Climate variation since the Last Interglaciation recorded in the Guliya ice core*

YAO Tandong (姚檀栋), L. G. Thompson**, SHI Yafeng (施雅风), QIN Dahe (秦大河), JIAO Keqin (焦克勤), YANG Zhihong (杨志红), TIAN Lide (田立德) and E. M. Thompson**

(Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, Lanzhou 730000, China)

Received January 16, 1997

Abstract The climatic and environmental variations since the Last Interglaciation are reconstructed based on the study of the upper 268 m of the 309-m-long Guliya ice core. Five stages can be distinguished since the Last Interglaciation from the $\delta^{18}O$ record in the Guliya ice core: Stage 1 (Deglaciation), Stage 2 (the Last Glacial Maximum), Stage 3 (interstadial), Stage 4 (interstadial in the early glacial maximum) and Stage 5 (the Last Interglaciation). Stage 5 can be divided further into 5 substages; a, b, c, d, e. The $\delta^{18}O$ record in the Guliya ice core indicates clearly the close correlation between the temperature variation on the Tibetan Plateau and the solar activities. The study indicates that the solar activity is a main forcing to the climatic variation on the Tibetan Plateau. Through a comparison of the ice core record in Guliya with that in the Greenland and the Antarctic, it can be found that the variation of large temperature variation events in different parts of the world is generally the same, but the variation amplitude of temperature is different.

Keywords: **climate variation, Last Interglaciation, Guliya ice core.**

Three ice cores with length of 308.7 m, 93.2 m and 34.5 m respectively, were drilled successfully at 6 200—6 700 m on the Guliya Ice Cap of the West Kunlun Mountains, Qinghai-Xizang (Tibetan) Plateau, the longest of which reached the bedrock. According to the work done before[1—4], the Guliya Ice Cap is the largest polar-type ice cap in the central Asia, with an area of 376 km^2. The 308.7 m ice core is drilled at 6 200 m, the ice temperature is -15.6℃, -5.9℃ and -2.1℃ respectively at 10 m, 200 m and the bottom of the borehole, and the annual precipitation is about 200 mm. Therefore, the Guliya ice core has the potential to provide long-term information about the climatic variation. All the three ice cores were divided after their extraction by Lanzhou Institute of Glaciology and Geocryology, CAS, and the Byrd Polar Research Center, Ohio State University. The ice core analyses and studies proceeded separately. The climatic variation in the Last Glacial Cycle discussed in this paper is based on the $\delta^{18}O$ record measured at Lanzhou Institute of Glaciology and Geocryology, CAS, China.

1 Measurement of $\delta^{18}O$

A lot of studies[5,6] have proved that $\delta^{18}O$ in precipitation is a reliable indicator to temperature in the north of the Tibetan Plateau. The Guliya Ice Cap is a polar-type glacier and, therefore, the $\delta^{18}O$ record in the Guliya ice core is more suitable to reflecting the temperature change.

* Project supported by the Climbing Program of the State Eighth Five-Year Plan and the National Natural Science Foundation of China.

** Byrd Polar Research Center, Ohio State University, Columbus, OH 43210, USA.

This can also be seen from the relationship between $\delta^{18}O$ in precipitation and annual temperature at several alpine sites by Broecker[7]. Guliya Ice Cap and Dunde Ice Cap are located in the upper left side of the regression line between $\delta^{18}O$ in precipitation and temperature, indicating the good correlation between $\delta^{18}O$ and temperature (figure 1).

$\delta^{18}O$ in the Guliya ice core was analyzed at Lanzhou Institute of Glaciology and Geocryology, CAS, using the MAT-252 mass spectrometer. More than 16 000 ice samples were analyzed, with one sample in 2 cm in average. The measured $\delta^{18}O$ has an accuracy of 0.1‰.

