PERGAMON

Quaternary International 97–98 (2002) 93–101

The relationship between climate change and Quaternary glacial cycles on the Qinghai–Tibetan Plateau: review and speculation

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Abstract

The Quaternary climatic history of the Qinghai–Tibetan Plateau is reconstructed using Quaternary glacial geologic data. Four major glaciations are recognized: the Xixiabangma, Naynayxungla, Guxiang (the Penultimate), and Baiyu (the Last) Glaciation. These are dated at about 800–1170, 500–720, 130–300, and 10–70 ka, respectively. These correspond to marine oxygen isotopic stages (MIS) $20\sim36$, $14\sim18$, $6\sim8$, and $2\sim4$. The most extensive glaciation occurred during the Naynayxungla Glaciation when there were many large ice caps, glacier complexes and great valley glaciers, covering a total area $\geqslant 500{,}000\,km^2$. The Guxiang Glaciation (Stage 6) was characterized by valley glaciers, while during the Baiyu Glaciation (Stages 2–4) the glaciers were more restricted in extent and covered a total area of $\sim 350{,}000\,km^2$. These data show that glaciation become less extensive throughout the Quaternary and may have been the result of variations in climate in response to changing patterns of insolation related to changes in the Earth's orbit. © 2002 Elsevier Science Ltd and INQUA. All rights reserved.

1. Introduction

Throughout the Tertiary, uplift of the Qinghai–Tibetan Plateau has caused environmental changes in Asia. In particular, it helped to initiate the south Asian summer monsoon and may have helped to force the onset of the Quaternary Ice Age. Based on scientific investigations and research during the last 30–40 yr, the total area of existing glaciers in the Qinghai–Tibetan Plateau has been mapped and calculated to be about $46{,}640\,km^2$ (Shi et al., 2000). Monsoon glaciers exist south of a line between Co Mai, Lhasri, Dengqen, Chola Shan, Naping and the southern side of the Himalaya. In these regions, the annual average precipitation is between 1000–2000 mm, with temperatures at the basal ice layer of glaciers of around 0°C. Glaciers move fast in these regions and they may extend into the forest zones at altitudes as low as 2500 m a.s.l. Examples of these types of glaciers are the Qaqin Glacier of Southeast Tibet, which is 35 km long and extends to an altitude of 2530 m a.s.l. and the Melang Glacier on the east slope of Mt. Kawagarbo (7640 m a.s.l.) that stretches 11.7 km and terminates at an altitude of 2660 m a.s.l. in dense *primerel* forest. The latter glacier has an average velocity of 533 m/yr. Continental glaciers are present in the northwest part of the Qinghai–Tibetan Plateau. Here, the annual average precipitation is <1000 mm, and the basal ice temperature is lower than 0°C. These glaciers advance slowly, usually between 2 and 10 m/yr, and are outside the permafrost zone. This is particularly the case in the West Kunlun Mountains at altitudes of >5000 m a.s.l., where many valley glaciers have lengths that exceed 20 km. These also include ice caps such as the Guliya Ice Cap that has an area of $376.05\,km^2$. On the ice surface of the Guliya Ice Cap at an altitude of 6700 m and an ice depth of 8 m, the ice temperature is -18.6°C. This is the lowest recorded glacier temperature in China. This is a polar-type glacier with annual precipitation of about 300–400 mm. The lowest air temperature, -60.5°C, was recorded at 6000 m on the Chongce Ice Cap during the winter of 1987–1988, and this is comparable with the lowest temperature (-59°C) recorded in Yakutzik in North Russia. Beyond the margin of the glaciers a high cold permafrost desert landscape exists.

Evidence for three to four Pleistocene glaciations is present on the Tibetan Plateau. During the maximum glaciation, the glacier types were composed of the large ice caps and great valley glaciers, with a total area of at least $500{,}000\,km^2$. However, during the Last Glacial, valley glaciers dominated, with a total area of $\sim 350{,}000\,km^2$ (Shi et al., 1995, 1997). During this time

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PII: S1040-6182(02)00054-X

there was no united ice sheet covering the whole plateau. The Pleistocene glacial history of the southeastern and eastern part of the plateau can be compared with the climate change record of the loess and lake deposits.

2. Pliocene paleogeographical environment

Since the beginning of the Tertiary, the Qinghai–Tibetan Plateau has undergone uplift and peneplanation. Two peneplains of Miocene to Pliocene age can be recognized on the Tanggula Pass region (Xu and Zhang, 1981). Miocene *Hipparion* faunas suggest that the plateau was at an altitude of ~1000 m a.s.l. during the Miocene (Huang and Ji, 1980; Xu, 1992).

Based on *Schizothorax* fauna in a Pliocene stratum of the Lunpola Basin in North Tibet, the plateau was probably at about 1000 m a.s.l. during the Pliocene (Cao et al., 1981). Paleokarst evidence also suggests that during this time peneplanation was occurring on a low tropical surface at an altitude of 1000 m a.s.l. Crystalline calcites within caves are dated at 15.7–11.7 Ma (Cui et al., 1995). As the plateau uplifted to elevations above 1500 m a.s.l., the monsoon began to develop. Tang and Liu (1995) suggest that this happened at the transition between the Pliocene and the Quaternary.

