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In situ cosmogenic ^{10}Be dating of the Quaternary glaciations in the southern Shaluli Mountain on the Southeastern Tibetan Plateau

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Abstract It is generally considered that four-times ice age happened during the Quaternary epoch on the Tibetan Plateau. However, the research on the chronology of the four-times ice age is far from enough. The Shaluli Mountain on the Southeastern Tibetan Plateau is an ideal place for plaeo-glacier study, because there are abundant Quaternary glacial remains there. This paper discusses the ages of the Quaternary glaciations, based on the exposure dating of roche moutonnée, moraines and glacial erosion surfaces using *in situ* cosmogenic isotopes ^{10}Be. It is found that the exposure age of the roche moutonnée at Tuershan is 15 ka, corresponding to Stage 2 of the deep-sea oxygen isotope, suggesting that the roche moutonnée at Tuershan is formed in the last glacial maximum. The exposure age of glacial erosion surface at Laolinkou is 130—160 ka, corresponding to Stage 6 of the deep-sea oxygen isotope. The oldest end moraine at Kuzhaori may form at 421—766 kaBP, corresponding to Stages 12—18 of the deep-sea oxygen isotope. In accordance with the climate characteristic of stages 12,14,16 and 18 reflected by the deep-sea oxygen isotope, polar ice cores and loess sequence, the oldest end moraine at Kuzhaori may form at stage 12 or stage 16, the latter is more possible.

Keywords: Quaternary, glaciation, glacial, cosmogenic isotope, dating, ^{10}Be, exposure dating, Tibetan Plateau, environmental change, surface dating, boulder, erosion.

Because of the particular geographic location, huge horizontal scale and vertical elevation, the Tibetan Plateau gives unique importance on the regional climate change, even on the global climate change. The research shows that, the Tibetan Plateau uplift plays an important role in the drying at the middle latitudes of the Northern Hemisphere[1,2], the formation and enhancement of Asian monsoon[3,4], the formation of Quaternary glaciations on the Northern Hemisphere[5] and even on the global cooling of climate in the late Cenozoic Era[6]. The research of Quaternary glaciations on the plateau will contribute a lot to understanding deeply the effect of the plateau environment change on the regional and global climate.

About the history of glacial actions on the Tibetan Plateau, it is generally considered that four-times ice age happened during the Quaternary period[7−10]. The four-times ice ages have been compared to those of

Europe and America, but their absolute ages have never been confirmed, except the Last Glactiation. Subsequently, by comparison with the deep-sea oxygen isotope curve, it is considered that the last two times of the ice age are corresponding respectively to stages 2—4 and stage 6 of the deep-sea oxygen isotope[7]. However, it is difficult to confirm the exact ages of the oldest two glaciations, though they were thought probably to correspond to stage 12 and stage 16 of the deep-sea oxygen isotope[11]. The Shaluli Mountain is located in the Southeastern Tibetan Plateau, with abundant glacial remains. The study on the chronology of Quaternary glacial remains on the Shaluli Mountain will improve our understanding of the sequence and environments of Quaternary ice ages of the plateau.

Some studies about the Quaternary glaciations have been carried out in the Shaluli Mountain. At least three periods of Quaternary glacial remains have been found on the Shaluli Mountain. They are called Zuqing ice age, Rongbacha ice age and Daocheng ice age[9,12]. Litang-Daocheng area formed an ice cap during the Quarternary epoch, which is located south of the Shaluli Mountain[7,9]. However, it is lack of enough absolute dating evidence for the Quaternary glaciations of this area. This paper tries to date the moraine, glacial erosion surface and drift boulders by using *in situ* cosmogenic isotopes ^{10}Be.

1 The location and background of the sample

Nine samples have been collected from the southern part of the Shaluli Mountain. According to "Map of Quaternary Glaciations of the Tibetan Plateau"[7], the roche moutonnée at Tuershan, the glacial erosion surface at Laolinkou and the end moraine at Kuzhaori must have been located respectively in the center, on the western and southwestern margins of the ice cap. Figs. 1, 2 and Table 1 show the sample location and position.