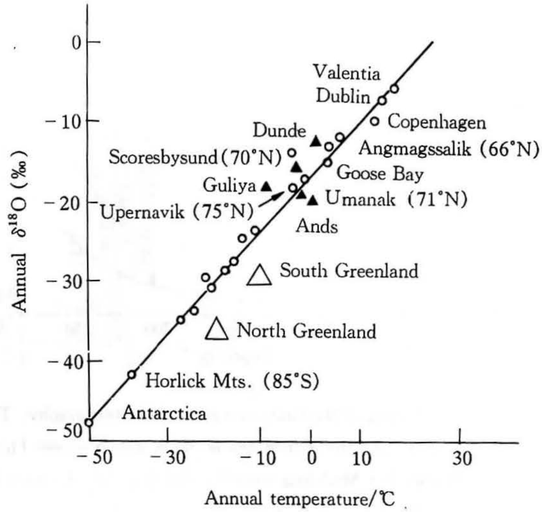

Fig. 1. $\delta^{18}O$ of the Guliya Ice Cap and Dunde Ice Cap in the global relationship between $\delta^{18}O$ and temperature.

2 Dating of Guliya ice core

Because of the extremely long history of the ice core and the quite different resolution of the ice core between the upper and the bottom parts (the resolution of the ice is one year in the upper part and hundreds of years at the bottom of the ice core), the dating methods are different in different parts of the ice core. In the upper 120 m of the ice core (corresponding to 1 700 a), the ice dating is based on the dust layer and $\delta^{18}O$ stratigraphy. Yao *et al*.[8] have analyzed in detail the climatic variation in the past 1 700 a recorded in the Guliya ice core using this method (fig. 2 (a)). In the middle of the ice core, the resolution of the ice core decreases from one year to several years, and the dust layer and $\delta^{18}O$ stratigraphy are no longer suitable for dating. The ice dating is based on modeling and reference layer methods. The reference layers that can be distinguished include the abrupt decrease of $\delta^{18}O$ occurring in the Last Glacial Maximum (LGM), the abrupt decrease of ice crystal size in the LGM. The reference layer indicated by $\delta^{18}O$ and ice crystal size both reflect the LGM is in about 170 m of the ice core. Therefore, the depth at 170 m of the ice core can be identified as the LGM, and the other climatic and environmental events can be interpolated based on the LGM layer. In the same way, the maximum $\delta^{18}O$ at about 268 m can be identified as the 5 e isotope stage. These reference layers can be used to verify the modeling results. The modeling formula suitable for the ice flow from the Last Interglaciation to about 1.7 ka B.P. is shown as follows:

$$T(z) = \int_0^z v(z)\mathrm{d}z, \tag{1}$$

where z is the ice depth equivalent, $v(z)$ is the vertical rate of ice deformation.

At the bottom of the ice core, the ice is extremely old, and ^{36}Cl dating is needed. In addition, ^{36}Cl method can also be used to verify the deposition of the nuclear test during the 1950s and the 1960s. Therefore, the layer identified by ^{36}Cl can be further used to date the upper part of the ice core. AMS is still an effective way for the ^{36}Cl dating. ^{36}Cl is used successfully in Greenland to identify the 1960 ^{36}Cl ice layer[9]. However, it is the first time to use the ^{36}Cl method to date the alpine ice core. Fig. 2(b) is the ^{36}Cl measurement result at the bottom of the ice core done by J.