In summary, during the Pliocene period, the height of the basins on the Qinghai–Xizang Plateau was ~1000 m a.s.l.. This became a barrier so that the *Hipparion* sp. became restricted to the northern part of the mountains that were now at an altitude of $\leqslant$2000 m a.s.l. (Xu, 1992). At this time, the climate of southern Tibet was hot and wet, but the northern regions were more arid and could not support glaciers.

3. Glaciations and paleoenvironment during the Quaternary

At about 3 Ma, the Tibetan Pliocene peneplain was uplifted and deformed. In North Tibet, however, uplift and deformation started earlier at 4.0 Ma. The Jinggou Conglomerate that overlies the Tertiary Red Clay is dated at 3 Ma, near Dongshanding, LinXia and Gansu. This is believed to be the result of Qingzang A movement (Li et al., 1995). At the Yaruxungla Pass of the China–Nepal Highway, sandstone at the base of the Gongba Conglomerate is unconformable with sandstone at the base of the Pliocene and corresponds to the Matanuya–Gauss paleomagnetic boundary (Qian, 1991). The Gongba Conglomerate is 210 m thick and coarsens upwards, suggesting that uplift became more important in creating higher topography that could support glaciers.

The earliest glaciation that is recognized on the Tibetan Plateau is the Xixiabangma Glacial. Its glacial remnants (erratic boulders) are present on mountain summits at altitudes of ~6200 m a.s.l. north of Mt. Xixiabangma and on mountain tops at altitudes of ~5100 m a.s.l. to the north of Dingkapuli Pass, Burang. These deposits are 400 and 200 m higher than highest moraine platform of the subsequent glaciation, the Naynayxungla (Zheng, 1988). Mineral analyses of the till of the Xixiabangma Ice Age suggest that its provenance is similar to the Gongba conglomerate (Zhang, 1982; Zheng, 1988). Therefore, the uplift (Yuanmu movement) of 1.6 Ma during the latter part of the Early Pleistocene helped to create the higher mountains of the Himalaya, allowing small ice cap or piedmont glaciers to form north of the Himalaya in regions such as northwest Tibet. During this time the elevation of the lake basin floors were ~2000–2500 m a.s.l. The climate had now become substantially colder.

Under the continuance of the uplift at the end of the Early Pleistocene, the height of the basins within the Tibetan Plateau reached 3000 m a.s.l. and the mountains were at altitudes of ~4000–4500 m a.s.l.. During the Naynayxungla Glaciation, the accumulation area was large and precipitation as snowfall was great. This resulted in extensive glaciers and produced ice caps as, for example, on the West Tanggula (24,519 km^2), West Kunlun (5609 km^2), Mt. Golog (1903 km^2), Haizi (6965 km^2) and Daocheng mountains (Shi et al., 1995). On the northern slope of Mt. Xixiabangma, the piedmont glacier of the Naynayxungla region was about 1140 km^2 in extent, and advanced over the Gongba Conglomerate.

The subsequent interglacial was warm and wet, producing a red soil on the upper section of the high moraine platform of Nyalam in Tibet. Ferric pans are present in the basal bed. The red paleosol on the moraine platform of Naynayxungla Glaciation can be compared with the Ferretto red paleosol of the European Alps. Zheng (1988) suggested that it is comparable to the Mindel-Riss interglacial soils in Europe. The layer is comparable with the S_4–S_3 paleosol of Lanzhou Loess, the red sand on the top of Yurunkax till (Chen and Zhang, 1993), West Kunlun Mountains, that is TL dated to 330 ka.

During the penultimate glacial (see Table 1 for local names for this glaciation), the extent of glaciers in the inner plateau was smaller than that of preceding glacials. In the West Kunlun Mountain, till of the penultimate glacial is TL dated at 202 ka (Zheng et al., 1990). However, the glacier extent was larger than that of the former glaciation, in the southern part of Himalaya and Southeastern Tibet. The precipitation is more than that of inner plateau, and as a result large glaciers developed, including the former palaeo-Cepu Glacier of the Boduaozanpo River, over 100 km long, and the former Aza Glacier that extended to Walung village.

Table 1
A comparison of Quaternary glaciations and glacier types in the Qinghai–Xizang Plateau

Period	Age (ka BP)	Glacials Interglacials	Diancang Mts.	Yulong Mts.	Southeast Tibet	Mt. Gongga	Mt. Qomolangma	Western Kunlun Mts.
Holocene		Modern	No glacier	Small glacier	Valley glacier	Valley glacier	Valley glacier	Valley glacier Ice cap
	0.5	Little Ice Age	No glacier	Small glacier	Modern end moraines	Three end moraines	3−4 end moraines	Three end moraines
	5.0	Neoglaciation		Lateral moraine	3−4 end moraines	Three end moraines	Three end moraines	Three end moraines
	7.5	Hypsithermal	Glacier greatly retreated; paleosol S_0					
	10	Early stage	Glacier slowly retreated					
Late Pleistocene		Last glaciation: L G M	Dali II (16 ka BP) Dali I (57.6 ka BP)	Dali 24 ka BP (valley glacier)	Baiyu (Valley glacier) 78 km	Gongga II (15−20 ka BP) Gongga I (>25 ka BP)	Rongbushi 18−70 ka BP Valley glacier	Litran II 16−25 ka BP Litian I 66 ka BP
		Last glaciation: Inter-stadial						
	70	Last glaciation: Early						
	130	Last interglacial	Brown paleosol S_1					
Middle Pleistocene	300	The penultimate glaciation	Lijiang little glacier 140.3 ka BP	Lijiang (Valley glacier) 316−259 ka BP	Guxiang (Large valley glacier) 100 km	Nanmengun (Large valley glacier)	Jilongshi (Valley glacier) 200 ka BP	Bulakebashi Valley glacier 206 ka BP
	500	The great interglaciation	Red paleosol					
	780	Naynayxungla glaciation	No glacier	Yunshaping 0.6 Ma BP (Piedmont glacier)	?	Yajiageng Piedmont glacier	Naynayxungla (Piedmont glacier)	Yulongkashi Piedmont glacier 0.7 Ma BP
Early Pleistocene	2500	First Interglaciation Xixiabangma glaciation Warm stage		Sheshan fomation Warm and Wet		Xigeda Formation Cold at Late Warm at Early	Pali lake Deposit Xixiabangma Gongba Conglomerate	Xiyu (the Western regions) Conglomerate

