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# Cosmogenic radionuclide evidence for the limited extent of last glacial maximum glaciers in the Tanggula Shan of the central Tibetan Plateau

Patrick M. Colgan [a,*], Jeffrey S. Munroe [b], Zhou Shangzhe [c]

[a] *Department of Geology, Grand Valley State University, 1 Campus Drive, Allendale, MI 49401, USA*
[b] *Department of Geology, Middlebury College, Middlebury, VT 05753, USA*
[c] *Department of Geography, South China Normal University, Guangzhou, PR China*

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**Abstract**

Cosmogenic radionuclide (CRN) exposure ages provide evidence for the limited extent of last glacial maximum glaciers in the Tanggula Shan, central Tibetan Plateau. The most extensive advances occurred during or before marine oxygen isotope stage 6 (MIS-6) based on previous CRN exposure ages. The second most extensive advance occurred during or before MIS-4 based on previous ages and new ages of 41,400 ± 4300, and 66,800 ± 7100 $^{10}$Be yr. A MIS-2 advance of less than 3 km occurred between 31,900 ± 3400 and 16,000 ± 1700 $^{10}$Be yr.


*Keywords:* Cosmogenic radionuclide; Tibetan Plateau; Glacial geology; Paleoclimatology; Quaternary Period

## Introduction

The extent and timing of glaciations on the Tibetan Plateau have long been a subject of debate, yet today, a consensus is emerging that glaciers were limited in extent during the last glacial maximum (LGM) and reached their maximum extent well before then (Binyuan and Jijun, 1991; Derbyshire et al., 1991; Shi, 1992; Zheng and Rutter, 1998; Lehmkuhl and Owen, 2005; Owen et al., 2005). Cosmogenic radionuclide (CRN) exposure dating methods have begun to shed light on the timing of glaciations in the region, and they also have demonstrated that ice was not extensive during the LGM (Schäfer et al., 2002; Owen et al., 2003a,b, 2005; Finkel et al., 2003). Here, we provide new CRN ages that reinforce this view.

Schäfer et al. (2002) produced an age of 67,500 ± 6000 yr (mean of the three isotopes $^{10}$Be, $^{26}$Al, and $^{21}$Ne) for a boulder on a moraine about 10 km from the present terminus of Tanggula glacier near Basicuo Lake. Three other ages of 83,400 ± 7700, 161,700 ± 13,200, and 169,300 ± 15,100 yr (means of three isotopes each) were produced for moraines about 25 to 30 km south of Tanggula Pass. A more extensive set of $^{10}$Be ages was obtained by Owen et al. (2005) and contains exposure ages that range from 33,850 ± 1280 to 215,000 ± 2810 $^{10}$Be yr. Their ages for the Basicuo moraine varied from 46,420 ± 1740 to 79,280 ± 4340 $^{10}$Be yr. Here, we discuss new $^{10}$Be ages that suggest that Tanggula Glacier advanced less than 3 km during the LGM.

## Methods

Moraines in the Tanggula Shan were mapped from topographic maps and satellite images. Fieldwork was carried out in 2002 near Tanggula Pass and Basicuo Lake, as well as the Longxiazai Valley (Fig. 1). Fifteen samples for CRN analysis were collected, and from these, four were prepared at the University of Vermont and then measured for $^{10}$Be at Lawrence Livermore National Laboratory. Field and laboratory methods are described in Bierman et al. (2002) and Colgan et al. (2002).

## Results

Mapping of moraines in the Tanggula Shan show that at least four phases of glaciation occurred (Fig. 1). The oldest,

* Corresponding author. Fax: +1 616 3313675.
*E-mail addresses:* colganp@gvsu.edu (P.M. Colgan), jmunroe@middlebury.edu (J.S. Munroe), zhzs@lzu.edu.cn (Z. Shangzhe).