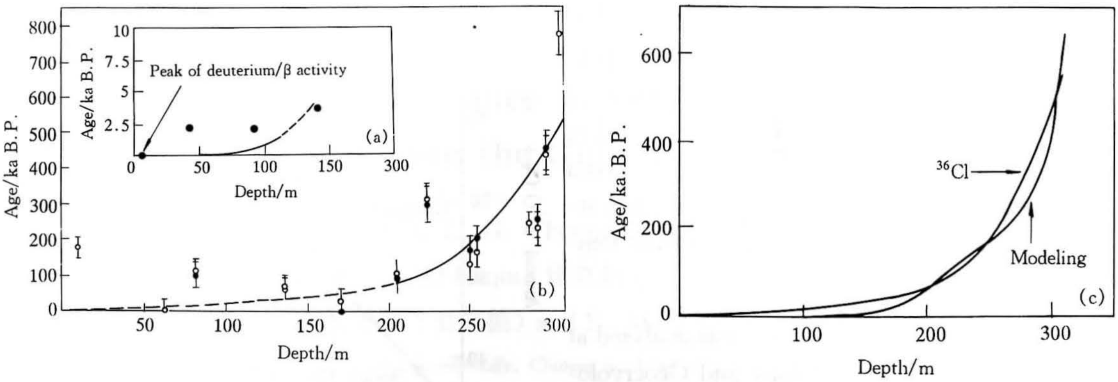

Fig. 2 Dating of the Guliya ice core. (a) Stratigraphy. The black circles represent ^{14}C dating, the solid line is the dust layer curve, and the dashed line is the modeling curve. (b) ^{36}Cl method. The black circles are $^{36}Cl/Cl$, and open circles are $^{36}Cl/g$. (c) Modeling method: showing the calculated result of the ice-flow model based on equation (1).

Beer from Institut für Mittelenergiephysik, Switzerland. Due to the intensive human activities, especially after the nuclear test in the late half of the 20th century, the background ^{36}Cl concentration has been largely disturbed. Therefore, the ice used for ^{36}Cl dating should be from where there is no human activities. The ice used for ^{36}Cl dating here is from the bottom of the ice core and is not disturbed by human activities. It can be calculated from fig. 2(b) that the ice at the bottom of the ice core was formed in about 700 ka B.P.

Based on the above, the ice in the upper part of the Guliya ice core can be dated in high resolution by dust layer and $\delta^{18}O$ stratigraphy, and the ice at the lower part of the ice core can be dated by ^{36}Cl method. The middle part of the ice core can be dated by modeling, which has been used for polar ice core[10] and alpine ice core[11]. Fig. 2(c) shows that the ice age at the bottom of the ice is about 700 ka, similar to that dated by ^{36}Cl. The prerequisite for the ice-flow model is that the glacial accumulation of the glacier was in the stable state in the whole period of accumulation. As far as the Guliya Ice Cap is concerned, this ice cap is a polar-type ice cap characterized by low temperature and less precipitation. From 700 ka B.P. to the present, the glacier size did not change much even in the LGM. According to Su Zhen, the glacial area of the West Kunlun glaciers in the largest glacial age is only 1.9 times larger than that of the existing glaciers. This may indicate that the precipitation in this area did not change so much in a long term, and the ice flow model is suitable for the ice dating. The similarity between the ice flow model curve and the ^{36}Cl curve also indicates the suitability of the ice-flow model. The time series of the ice core can also be set up through curves matching. Parterson has studied curve matching in ice core in detail[12]. All the methods mentioned above are used to obtain a best method to reconstruct the climatic variation since the Last Interglaciation (268 m in the ice core). In the present paper, the time series is established by a combination of curve matching and modeling.

3 Reconstruction of the climatic variation since 125 ka B.P.

Figure 3 shows the temperature variation since 125 ka B.P. according to the $\delta^{18}O$ record in the Guliya ice core. Comparing it with the deep-sea $\delta^{18}O$ record, we can distinguish five stages in the Guliya ice core $\delta^{18}O$ record: Stage 1 (Deglaciation), Stage 2 (late stadial of the Last Glacial Age or the LGM), Stage 3 (interstadial of the Last Glacial Age), Stage 4 (early stadial of the Last Glacial Age) and stage 5 (Last Interglaciation). Stage 5 can be divided further into 5 substages: a, b, c, d and e. Furthermore, the Younger Dryas (YD) is also marked in figure 3.

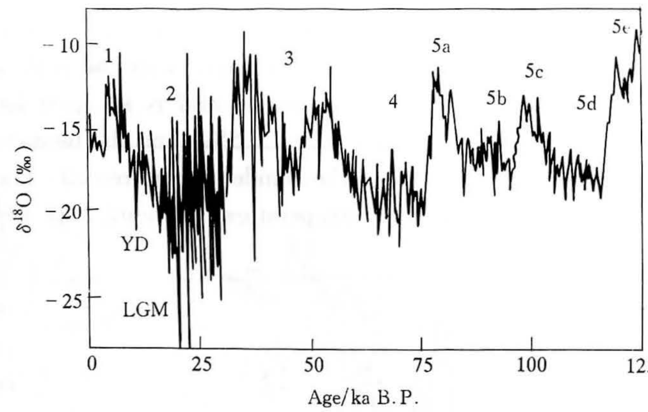

Fig. 3. High resolution temperature variation since 125 ka B. P. reconstructed from the $\delta^{18}O$ record in the Guliya ice core. Each point represents 0.1 ka.