During the penultimate glacial, the glaciers in Baishui River valley on the east slope of Mt. Yulong were larger than that of Naynayxungla (locally called the Yushaping) Glacial that was dated at $\sim$0.6 Ma. ESR dates on the high lateral moraine of the penultimate glacial are 316.2 ± 63.2 ka and ESR 257.2 ± 51.4 ka. A red soil developed on the tops of moraines is comparable with paleosol (S_1) of the loess sequences.

At about 70 ka, the mountains were uplifted and the climate became colder and drier. This is coincident with the deposition of the Malan Loess (Liu Tungsheng, 1985). In the early stage of the Last Glacial, the extent of glaciation was still small. At about 36–40 ka, lake levels were higher in the Tianshuihai area, and lacustrine deposits lying under the outer end moraines of Chongce Glacier have been dated at 30.9 ± 1.7 ka (Zheng et al., 1990). At 13ka, the climate began to warm up and the glaciers retreated. During the Younger Dryas, the glaciers advanced in front of the Guliya Ice Cap; the end moraine is radiocarbon dated to $10{,}990 \pm 190$ and $10{,}553 \pm 123$ yr BP (Jiao and Yao, 1995).

The glaciers and environments have changed throughout the Holocene. Three stages can be recognized: (1) early Holocene glacier retreat; (2) extensive retreat during the middle Holocene (7500–5000 yr BP); and (3) four glacier advances during the Neoglacial that are referred to as the Chongce (3983 ± 120 yr BP), the Xuedam (2980 ± 150 yr BP), the Rougou (1920 ± 110–1540 ± 85 yr BP), and the Hailuogou (940 ± 85–780 ± 90 yr BP) (Zheng and Rutter, 1998). The Little Ice Age began in Tibet about 500 yr ago and is represented by 3–4 moraines that represent centennial scale oscillations (Zheng and Ma, 1994). A comparison of local chronologies and glacier types throughout in the Tibetan Plateau is shown in Table 1.

4. The relationship between glacial cycles and climate change

Glaciation is controlled by the climatic and geomorphologic conditions in the mountains of middle latitudes. Although the record of the deep-sea core and the Lanzhou Loess shows 51 stages of global climatic change (Chen and Zhang, 1993), there is only evidence for four major glaciations in Tibet. This is not only due to lack of preservation of glacial geologic evidence because later larger glaciers easily destroy the evidence, but also due to the glacier feedback that affects the climate. Therefore, even though the climate became colder, if the mountain height is below the snowline, no glaciers can form. However, in the Ice Age, if the mountain heights were above the snowline, glaciers could form and become cold sources acting as feedback mechanisms. In this condition, the mountain glaciers would not disappear completely in the following global warming period. Therefore, the number of glacial and interglacial periods in the mountains may not be the same as the number of cold and warm stages in the record of deep-sea cores and loess. However, the lacustrine record in the interior and along the margins of the Tibetan Plateau has a closer relationship with the glacial changes. For example, the records in sediment organic matter (Zhang et al., 1995) and the sporo-pollen analysis (Liu et al., 1995) of RH core of Zoige Basin show the relationship of climate and glacial change (see Fig. 1).

We consider that the dominantly cold section within the RH core of Zoige Basin is approximately equivalent to the Quaternary Ice Age. Fig. 2 shows the climatic change that is similar to the glacial history that was presented above (for the eastern part of the Tibet Plateau). This includes:

(1) MIS 2 and 4 of Last Glacial (70–10 ka BP) that included two stadials, the younger being much colder than the former, i.e., the Last Glacial Maximum (25–15 ka BP). These stadials were separated by a warm stage at 30–25 ka. This is consistent with the interstadial (^{14}C dating: 24390 ± 750 yr BP) of the last glaciation of Mt. Gongga (Zheng and Ma, 1994).
(2) The last inter-glaciation (130–70 ka BP) is equivalent to MIS5. This can be divided into three warmer stages and two colder stages and is equivalent to the S_1 loess.
(3) The Penultimate glaciation (300–130 ka BP) is equivalent to MIS 6–8.
(4) The great interglaciation (500–300 ka BP) is equivalent to MIS 9–13 and includes three warm stages. These warm stages were probably contemporaneous with the paleosols (S_3 and S_4) of the Jiuzhoutai loess succession near Lanzhou. Paleosol