2 *In-situ* cosmogenic isotopes dating method

In-situ cosmogenic isotope dating is the new method that has been well developed since the 1980s. The principle is that once a surface of rock is exposed, some elements in the rock are bombarded by the cos-

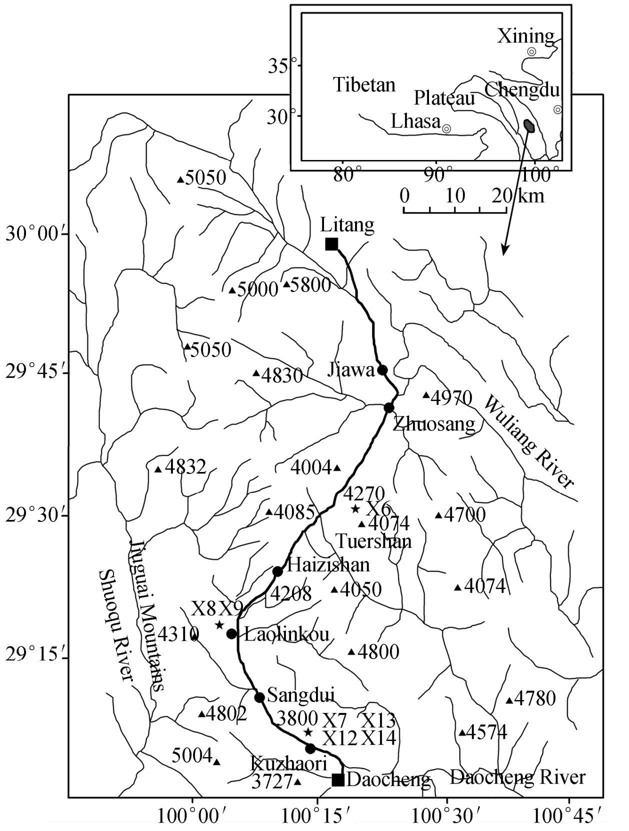

Fig. 1. The study area and the sample locality.

mic particles and some new elements called "*in situ* cosmogenic isotopes", such as ^{3}He,^{10}Be,^{21}Ne,^{26}Al,^{36}Cl and so on, are produced. As the exposure time increases, the *in situ* cosmogenic isotopes accumulate in the rock. Therefore, the exposure time of the rock surface can be calculated based on the concentration of the cosmogenic isotopes in the rock. The *in situ* cosmogenic isotopes ^{10}Be deriving from mineral quartz have been widely used and well-developed to estimate the exposure time[13].

The ^{14}C method is the traditional one to estimate the age of the glacial event. But it is very difficult to be applied to the older ice ages of the Quaternary, because ^{14}C dating method is limited in the range of several tens of thousand years[14]. The cosmogenic isotope dating method has some advantages to reconstruct the Quaternary glacial history by dating the exposure ages of the glacially-polished surface, erratic boulder and moraine surface[14−21]. Dom and his collaborators found that Makanakan glacier has been melted out at about 15 ka BP, in terms of the cosmogenic isotope

Fig. 2. The photo to show the position of samples. (a) The glacial erosion surface at Laolinkou and the position of sample X8 and X9; (b) the difference of erosion quantity of glacially polished surfaces at Laolinkou; (c) the oldest end moraine at Kuzhaori; (d) the top of the oldest end moraine at Kuzhaori and the position of sample X13; (e) the boulder on the top of the oldest end moraine at Kuzhaori; (f) the close shot of the boulder on the top of the oldest end moraine at Kuzhaori and the position of sample X12 and X14.

Table 1 Background of the samples

No.	Sample ID	Sample site	Elevation (m)	Latitude	Longitude	Rock type	Sample position	Burial depth (cm) (cover material)
1	X8	Laolinkou	4310	29°19.2′N	100°05.1′E	granite	glacial erosion surface	5 (grass)
2	X9	Laolinkou	4310	29°19.2′N	100°05.1′E	granite	glacial erosion surface	5 (grass)+10 (rock)
3	X6	Tuershan	4300	29°33.35′N	100°08.18′E	granite	roche mountonnee	0
4	X14a	Kuzhaori	3890	29°07.48′N	100°13.31′E	granite	big drift boulder on end moraine	40 (till)
5	X14b	Kuzhaori	3890	29°07.48′N	100°13.31′E	granite	big drift boulder on end moraine	40 (till)
6	X14	Kuzhaori	3890	29°07.48′N	100°13.31′E	granite	big drift boulder on end moraine	40 (till)
7	X12	Kuzhaori	3890	29°07.48′N	100°13.31′E	granite	big drift boulder on end moraine	40 (till) +40 (granite)
8	X13	Kuzhaori	3890	29°07.48′N	100°13.31′E	sand-gravel	end moraine top	40 (till)
9	X7	Kuzhaori	3890	29°07.48′N	100°13.31′E	sand-gravel	end moraine inner	400(till)