The temperature variation in the Last Interglaciation (75—125 ka) is large. $\delta^{18}O$ in the three warm substages (5a, 5b, 5c) is 1.7‰, 0.5‰ and 3.2‰ higher respectively than that at present, corresponding to a temperature increase of 3℃, 0.9℃ and 5℃ respectively. The temperature in substages 5b and 5d is 3℃ and 4℃ lower than substages 5e and 5c respectively. In addition, there also exist temperature variations in century time scale in each substage. What is more noteworthy is that all the transition periods (from 5e to 5d, from 5c to 5b, from 5a to Stage 4) are characterized by dramatic cooling, while the warming from 5d to 5c, from 5b to 5a, is gradual. This may be useful for predicting the future global warming.

The coming of the Last Glacial Stage is quite abrupt. During the 3 000 a from substage 5 to Stage 4, $\delta^{18}O$ decreases by 7.5‰, corresponding to a temperature decrease of 12℃. The duration of the two cold periods, Stage 4 (75—58 ka B.P.) and Stage 2, is much the same. The average temperature decrease of Stage 4 is larger than that of Stage 2, although the extremely low temperature occurs in about 23 ka ($\delta^{18}O$ is low to −25‰) in Stage 2. It has been found in several mountain regions of the Qinghai-Xizang (Tibetan) Plateau (the south and north slopes of the Karakorum Mountains, north slope of the Qomolangma, Nianqingtanggula Mountains, Bayankara Mountain and Nianbaoyuze Mountains) that the glacier scale is larger in the early glacial stadial than that in the late glacial stadial. This is in agreement with the temperature recorded in the Guliya ice core. It is generally considered that the LGM is at 18 ka B.P., whereas in the Guliya ice core record, the duration of the 18 ka cold period lasts about 3 000 a. In addition, during the 23—30 ka B.P. cold period, the average $\delta^{18}O$ is 6‰ lower than that at present, corresponding to a temperature decrease of about 10℃. Substage 3 is usually called an interstadial, a weak warm period in both deep-sea $\delta^{18}O$ record and Vostok ice core record. Though the temperature in the period is higher than Stage 2 and Stage 4, it is remarkably lower than the Holocene and the Last Interglaciation. However, in the Guliya ice core record, the temperature in Stage 3 (58—31 ka B.P.) is abnormally high, higher than today. In other words, the climatic warming in Stage 3 can be compared to the Last Interglaciation. The paleo-lake and paleo-vegetation studies have proved the abnormally warm period on the plateau. A unique discovery is that there are at least 4 cold events in Stage 3 of the Guliya ice core record. The two cold periods occurred in 47 ka and 43 ka, $\delta^{18}O$ decreases to as low as in Stage 2 and Stage 4.

Temperature increases from 15 ka B. P. $\delta^{18}O$ increases from −20‰ in 16 ka B. P. to

−16‰ in 12 ka B.P. $\delta^{18}O$ decreases to −19‰ in Younger Dryas, and increases again from 10.5 ka B.P. In the Holocene, climatic warming is the general trend though there is a cold event in 9—8 ka B.P. The warmest period is in 7—6 ka B.P. in the Guliya ice core record. The $\delta^{18}O$ value increases to −12.5‰, and the temperature is 1.5℃ higher than that at present. This is the same as the Dunde ice core record. The temperature decreases abruptly in about 5 ka B.P., and the low temperature lasts until 2 ka ago and increases again.

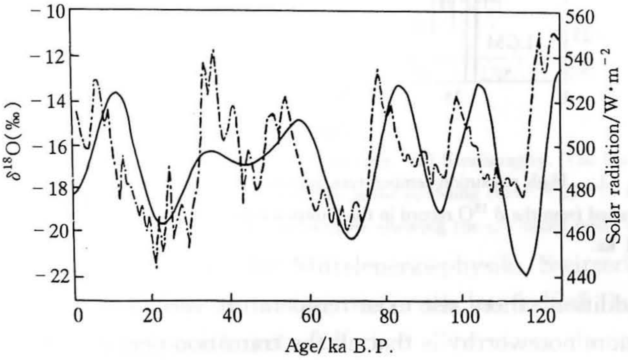

Fig. 4. Comparison between the $\delta^{18}O$ record in the Guliya ice core and the solar radiation at high latitude of the North Hemisphere. Each point in the figure represents 1 ka.