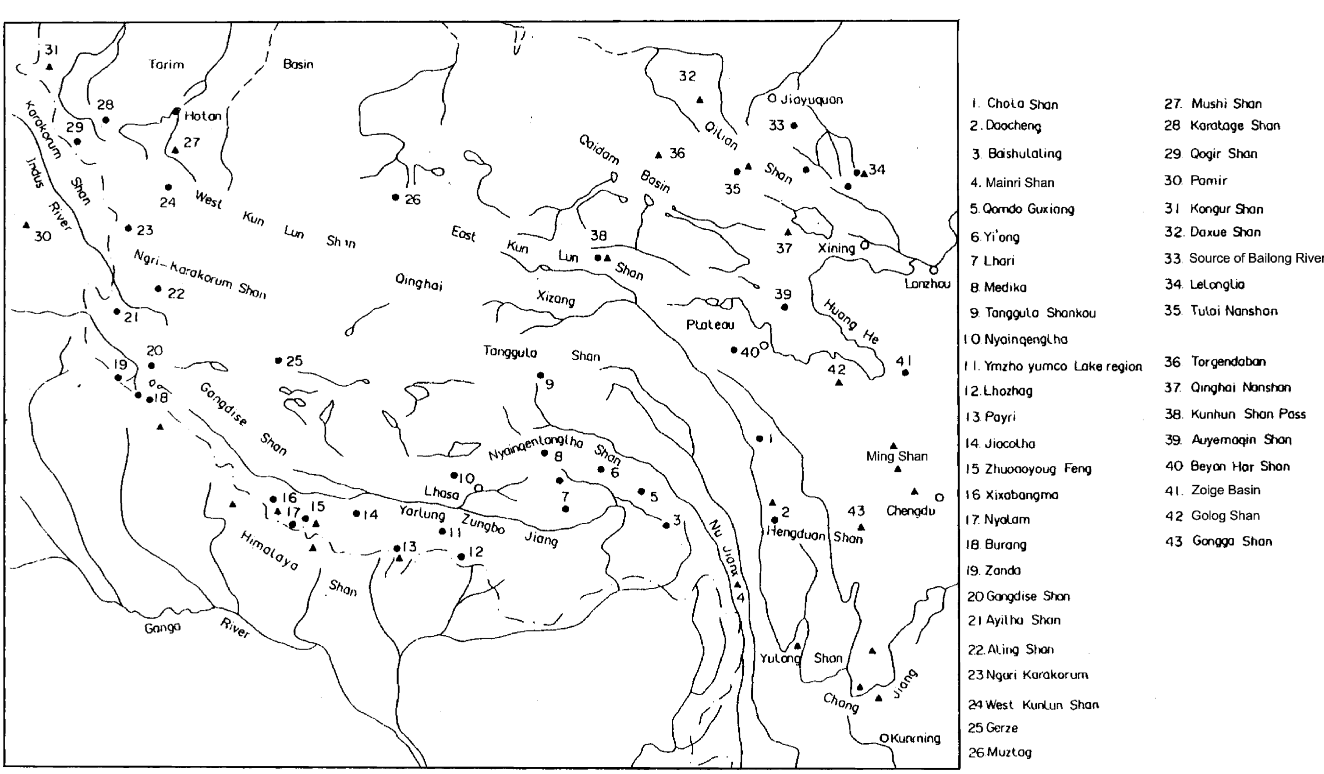


Fig. 1. Areas in which glacial evidence has been studied across the Qinghai–Xizang Plateau and key localities referred to in text.

