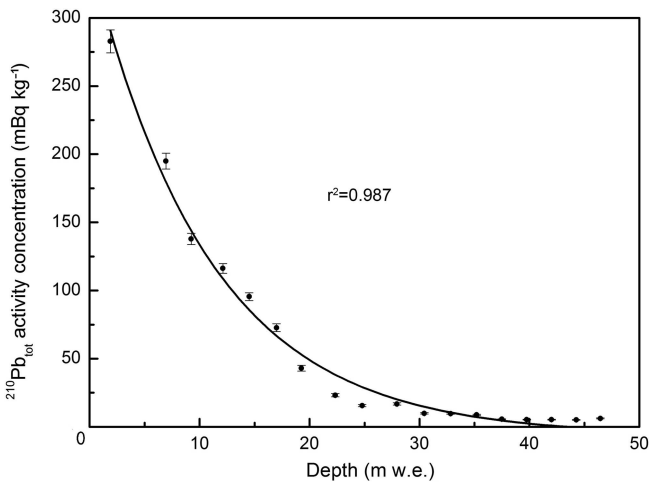

Fig. 3. Correlation between $^{210}Pb_{tot}$ activity concentrations and depth of ice core from Miaoergou flat-topped glacier. An exponential fit function was applied to the scatter plots, and the coefficient of determination (r^2) was 0.987. The $^{210}Pb_{tot}$ activity concentrations show a negative exponential decrease as function of depth in line with radioactive decay law.

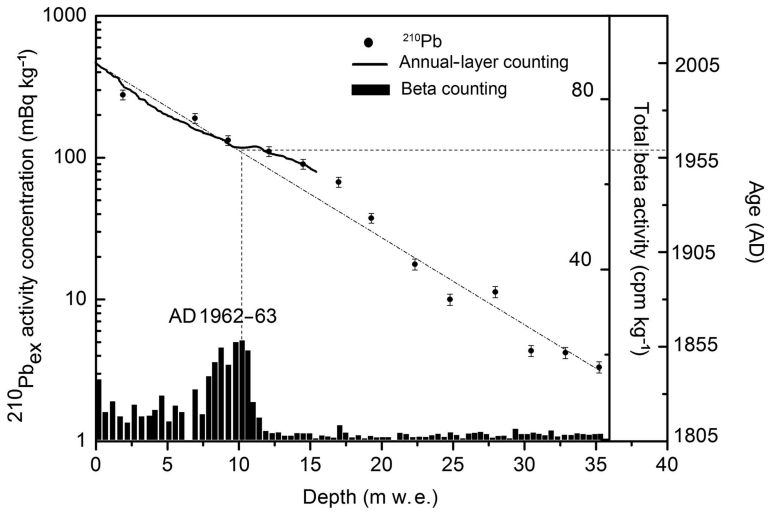

Fig. 4. $^{210}Pb_{ex}$ activity concentrations (scatter plots, left-hand logarithmic scale), annual-layer counting (solid line) and β-counting (bars) of ice core from Miaoergou flat-topped glacier. The rightmost axis depicts the age deduced from the $^{210}Pb_{ex}$ measurement. The estimated age–depth relation has uncertainties of ± 6 years. The dot-dashed line indicates the average ^{210}Pb decrease. The dashed line indicates the bomb horizon deduced from β-counting assigned to the period AD 1962–63, which agrees well with the results of annual-layer counting and the ^{210}Pb dating method.

value of 5.48 ± 0.16 mBq kg^{-1}. This value was taken as supported ^{210}Pb from the mineral dust contained in the ice core and was therefore subtracted from all total ^{210}Pb activity concentration above 35.2 m w.e. to obtain the $^{210}Pb_{ex}$ values.

The data depicted in Figure 4 represent the resulting $^{210}Pb_{ex}$ activity concentrations as a function of depth. We observed some fluctuations in the exponential decrease of the $^{210}Pb_{ex}$ activity concentrations, which we ascribe to variations in precipitation rates (see below). This indicates that the input of ^{210}Pb at this drilling site was on average constant during the dating period, in accord with the assumption of the CF:CS dating model. From the linear regression of the logarithmic ^{210}Pb activities against depth we conclude that at a depth of 35.2 m w.e. of ice core the year AD 1851 ± 6 is reached. The value of the axis intercept ($\sim$400 mBq kg^{-1}) corresponds to the $^{210}Pb_{ex}$ activity at the surface of Miaoergou glacier. From the slope of the regression line, we derive a mean annual net accumulation rate of 229 ± 7 mm w.e. a^{-1}. The estimated age–depth relation has an uncertainty of ± 6 years.