Guliya ice core record reveals clearly the close correlation between the temperature variation on the Qinghai-Xizang (Tibetan) Plateau and the solar activities[13]. From fig. 4, the 20 ka cycle and the 40 ka cycle can be observed. Several cold events occur in 116, 98, 75, 58 and 31 ka B.P., with an average cycle of 20 ka. The cold events with the 40 ka cycle are 116, 76 and 31 ka B.P. respectively, with an average interval of 43 ka. Fig. 4 reveals the similarity between the $\delta^{18}O$ record in Guliya ice core and the solar radiation variation 60° N[13]. Another important feature discovered in the Guliya ice core is that the solar radiation variation always leads to the temperature variation in the Guliya ice core record. This is an important evidence that the solar radiation is a main forcing to climate change on the Qinghai-Xizang (Tibetan) Plateau.

A pronounced feature of the $\delta^{18}O$ record in the Guliya ice core record is that the cold events and the warm events are evident. The amplitude of $\delta^{18}O$ variation is very large. The amplitude of $\delta^{18}O$ in Greenland ice core is smaller than that of the Guliya ice core not only in the two cold periods (5b and 5d) of the Last Interglaciation[14], but also in the Last Glacial Age. This may reflect a fact that the Qinghai-Xizang (Tibetan) Plateau where the Guliya ice core is extracted is more sensitive to climate change than that of Greenland. The mechanism might be that the cold climate results in thicker, larger and longer-lasted snow cover on the Qinghai-Xizang (Tibetan) Plateau, which can intensify the cooling further. As a result, the cooling has been amplified. Whereas in Greenland, the surface is covered by snow and ice all the time and, therefore, the climate change is less likely being amplified. Additionally, the top of the Guliya ice core is located at the mid-upper troposphere and can record the atmospheric process directly. Therefore, it is more sensitive to climate change compared to other records in the same region.

The Guliya ice core record may be most essential to comprehensive study in the climate and environment in the "Three Polar Regions": The Antarctica, Arctica and Qinghai-Xizang (Tibetan) Plateau. From the climatic variations recorded in ice cores of the three polar regions (fig. 5), it can be seen that the major climate events in the Guliya ice core is similar to that of the other two polar regions. The difference is that the amplitude of climate variation on the Qinghai-Xizang (Tibetan) Plateau is larger than that in the Antarctica and Arctica. Furthermore, small-scale climate events in each cold and warm period are also recorded in detail in the Guliya ice core. This means that the Guliya ice core record in the mid-latitude continent is more sensitive to climate change than that in the Antarctic and Arctic regions.

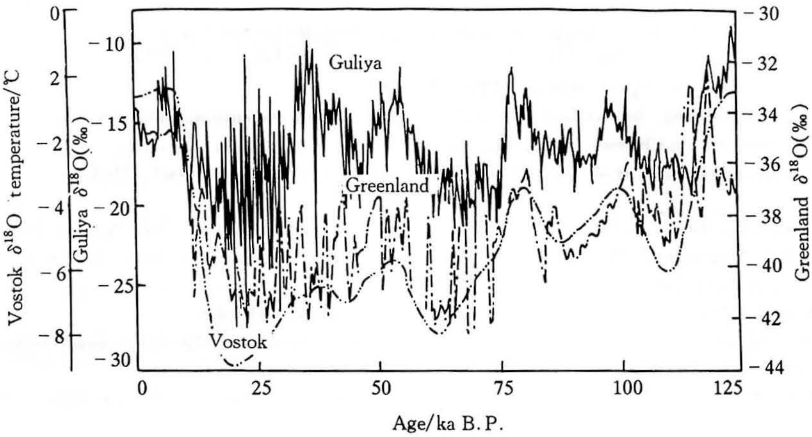

Fig. 5. $\delta^{18}O$ records in the "Three Polar Regions".