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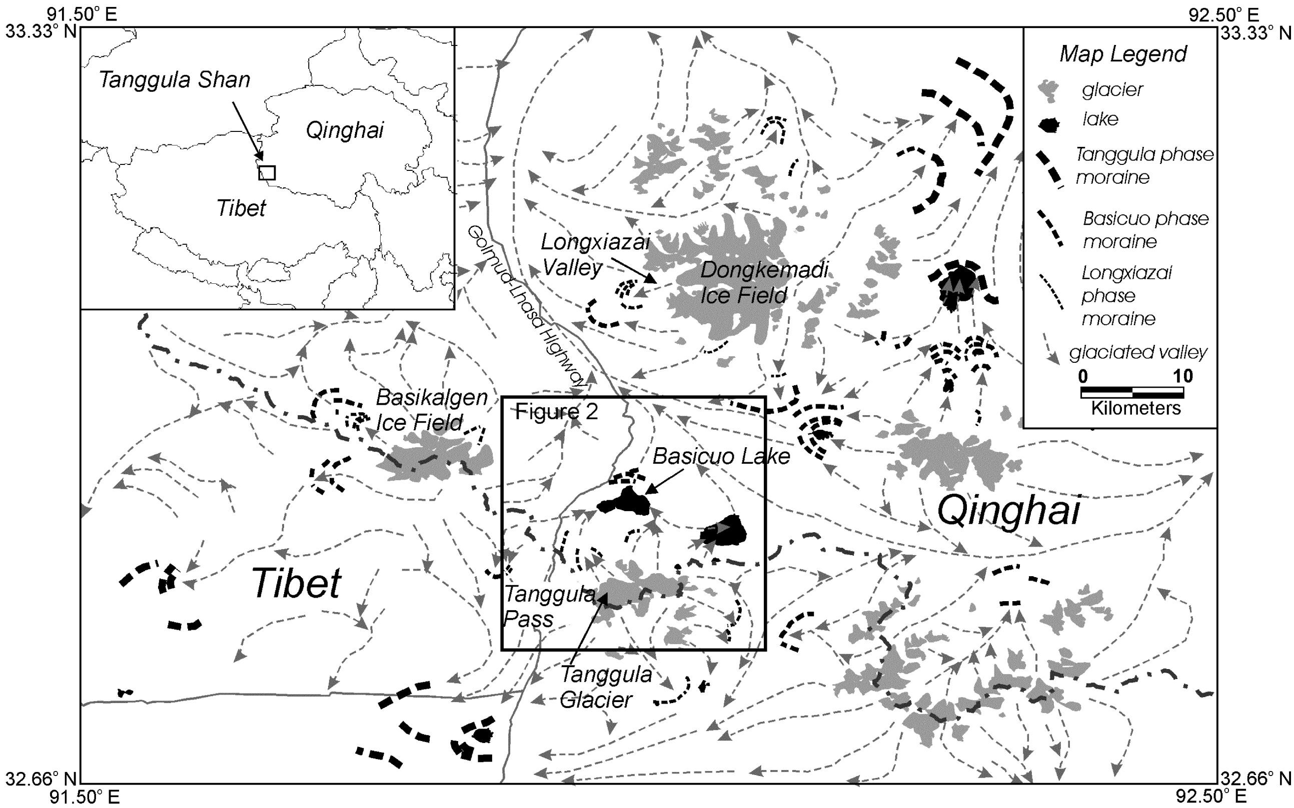


Figure 1. Map of glaciers and moraines in the northwestern Tanggula Shan. Dashed lines with arrows indicate direction of maximum glacier flow in glaciated valleys during the Tanggula and Zhajiazangbo phases. Heavy dashed line is Tibet–Qinghai border.

the Tanggula and Zhajiazangbo, are represented by extensive areas of hummocky topography and large moraines extending below 5050 m asl and 16 to 25 km from modern glacier margins. These moraines define the margins of piedmont glaciers that drained large ice fields. The Basicuo phase is represented by moraines 5 to 10 km from modern glacier margins, between elevations of 5050 and 5150 m asl. The surfaces of these moraines are weathered, and boulders are composed of resistant meta-sedimentary and igneous rocks. During the Basicuo phase, the Tanggula Shan were partially inundated by smaller ice fields. While many of the moraines are large (several km long, up to 2 km wide, and 60 m high), small-scale moraine relief (hummocks and kettles) is very low (<2 m) indicating that periglacial processes have eroded and smoothed the surfaces of these moraines. The Longxiazai phase moraines are low and poorly preserved (<20 m high, with smooth moraine crests) and located less than 5 km from modern ice margins at elevations above 5150 m asl. Ice at this time was restricted to valleys and in ice fields (Munroe et al., 2003). Finally, small well-preserved end moraines (steep sided and sharp moraine crests) located less than 1 km from the margins of modern glaciers likely record the extent of a recent advance.