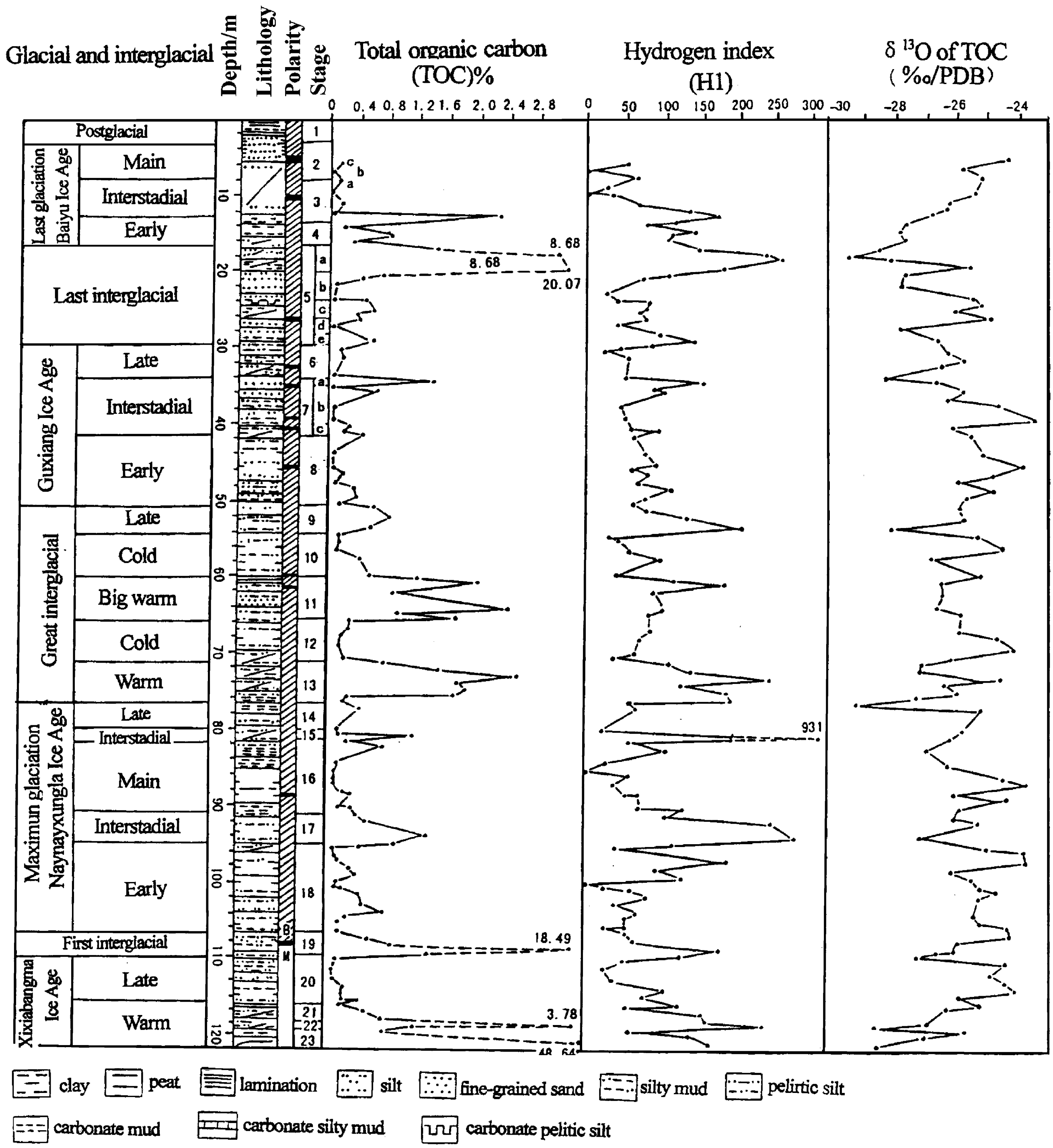
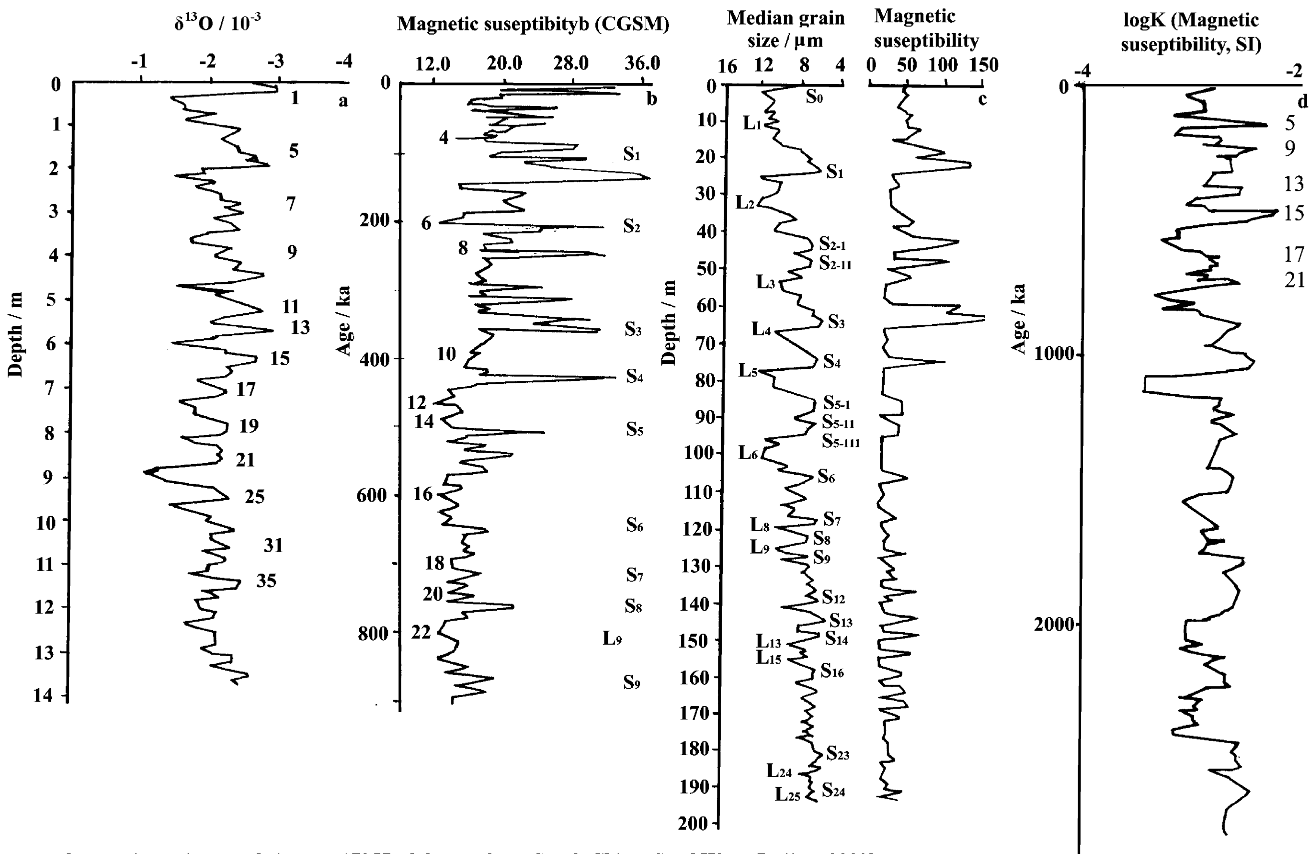


Fig. 2. Comparison between the vertical distributions of TOC, H1 and $\delta^{13}C$ of TOC in the RH core and the glacial cycles of the Qinghai–Xizang Plateau.