4 Conclusions

The Guliya ice core record reveals with high resolution the climate variations since the Last Interglaciation on the Tibetan Plateau. The study in the Guliya deep ice core record indicates that the Qinghai-Xizang (Tibetan) Plateau is more sensitive to the climate changes compared to the Antarctica and Arctic. In the Last Interglaciation, the amplitude of temperature increase is larger than the global average (temperature increased by 5℃ in 5e in the Guliya ice core $\delta^{18}O$ record, 2—3℃ higher than the global average). In the Last Glacial Age, the amplitude of temperature decrease is also very large. The proposed mechanism is that the cold climate results in the thicker, larger and longer-lasted snow cover on the Plateau, which can intensify the cooling further and, therefore, the cooling is amplified. Comparing the ice core records in the Three Polar Regions, it can be found that the major climate events are generally in agreement on the earth, but the amplitude of temperature variations and the small climate events are different in different regions. On one hand, the amplitude of temperature variation record in the Guliya ice core is larger than that in the Arctic and Antarctic regions. On the other hand, the small climate variations in each cold and warm period are recorded in more detail in the Guliya ice core than in the Arctic and Antarctic regions. There exists good correlation between $\delta^{18}O$ record in Guliya ice core and the solar activities, indicating that the solar activity is a main forcing to the climate variation in this region.

Acknowledgement Thanks are given to Huang Yanhong for typing and Jin Zhengmei for plotting.

References

1 Yao Tandong, Jiao Keqin, Tian Lide *et al.*, Climatic and environmental records in Guliya Ice Cap, *Science in China*, Ser. B, 1994, 38: 228.

2 Yao Tandong, Jiao Keqin, Yang Zhihong *et al.*, Climate change since the Little Ice Age recorded in the Guliya Ice Cap, *Science in China* (in Chinese), Ser. B, 1995, 25: 1108.

3 Yao Tandong, Thompson, L.G., Jiao Keqin *et al.*, Recent warming as recorded in the Qinghai-Tibetan Plateau, *Annals of*

Glaciology, 1994, 21: 323.
4 Yao Tandong, Jiao Keqin, Zhang Xinping *et al.*, Glaciological study in Guliya, *J. Glacio. & Geocryo.* (in Chinese), 1992, 14: 233.
5 Yao Tandong, Lonnie, G. T., Thompson, E. M. *et al.*, Climatological significance of $\delta^{18}O$ in the north Tibetan ice cores, *J. Geophys. Res.*, 1996, 101(D23): 29531.
6 Zhang Xinping, Shi Yafeng, Yao Tandong, Characteristics of $\delta^{18}O$ in the northeast of the Tibetan Plateau, *Science in China* (in Chinese), Ser. B, 1995, 25: 540.
7 Broecker, W S., Cooling the tropics, *Nature*, 1995, 376: 212.
8 Yao Tandong, Yang Zhihong, Jiao Keqin *et al.*, High resolution climatic and environmental variation record in the past 2 ka, *Chinese Science Bulletin* (in Chinese), 1996, 41: 216.
9 Suter, M., Beer, J., Bonani, G. *et al.*, ^{36}Cl studies at the ETH/SIN-AMS facility, *Nucl. Meth. Phys. Res.*, 1988, B29: 211.
10 Lorius, C., Jouzel, J., Ritz, C. *et al.*, A 150 000-year climatic record from Antarctic ice, *Nature*, 1985, 316: 591.
11 Thompson, L. G., Thompson, E. M., Davis, M. E. *et al.*, Holocene-Late Pleistocene climatic ice core records from Qinghai-Tibetan Plateau, *Science*, 1989, 246: 474.
12 Paterson, W. S. B., *The Physics of Glaciers*, Oxford: Pergamon, 1994, 403—406.
13 Dansgaard, W., Johnsen, S. J., Clausen, H. B. *et al.*, Evidence for general instability of past climate from a 250-kyr ice-core record, *Nature*, 1993, 364: 218.
14 GRIP Members, Climate instability during the last interglacial period recorded in the GRIP ice core, *Nature*, 1993, 364: 203.