Figure 4 compares the ^{210}Pb dating results with the chronological sequence obtained from annual-layer counting results (until 1953) and the β-counting method which assays the β-activity peak of ^{90}Sr and ^{90}Y from the atmospheric nuclear testing period AD 1962–63. The ^{210}Pb dating agrees within error well with the bomb horizon during AD 1962–63 at 11 m w.e. but also with the annual counting result of AD 1953 at 14 m w.e. The results of different dating methods are therefore highly consistent, indicating that the result of the ^{210}Pb dating method applied to the Miaoergou ice core is reliable. The linear decay of the depicted $^{210}Pb_{ex}$ activity concentrations with depth also corroborates the assumption that no significant thinning of the ice core can be observed down to 35.2 m w.e.

$^{210}Pb_{ex}$ activity at the surface

The surface activity concentration of $\sim$400 mBq kg^{-1} is remarkably high, even higher than observed at other continental sites such as at Belukha, Russia (280 mBq kg^{-1}; Olivier and others, 2006), or nearby Tsambagarav, Mongolia (Herren and others, 2011), with the same surface activity concentration. This means that the ^{222}Rn concentration in air in the eastern Tien Shan must be very high and the ^{238}U concentration in soil of the regional environment must also be high. In addition, emanation of ^{222}Rn is closely related to the geographical and climatic conditions of the study area. Any changes in atmospheric pressure, temperature, weather conditions, soil moisture, vegetation coverage, etc., will affect the release of ^{222}Rn from the Earth's surface, and thus affect the ^{210}Pb concentration in the atmosphere. It might therefore be desirable to measure ^{222}Rn activity concentrations in the study area as well as ^{238}U concentration values in soil.

Mean net accumulation rates

Glaciers in this area near the Gobi Desert are the major water supply for the extremely arid land of Hami, an oasis city close to the Miaoergou flat-topped glacier. Luo and others (2002) and Zhang and Liu (2011) pointed out that, based on field studies, precipitation rates in the area above 4000 m a.s.l. in the Yushugou basin (43°02′–43°11′ N, 93°57′–94°19′ E) are up to 400–500 mm a^{-1}. This value is in reasonably good agreeement with our value of 229 ± 7 mm w.e. a^{-1}. From the 1957–2005 precipitation data at Hami weather station we obtain an average annual precipitation rate of 38 mm a^{-1} (Fig 5). The precipitation rates at Hami show a weak trend towards increasing values, in accordance with the trend of warmer and wetter climate in northwest China (Shi and others, 2003).

CONCLUSIONS

The ^{210}Pb dating method has been applied to a 57.6 m ice core from Miaoergou glacier recovered at 4512 m a.s.l. in 2005. The investigated samples have been worked up for ^{210}Po which was assayed by α-spectroscopy to deduce the ^{210}Pb activity concentration at secular equilibrium. The surface activity concentration of $^{210}Pb_{ex}$ at this site is $\sim$400 mBq kg^{-1} which is very high compared to other sites

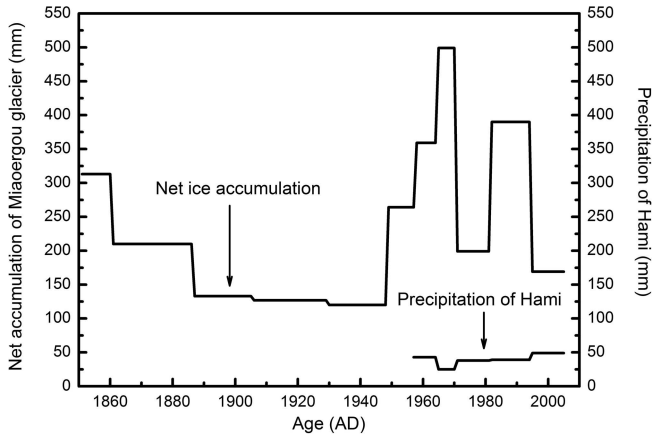

Fig. 5. Changes in net accumulations of Miaoergou flat-topped glacier from AD 1851 to 2005 deduced from the $^{210}Pb_{ex}$ values and the precipitations of Hami from AD 1957 to 2005. For the period 1851–2005, we calculated the net accumulations at different time intervals according to the results of the ^{210}Pb dating method. For the period 1957–2005, we calculated the precipitations of Hami at the same time intervals as the net accumulations.

worldwide. Using the ^{210}Pb CF:CS dating model, we conclude that at a depth of 35.2 m w.e. the year AD 1851 $\pm$ 6 is reached The resulting mean net annual accumulation rate is 229 ± 7 mm w.e. a^{-1}. The results of the ^{210}Pb dating method, of annual-layer counting and of β-counting are highly consistent, which indicates that the result of the ^{210}Pb dating method applied to the Miaoergou ice core is reliable and can be used to date the ice core to ages older than 1953, the limiting age prior to this study.

This work shows for the first time that ^{210}Pb dating is a suitable method for dating glaciers in the eastern Tien Shan. This method could also be used to date other ice cores recovered from the mountains of western China.

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