S_4 indicates a warmer and wetter climate, and its magnetic susceptibility is the highest (Fig. 3b). Sporo-pollen analysis of this paleosol indicates that warm conditions (Chen and Zhang, 1993). The paleosol is very thick and is regarded as the diagnostic stratum. Other evidence from the Chashmanigar loess-soil section, Tadzhikistan, and Core 17957 from the South China Sea suggests that the warmest period occurred during MIS 13 (Yu and Ding, 2001; Wang et al., 2000: see Fig. 3).

(5) The largest glaciation of the Middle Pleistocene is the Naynyxungla Glaciation in the Tibetan



a. Oxygen isotopic records in core 17957 of the southern South China Sea [Wang Rujian, 2000]
b. Magnetic susceptibility of Lanzhou loess-soil sequence [Chen Fuha, 1993]
c. Median grain size and magnetic susceptibility of Chashmanigar loess-soil sequence, Tadzhikistan [Yu Zhiwei et al, 2001]
d. Variations of magnetic susceptibility in Luochuan loess-paleosol section [Liu Dongsheng et al, 1985]

Fig. 3. Comparison between oxygen isotopic records in core 17957 of the southern South China Sea, magnetic susceptibility of Lanzhou loess-soil sequence, median grain size and magnetic susceptibility of Chashmanigar loess-soil sequence, Tadzhikistan and magnetic susceptibility in Luochuan loess-paleosol section.

plateau. The style of this glaciation varies between regions.

In the Qilian Mountains, the largest glaciation is the Zhongliangan Glaciation, dated by ESR methods at 460 ± 45 ka BP in the Bailang river basin. It is approximately coincident with the Shangwangfeng Glaciation in the Urumqi River Basin of eastern Tianshan, also dated with ESR methods at ~ 470 ka (Zhou et al., 2001). This glaciation is coincident with MIS 12. The magnetic susceptibility of the Chashmanigar loess-soil section in Tadzhikistan (Yu and Ding, 2001) showed that the warmest time was during S_3, coincident with MIS 11. This is represented by a red sand layer on the top of the moraines that formed during the Yurunkax Glaciation in the west Kunlun Mountains (Zheng et al., 1990). This suggests that the Yurunkax or Zhongliangan Glaciation developed during MIS 12 in some places in China.

However, the magnetic susceptibility of paleosol S_5 is the highest (Fig. 3d). This shows that the climatic was warmest in the loess plateau to the east of Liupanshan Mountain (Liu et al., 1985). However, the warmest peak value in the west Loess Plateau occurred near the end of the great interglacial period. At the beginning of the global warming following the Naynayxungla maximum glaciation, glacier ablation consumed a large quantity of heat. Therefore, the beginning of the great interglacial period was late, and the maximum glaciation (Naynayxungla Glaciation, 720–500 ka) in the Tibetan Plateau was equal to MIS 14–18. There were two large cold periods in Zoige Basin, which can be compared with the two glacial stages of Naynayxungla of Mt.Xixiabangma Region in the Himalayas. Wu and Li (1990) also divided this into two glaciations. The sporo-pollen analysis shows that the climate between the two cold stages was not entirely warm, indicating an interstadial stage. However, this glaciation extended to MIS 12 (460–470 ka) in the West Kunlun Mountains, Tianshan and Qilian Mountains of China.

(6) The first interglacial (800–720 ka) is broadly equivalent to MIS19, approximately at the Brunhes/Matuyama paleomagnetic boundary. In that time, the record of RH core indicates the existence of a warmer climate. The total organic carbon of sediment is very high (18.49%).

(7) The oldest glaciation—Xixiabangma Ice Age (1170–800 ka). Only remnants of this glacial are present in the Mt. Xixiabangma and Burang regions of the middle Himalaya (Zheng, 1988). There are no remnants in the region to the north of Himalaya. Based on the record of the RH core (112.4–110.7 m depth) of Zoige Basin, this event is equivalent to MIS 20. Its TOC and HI are also the lowest, and the $\delta^{13}C$ value of TOC is the highest. This illustrates a complete exposure of RH Core sediments to the surface, decreasing supply of organic matter or stronger oxidation. It may be compared to the oldest glaciation of Qinghai–Xizang Plateau. Furthermore, the pollen record indicates cold conditions at this time (Zhang et al., 1995; Liu et al., 1995).

Based on the recent research of Liu et al (1997), the environment of Chengjiawo, Lantian was a cold, temperate steppe at $\sim$0.9 Ma. It is equal to the lower section of Lishi loess. While the record of Jiuzhoutai loess shows that since the 1400 ka, among the climatic changes and the glacial cycle, a strong arid event (the earliest cold period) appeared in 1.10–1.17 Ma. This is equivalent to the lower sandy loess of Lishi Loess, the coarsest and least magnetic of all the loess units, suggesting a arid-cold environment of deposition. This is of significance for the whole Loess Plateau and North China. It may have formed during the Xixiabangma Glacial and may have extended from 1170–800 ka, including several interstadials.