dating of the glacial erosion surface and drift boulder on the Mauna Kea area in Hawaii[22]. In addition, in the direction of the glacier retreating, the exposure time of the outcrop of glacially-polished surface can be calculated and the retreat rate of glacier can be calculated by *in-situ* cosmogenic isotope dating method[14]. Owen *et al.*[23] found that the Last Glacial Maximum (LGM) of south Mt. Himalaya did not happen at Stage 2 but at Stage 3 of the deep-sea oxygen isotope, in terms of cosmogenic isotope dating of the glacial moraine and erosion surface in that region. However, so far, it is absent of cosmogenic isotope dating data for the Quaternary glaciations in the southern part of Shaluli Mountain. A case study has been carried out in this paper.

2.1 Experiment

The samples were ground and the particles of 0.25—1.0 mm in size were sieved out. The quartz particles hand-picked out, chemically separated and purified[24]. Then we took the following procedures: taking about 20 g pure quartz, adding 0.250 mg Be^9 carrier (Merck Art. 9922, with concentration of 0.001 g/g, corresponding to $6.02\times10^{23}\times0.250\times10^{-6}/9$ atoms of Be^9) into it, and then dissolving it in pure HF of 40%, evaporating it to dryness and converting it into HCI solution. In order to evaluate the presumable influence of the environmental background on the experimental results, a blank sample was equipped for each eight-sample group. After that, the element Be was separated from other elements through ion exchange, by adding NH_4OH solution the pH value reached about 8 so as to deposit $Be(OH)_2$. Doing it several times to avoid possible influence of the element B. Then $Be(OH)_2$ was oxidized to BeO at 900℃ in an electric oven. Preparation of targets for ^{10}Be measurements followed the procedures described by Yiou *et al.*[25]. All the measurements were performed by the accelerator mass spectrometry (AMS) at the Tandetron AMS facility at Gif-sur-Yvette, France. The measurement results of blank samples show that the average background uncertainty of the experiment is from 0.629% to 0.874%. The measurement results of the coeval samples suggest that the overlap of experiment ranges from 94.7% to 100%.

2.2 Calculation

According to Lal[26],

$$C_t = C_0 e^{-\lambda t} + \frac{P}{\lambda + E/L}(1 - \mathrm{e}^{-(\lambda + E/L)t}), \qquad (1)$$

and the effect of elevation changes is similar to that of erosion. Therefore, in the case of uplifting place, the relationship of the concentration of *in situ* cosmogenic isotope ^{10}Be with the exposure age "*t*" can be expressed as

$$C_t = \frac{P}{E/L + \lambda + U/La} \times (1 - \mathrm{e}^{[-(E/L + \lambda + U/La)t]}) + C_0 \times \mathrm{e}^{-\lambda t}, \qquad (2)$$

where P is the cosmogenic isotope production rate at the place where the samples are collected and can be calculated based on the elevation and latitude of the samples. λ is the decay coefficient, being a constant to a specific cosmogenic isotope. L is the attenuation length of the cosmogenic isotope ^{10}Be production rate in the rock or sediments, La is the attenuation length of cosmogenic isotope ^{10}Be production rate in the atmosphere at the study area, t is the exposure time, C_t is the cosmogenic isotope concentration after an exposure for a period of t, C_0 is the initial cosmogenic isotope concentrations before the formation of the surface, E is the erosion rate of the ground surface, and U is the uplift rate of the ground surface.

For the glacially polished surfaces, the C_0 can be considered as zero because the rocks have been strongly eroded. For the moraine deposit, C_0 can be estimated by measuring the ^{10}Be concentrations of moraine deposit both on the top and in the inner of the moraine at a depth of several meters.

Exposure ages can be calculated by eq. (2), where L = 160 g cm^{-2}[27]. According to Dunai's calculation method[28], the attenuation length of cosmogenic isotope ^{10}Be in the atmosphere (La) at the study area is 144 g cm^{-2}. The ^{10}Be production rate in quartz of the rock surface at the sampling locality can be calculated based on Lal's (1991) and Dunai's (2001) calculation methods, and the influence of air pressure can be corrected according to Stone's model (2000)[29]. The decay coefficient of ^{10}Be (λ) is 4.62×10^{-7} a^{-1}. Because the top surface of some samples is not horizontal, the

Table 2 The exposure age of the glacially polished surface at Laolinkou

Sample ID	Burial depth (cm)	^{10}Be production rate at sampling place (atoms/g a^{-1})	^{10}Be concentration in quatz sampled (10^5 atoms/g)	Minimum exposure age (ka)	Exposure age (ka) (assumed the uplift rate is zero, the erosion rate is 6.923×10^{-5} cm/a)	Exposure age (ka) (assumed the uplift rate is 1.5 km/Ma, the erosion rate is 6.923×10^{-5} cm/a)
X8	5	60.47	68.66	116.6	125.3	135.0
X9	15	51.25	67.87	136.6	148.9	163.0

production rate is corrected based on Dunne *et al.*'s model[30].