The samples show a consistent pattern of CRN exposure ages as one goes from the farthest moraine ridge (north of Basicuo Lake) to the modern glacier terminus of Tanggula Glacier (Table 1). The oldest age (66,800 ± 7100 $^{10}$Be yr) comes from an erratic boulder located on a divide between the Tanggula Glacier and Basikalgen ice field (Fig. 2). The second-oldest age (41,400 ± 4300 $^{10}$Be yr) is from the proximal side of the inner Basicuo moraine about 10 km from the terminus of Tanggula Glacier (Fig. 2). The next oldest age of 31,900 ± 3400 $^{10}$Be yr comes from a boulder on an end moraine located about 3 from the terminus of Tanggula Glacier (Fig. 2). All of these ages are probably minimum limiting ages because of periglacial erosion and boulder exhumation after moraine

Table 1
Sample numbers, location, and CRN $^{10}$Be data for boulders on moraines of the Tanggula Shan

| Sample # | Latitude (degrees) | Longitude (degrees) | Elevation (meters) | $^{10}$Be measured ($\times 10^6$ atoms/g) | $^{10}$Be corrected* ($\times 10^6$ atoms/g) | $^{10}$Be model** exposure age |
|---|---|---|---|---|---|---|
| TS-02-05 | 32.932 N | 91.966 E | 5198 | 4.816 ± 0.132 | 0.213 ± 0.006 | 41,400 ± 4300 |
| TS-02-10 | 32.857 N | 91.941 E | 5310 | 1.976 ± 0.052 | 0.083 ± 0.002 | 16,100 ± 1700 |
| TS-02-11 | 32.861 N | 91.940 E | 5272 | 3.834 ± 0.142 | 0.164 ± 0.006 | 31,900 ± 3400 |
| TS-02-12 | 32.888 N | 91.906 E | 5380 | 8.27 ± 0.26 | 0.342 ± 0.011 | 66,800 ± 7100 |

* Correction according to Lal (1991).
** Calculated using a production rate of 5.17 atoms $g^{-1}$ $y^{-1}$.