5. Relationship between glacial cycles and changes in geometry of Earth's orbit

The average insolation in the summer half-year of the Northern Hemisphere or in the winter half-year of the Southern Hemisphere on the Earth's surface can be calculated for each oxygen isotopic stage (Xu and Huang, 1993) (Table 2). The relationship between winter insolation and the winter temperature in the world can be essentially positively correlated, and the relationship between summer and the summer insolation temperature in the world is essentially a negative correlation. Because the variations of temperature in both winter and summer are similar (Xu, 1988), the relationship between D_i (mean winter insolation) and the worldwide temperature is evidently a positive correlation. Therefore, climate has changed regularly in accordance with variation in the average incoming solar radiation in the winter half-year of the Northern Hemisphere on the Earth's surface in each oxygen isotopic stage (Table 2) during the past 730,000 yr (Xu, 1992). The phenomena of the classical North European glacial stages can be explained with applications of the D_i data (Table 2). Many interesting phenomena during the past 730,000 yr may also be explained with applications of these data (Xu, 1991, 1992).

In the past 730,000 yr, the coldest climate is likely to have occurred during MIS16 (i.e. during the Naynayxungla Glaciation) (Table 1). This may help explain why the Naynayxungla Glaciation was the most extensive on

Table 2
The time scale, the average variations $\delta^{18}O$ and average incoming solar radiation in each oxygen isotope (i.e. D_i and X_i) in the past 734,000a (Ly/day) and comparison with Quaternary glaciations in the Qinghai–Xizang Plateau

Mean stages $\delta^{18}O$	Specmap time scale (ka BP)	Disr. time scale (ka BP)		Mean winter insolation (D_i)	Mean summer insolation (X_i)
2–4	12–70(59)	11–65(58)	1.00	458.84	460.29
5	71–127(57)	69–126(58)	−1.18	460.29	458.90
6	128–185(59)	127–183(57)	0.66	458.09	461.05
7	186–244(59)	184–241(58)	−0.75	461.05	458.22
8	245–302(58)	242–291(50)	0.21	459.07	460.11
9	303–338(36)	295–333(42)	−0.92	460.38	458.86
10	339–361(23)	334–370(37)	0.70	458.80	460.34
11	362–422(61)	371–407(37)	−0.87	459.77	459.37
12	423–477(55)	408–464(57)	0.58	459.25	459.89
13	478–523(46)	465–504(40)	−0.27	460.36	458.79
14	524–564(41)	505–561(57)	0.18	457.84	461.30
15	565–619(55)	562–619(58)	−0.31	461.41	457.76
16	620–658(39)	620–655(36)	1.01	457.27	461.88
17	659–688(37)	656–691(36)	−0.07	461.69	457.45
18	689–725(37)	692–713(22)	0.55	458.61	460.53
19	726–735(10)	714–733(2)	−0.35	459.73	459.41

the Tibetan Plateau during the Quaternary. During the Guxiang Glaciation (MIS 6) the snowline was at about 4200 m a.s.l. on the Qilian Mountains and Queer Shan, while in Baiyu Glaciation (MIS 2–4), the snow line was 300 m lower than in Stage 6. The moraines of the Guxiang Glaciation (Stage 6) indicate a much larger area of glaciation than the Baiyu Glaciation (Stages 2–4) on the Qinghai–Xizang (Tibetan) Plateau. The mean winter insolation of Stage 6 (D6) is 456.09 Ly/day (Table 2). This is less than the 458.84 Ly/day associated with Stages 2–4. Thus, the climate in Stage 6 must be much colder than that in Stages 2–4, and there appears to be a positive correlation between lower winter insolation values and greater ice extent. This suggests that variation in climate is a response to changes in insolation due to variations in the Earth's orbital parameters on 10,000–100,000 yr time scales in Tibet.

Acknowledgements

We wish to thank Lewis A. Owen for critically reviewing and editing the manuscript, and for rendering it into English. Research for this study was jointly funded by the Chinese Academy of Sciences (KZCX 1-10-06) and the National Natural Science Foundation of China (NSFC 49871021).

References

Cao, W., Chen, Y., Wu, Y., Zhu, S., 1981. Origin and evolution of Schizothoracine fishes in relation to the upheaval of the Qinghai–Xizang Plateau. In: Studies of the Period, Amplitude and Type of the Uplift of the Qinghai–Xizang Plateau. Science Press, Beijing, pp. 130–137.

Chen, F., Zhang, W., 1993. The Loess-Stratigraphy and Problem of Quaternary Glaciation in Gansu–Qinghai region. Science Press, Beijing, pp. 114–149.

Cui, Z., Hong, Y., Chen, H., 1995. The new discovery of the paleo karst on Qinghai–Xizang plateau. In: The Research of the Formation, Evolution, Environmental Changes and Ecological System of the Qinghai–Xizang Plateau (1994). Science Press, Beijing, pp. 120–125 (in Chinese).

Huang, W., Ji, H., 1980. The first discovery of Xizang Hipparion fauna and its significance to the plateau rise. Kexue Tongbao 24 (19), 885–888 (in Chinese).

Jiao, K., Yao, T., 1995. Variation of the Guliya Ice Cap and climatic record since the Younger Dryas. In: The Research of the Formation, Evolution, Environmental Changes and Ecological System of the Qinghai–Xizang Plateau (1994). Science Press, Beijing, pp. 34–40. (in Chinese).