2.3 *The least exposure age*

When the surface elevation keeps stable, the concentration of cosmogenic isotope derived from the rocks is the function of the exposure age and the erosion rate. It, if in steady state, could be deduced the least exposure age as follows (Lal, 1991):

$$T = -Ln\ (1 - C_T \times \lambda / P) / \lambda, \quad (3)$$

where T is the least exposure age, P is the cosmogenic isotope production rate at the place, C_T is the *in-situ* cosmogenic isotope concentration, λ is the attenuation coefficient. From that, the least exposure age can be calculated.

3 Results and discussion

3.1 *The exposure age and the erosion rate of the glacially polished surface*

Generally, it is difficult to determine simultaneously both the exact exposure age and the accurate erosion rate of the ground surface. However, if the erosion rate of the surface can be calculated by other methods, it is easy to estimate accurately the exposure age. A big drift boulder on the glacially polished surface has been found at Laolinkou (Fig. 2(a)). In order to estimate the erosion rate of the surface, we observed the glacially-polished surfaces and measured the height difference of the erosion surface in different parts of the surface. We found that the part of the surface underneath the boulder preserved well due to the shield of the boulder, while other part of the surface without the shield of the boulder, is obviously eroded. The relative difference between them is in the range from 6 cm to 10 cm with an average of 9 cm, which may represent the total erosion quantity after the formation of the polished surface. The exposure ages of the polished surface by cosmogenic ^{10}Be are in the range of 113.8—163.2 ka BP (Table 2), corresponding to Stage 6 of the deep-sea oxygen isotope. Stage 6 of the deep-sea oxygen isotope averagely ended at 130 ka BP, so that it can be inferred that the average erosion rate of the polished surface (E) is 6.923×10^{-5} cm/a, i. e. 1.869×10^{-4} gcm^{-2} a^{-1}.

3.2 *Estimations of the exposure ages about the end moraine at Kuzhaori*

The locality of samples X8 and X9 is 3890 m a.s.l. at 30°N, ^{10}Be production rates in quartz of the rock surface at the sampling locality are respectively 60 atoms g^{-1} a^{-1} or 62.3 atoms g^{-1} a^{-1} based on the calculation of Lal[26] or Dunai[28]. The latter is selected as the ^{10}Be production rate and the influence of air pressure is corrected according to Stone[29]. After correction, the ^{10}Be production rate is 52.66 atoms g^{-1} a^{-1}. The density of the till of the end moraine in Kuzhaori is 1.8 g/cm^3, in terms of measurement. Because the attenuation length of cosmogenic isotope ^{10}Be is 160 g/cm^2 (Brown, 1991), the production rate of ^{10}Be at the burial depth of 40 cm can be calculated, that is, 33.58 atoms/g^{-1} a^{-1}. The influence of weathering and transportation on ^{10}Be concentration can be eliminated by combining the ^{10}Be concentration of the samples on the top surface and in the inner of the end moraine. Thus the formation age of the end moraine can be calculated as

$$\Delta C = \frac{P \times (1 - e^{(-(\lambda + E/L + U/La)t)})}{(\lambda + E/L + U/La)}, \quad (4)$$

that is, $$t = \frac{Ln(1 - \Delta C \times (\lambda + E/L + U/La)/P)}{-(\lambda + E/L + U/La)}, \quad (5)$$

where ΔC is the difference of the *in-situ* ^{10}Be concentration between the top sample and the inner sample of the end moraine. The formation age of the end moraine can be calculated in different conditions (Table 3).