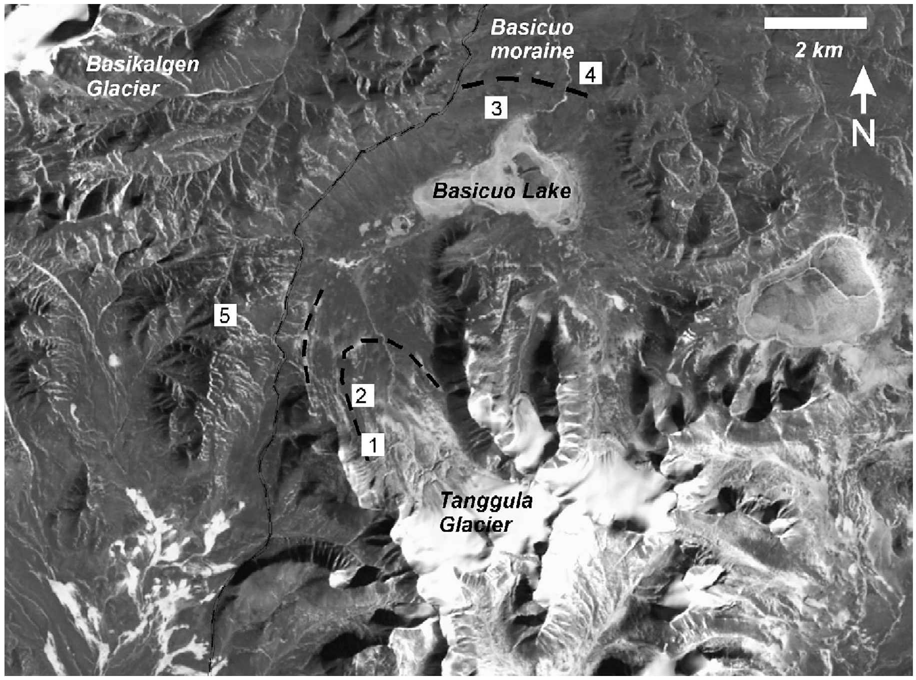


Figure 2. CRN exposure ages for samples in the Tanggula Pass and Basicuo Lake area. Image is a Landsat image from January 19, 1989. (1) Outcrop of striated bedrock (TS-02-10, 16,100 ± 1700 $^{10}$Be yr). (2) Boulder on eroded Longxiazai phase moraine (TS-02-11, 31,900 ± 3400 $^{10}$Be yr). (3) Felsic volcanic boulder on Basicuo phase moraine (TS-02-05, 41, 400 ± 4300 $^{10}$Be yr). (4) Quartz-andesite boulder on Basicuo moraine analyzed by Schäfer et al. (2002) as 67,500 ± 6000 yr (average of three isotopes). (5) Erratic boulder on a high drainage divide between Tanggula and Basikalgen glaciers (TS-02-12, 66,800 ± 7100 $^{10}$Be yr).

deposition. Four to seven CRN samples from each moraine would be needed to better determine the age of these moraines (Putkonen and Swanson, 2003). The youngest $^{10}$Be age comes from a striated outcrop about 2 km from the modern terminus of Tanggula Glacier (Fig. 2). This outcrop shows evidence of glacial abrasion (striae and grooves) and plucking along joint blocks. The sample was taken from the abraded top of the outcrop. The age of 16,100 ± 1700 $^{10}$Be yr suggests that the outcrop has been ice-free at least that long. The outcrop has a relief of about 2 m and it is unlikely that it was covered by till since it was eroded and abraded by ice.

## Discussion

The CRN ages suggest that the advance of ice that built the Basicuo moraine was well before the LGM. Our ages and the $^{10}$Be ages of Owen et al. (2005) along with the age of 67,500 ± 6000 yr (see Fig. 2) reported by Schäfer et al. (2002) all suggest that ice last filled the valley sometime before marine oxygen isotope stage 3 (MIS-3). The extensive weathering and low relief of moraines in this area are consistent with a pre-MIS-2 advance. Our $^{10}$Be ages of 16,100 ± 1700 yr on striated bedrock and the age of 31,900 ± 3400 yr on a moraine boulder suggest a MIS-2 extent of no more than 3 km farther than the present terminus of Tanggula Glacier. The thin glacial cover in this area makes it unlikely that the outcrop was only recently exhumed by postglacial erosion. It is possible that the outcrop contains some inherited nuclides from previous exposure before the LGM, so this age could be increased by an unknown amount. The pre-LGM CRN exposure ages suggest that most of the valley in front of Tanggula Glacier and near Basicuo Lake has been exposed to cosmic radiation for at least 30,000 years. This would imply a very limited extent of Tanggula Glacier since this time. Because this valley lies at the very heart of the Tanggula Shan, the limited extent of Tanggula Glacier suggests that it is unlikely that the Tanggula Shan were extensively glaciated at the LGM as suggested by Kuhle (1998).

The maximum extent of glaciation in the Tanggula Shan appears to have occurred well before MIS-2 (Schäfer et al., 2002). CRN ages obtained by Schäfer et al. (2002) and Owen et al. (2005) on piedmont moraines (and presumably Tanggula and Zhajiazanbo phase moraines) south of the Tanggula Shan produced ages consistent with MIS-6 or older glaciations. The Basicuo phase based on our ages, those of Schäfer et al. (2003), and those of Owen et al. (2005) suggest an age of at least MIS-3 and more likely MIS-4. The MIS-2 (LGM) position of the glacier was less than 3 km from the present terminus. Our results agree with those of Chaolu et al., (2002) who dated LGM moraines located between 3.7 and 5.5 km from the margin of the Puruogangri ice field in the northwestern Tanggula Shan (33°52′ N; 89°15′ E).

Recent interpretations of CRN exposure ages in the Himalayas (Finkel et al. 2003) and in the northeastern Tibetan Plateau (Owen et al., 2003a,b), hypothesize that glaciers reached their maximum extent when the south Asian monsoon was enhanced by increased insolation during MIS-3. Glaciers in the central part of the Tibetan Plateau might also have responded to increased precipitation during MIS-3. Glaciers in the Tanggula Shan are of the summer accumulation type (Ageta et al., 1991; Fujita et al., 2000) and should be more sensitive to precipitation changes than to changes in temperature. Many more CRN ages will be needed from well-mapped valleys and from multiple moraines to test this hypothesis.

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