Li, J., Fan, X., Zhu, J., 1995. Paleomagnetic chronology and type sequence of the Cenozoic stratigraphy of the Linxia Basin in Gansu province of China. In: the Research of the Formation, Evolution, Environmental Changes and Ecological System of the Qinghai–Xizang Plateau (1994). Beijing, Science Press, pp. 41–54 (in Chinese).

Liu T., 1985. Loess and the Environment. China Ocean Press, Beijing.

Liu, G., Shen, Y., Wang, S., 1995. Vegetation history and environmental interpretation of RH core from Zoige Basin. In: The Research of the Formation, Evolution, Environmental Changes and Ecological System of the Qinghai–Xizang Plateau (1994). Science Press, Beijing, pp. 199–208 (in Chinese).

Liu, T., Ding, Z., Yuan, B., 1997. Sequence of Quaternary events in China: dating by a loess orbital time scale. In: Jablonski, N.G. (Ed.), The Changing Face of East Asia During the Tertiary and Quaternary. Center of Asian Studies. The University of Hong Kong, pp. 23–33.

Qian, F., 1991. The age and formation environment of Gongba conglomerate at Tingri County, Tibet. In: Quaternary Glacier and Environment Research in West China. Beijing Science Press, pp. 285–291 (in Chinese).

Shi, Y., Zheng, B., Li, S., Ye, B., 1995. Studies on altitude and climatic environment in the middle and east parts of Tibetan Plateau during Quaternary maximum glaciation. Journal of Glaciology and Geocryology 17 (2), 97–112.

Shi, Y., Zheng, B., Yao, T., 1997. Glaciers and environments during the last glacial maximum (LGM) on the Tibetan Plateau. Journal of Glaciology and Geocryology 19 (2), 97–115.

Shi, Y., Huang, M., Yao, T., 2000. Glaciers and their Environments in China. Science Press, Beijing, pp. 9–53.

Tang, M., Liu, X., 1995. A new sign of delimit Quaternary period. Quaternary Research 1995 (1), 82–88.

Wang, R., Andrea, A., Huang, B., 2000. Relative abundance changes, stratigraphic and paleo-oceanographic significance of radiolarian *Botryocyrtis scutum* in South China Sea since Pleistocene. Earth Science—Journal of China University of Geosciences 25 (6), 553–556 (in Chinese).

Wu, X., Li, Y., 1990. Moraine and environments in the Qinghai–Xizang (Tibetan) Plateau. Quaternary Sciences (2), 146–158 (in Chinese).

Xu, Q., 1988. *Home erectus lantianensis* at Chenjiawo, the first appearance of Peking man in China. The paleoenvironment of East Asia from the Mid-Tertiary, Center of Asian Studies, University of Hong Kong, Hong Kong, pp. 401–413.

Xu, Q., 1991. Astroclimatology. China Science and Technology Press, Beijing, pp. 14–71.

Xu, Q., 1992. The first appearance of Himalayas and its relation to global climatic events. In: Proceedings of the First Symposium on the Qinghai–Xizang Plateau. Science Press, Beijing, pp. 296–301 (in Chinese).

Xu, Q., Huang, Y., 1993. Periodic table of climatic changes during the Quaternary. Evolving Landscapes and Evolving Biota of East Asia since the Mid-Tertiary, Center of Asian Studies, University of Hong Kong, Hong Kong, 1993, pp. 93–113.

Xu, S.-y., Zhang, L.-y., 1981. A geomorphological analysis of ages and amplitudes of the Tanggula Mountain upheaval, on the problem of the period, amplitude and type of the uplift of the Qinghai–Xizang Plateau, 64–77. Science Press, Beijing (in Chinese).

Yu, Z., Ding, Z., 2001. Calculations of time scale for paleoclimate records and phasing relationship between different climate-proxy time series: a case study of Chashmanigar loess-soil section, Tadzhikistan. Quaternary Sciences 21 (2), 123–133 (in Chinese).

Zhang, S., 1982. Study on Quaternary moraine debris of Mt. Xixiabangma Region. In: Reports of Scientific Expedition of Xixiabangma Region 1-127-143. Science Press, Beijing (in Chinese).

Zhang, P., Wang, X., Chen, J., Li, C., Wang, S., 1995. $\delta^{13}C$ values and hydrogen index records in sediment organic matter of RH core of Zoige Basin eastern Qing–Zang (Tibet) Plateau and their environmental significance. Science in China (Series B) 38 (8), 1015–1024.

Zheng, B., 1988. Quaternary glaciation of Mt. Qomolangma–Xixiabangma Region. GeoJournal 17 (4), 525–543.

Zheng, B., Ma, Q., 1994. The glacier variation, climatic change and the river valley development in the Holocene on the Gongga Mountains. Acta Geographical Sinica 49 (6), 500–508.

Zheng, B., Rutter, N., 1998. On the problem of Quaternary Glaciations, and the extent and patterns of Pleistocene ice cover in the Qinghai–Xizang (Tibet) Plateau. Quaternary International 45/46, 109–122.

Zheng, B., Jiao, K., Ma, Q., Li, S., Hiroji, F., 1990. The evolution of Quaternary glaciers and environmental change in the West Kunlun Mountains, West China. Bulletin of Glacier Research 8, 61–72.

Zhou, S., Li, J., Zhang, S., Zhao, J., 2001. Glacial Geomorphology and ice ages in the Bailang river basin, Qilian Mountains. Journal of Glaciology and Geocryology 23 (2), 131–138 (in Chinese with English Abstract).