Table 3 Estimations of the ages of the end moraine at Kuzhaori in different conditions

Assumed surface erosion rate (g cm^{-2} a^{-1})	Assumed surface uplift rate (km/Ma)	Calculated age of end moraine (kaBP)
0	0	298.3
1.869×10^{-4}	0	371.5
2.6522×10^{-4}	0	421. 4
3.4355×10^{-4}	0	497.6
1.869×10^{-4}	1.0	448.8
2.6522×10^{-4}	1.0	544.8
3.4355×10^{-4}	1.0	766.6
1.869×10^{-4}	1.5	510.7
2.6522×10^{-4}	1.5	673.0
3.4355×10^{-4}	1.5	∞

It is assumed that $E = 0$, $U = 0$, the least exposure age can be calculated. It is 298.3 ka. That is, the formation of the end moraine in Kuzhaori is much earlier than the last glaciation, and earlier than Stage 6 or Stage 8 of the deep-sea oxygen isotope. Therefore, it may be formed at Stage 10 or Stage 12 of the deep-sea oxygen isotope, or even earlier.

In fact, the erosion rate of Tibetan Plateau cannot be zero. Based on the measurement of the glacially polished surfaces developed at Stage 6 of the deep-sea oxygen isotope, the longtime average erosion rate of horizontal granite surface is 6.923×10^{-5} cm/a (that is 1.869×10^{-4} g cm^{-2} a^{-1}). The erosion rate of the end moraine should be bigger than that of granite surface. Suppose that there is no uplift of the ground and the cosmogenic isotope ^{10}Be were in the steady state, the largest erosion rate can be calculated, that is, 5.002×10^{-4} gcm^{-2}a^{-1} which is much larger than the average erosion rate of horizontal granite surface. Assuming the long-time average erosion rate of the end moraine is the average of both (i.e. 3.4355×10^{-4} gcm^{-2}a^{-1}), the estimations of the age of the end moraine are 497.6 or 766.6 ka respectively when the uplift rate of the ground surface is 0 or 1.0 km/Ma. Assuming the erosion rate of the end moraine is 2.65 gcm^{-2}a^{-1} (the average of 1.869×10^{-4}gcm^{-2}a^{-1} and 3.4355×10^{-4} gcm^{-2}a^{-1}), the estimations of the age of the end moraine are respectively 421.4, 544.8 or 673.0 ka when the uplift rate of the ground surface is 0, 1.0 or 1.5 km/Ma (Table 3). Because the erosion rate of end moraine should be smaller than 5.002×10^{-4} gcm^{-2}a^{-1} and bigger than 1.869×10^{-4} gcm^{-2}a^{-1}, the age of the end moraine at Kuzhaori should be in the range between 371.48 and 766.62 ka, more possible in the range between 497.6 and 766.6 ka, corresponding to Stages 12—18 of the deep-sea oxygen isotope. In accordance with the climate characteristic of stages 12, 14, 16 and 18 reflected by the deep-sea oxygen isotope, polar ice cores and loess sequence, the end moraine may form at stage 12 or stage 16, and the ESR dating of the end moraine is 571.2 ka[31], so stage 16 is more possible.

The exposure age of the big drift boulder on the end moraine (X12, X14, X14a, X14b) is only 100.6—146.5 ka, obviously younger than the foregoing estimation of the exposure ages of the end moraine. That is probably because of the long-time burial and recent exposure of the big drift boulder. The field observation gives some evidence: about 40-cm red weathering crust exists in some places on the top of the end moraine, but little left on the big drift boulder. In fact, the result accords with Hallet and Putkonen's simulation result: young boulders on aging moraines, and the exposure of the inside boulder due to the erosion of the moraine[32].

3.3 Estimation of the exposure age of the roche moutonnée at Tuershan

The estimation method of the exposure age of the roche mountonnée is the same as that of glacially polished surfaces. Without the consideration of the influence of surface erosion and surface uplift, the least exposure age of the roche moutonnée at Tuershan is 14.94 ka. If the influences are considered, the exposure age is 15.07—15.19 ka. The result shows that the roche moutonnée at Tuershan is formed at the Last Glacial Maximum, corresponding to Stage 2 of the deep-sea oxygen isotope.

4 Conclusions

At least three glaciations occurred in southern part of Shaluli Mountain during the Quaternary, based on the analysis of *in situ* cosmogenic isotope ^{10}Be of the roche moutonnée, glacially polished surfaces and end moraine in that region. The exposure age of the roche mountonnee at Tuershan is 15 ka, which is the result of glaciation during the LGM, corresponding to Stage

2 of the deep-sea oxygen isotope. The exposure age of glacially polished surfaces at Laolinkou is 130—160 ka, corresponding to Stage 6 of the deep-sea oxygen isotope. The oldest end moraine at Kuzhaori has the exposure age of 421—766 ka, corresponding to stages 12—18 of the deepsea oxygen isotope, of which Stage 12 or Stage 16 is more possible. And Stage 16 is the most possible.

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