Climatic and environmental records in Guliya Ice Cap

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Abstract The Guliya Ice Cap is the largest (with a total area of 376.1 m^2 and an area of 131.2 m^2 at the flat top), highest (6 700 m a.s.l.) and coldest (with an ice temperature of −19℃ at 10 m depth) ice cap found in Central Asia so far. From 1990 to 1992, the oxygen isotope ratios, microparticle concentrations, anions, cations of a large number of samples from snow pits and ice cores were analysed to study the climatic and environmental characteristics of the Guliya Ice Cap. Being frozen to bedrock and with extremely low ice temperature, the ideal climatic and environmental informarion was recorded in Guliya Ice Cap. The distinct annual and seasonal cycle characteristics of the oxygen isotope ratio, microparticle concentration, anion and cation provide bases to date precisely the high-resolution time series in the ice cap. Oxygen isotope ratios decreased, microparticle concentrations and various chemical elements increased in the colder periods, while oxygen isotope values increased, microparticle concentrations and various chemical elements decreased during warmer periods, and the interpretation of various abrupt events will be the key to restore systematically various kinds of climatic and environmental information recorded in this ice cap. The records in the Guliya ice cores indicate that climatic warming which happened in the middle 1980s was one of the most impressive events during the past several decades.

Keywords: Guliya, ice cap, palaeoclimate.

As the largest (with a total area of 371.1 m^2 and an area of 131.2 m^2 at the top), highest (6 700 m a.s.l.) and coldest (with lowest air temperature of −24.1℃, monthly mean temperature of −17.8℃ in May and −19℃ of ice temperature at 10 m depth) ice cap discovered in Central Asia, the Guliya Ice Cap is one of the favorable sites to study ice cores. The ice cap (35.2°N, 81.5°E) lies on the western part of the Kunlun Mts. in the Qinghai-Tibet Plateau (fig. 1), where enormous glaciers exist. In this area and its surroundings (from the valley of the Yarkant River to 83°30′E), 4 306 glaciers developed, with a glacier area of 8 438 m^2, accounting for three fourths of the total glacier area of the Kunlun Mts. Especially from Tianshuihai to Guliya mountain mouth, glaciers are more concentrated, with an area of 3 300 m^2.

The authors studied from 1990 to 1992 the climatic and environmental characteristics of the Guliya Ice Cap[1], and investigated the elementary characteristics of the ice cap and drilled an 8-m-long ice core in 1990. In 1991, the authors continued their previous work, at the same time drilled 3 ice cores, 30 m long, 20 m long and 15 m long respectively. In addition, the authors also measured the ice temperature along a 15-m borehole and a 30-m borehole. From the results of 1990 and 1991 and the analysis results of the shallow ice cores mentioned above, the primary characteristics of climatic and environmental records in the Guliya Ice Cap can be basically demonstrated. It is particularly worthy to be mentioned that we recovered a 309-m ice core, the longest ice core outside polar regions. The ice sample analysis will be finished in 2 years. The purpose of the present paper is to study the climatic and environmental characteristics recorded in the Guliya Ice Cap, and to provide a key for interpreting this long ice core.

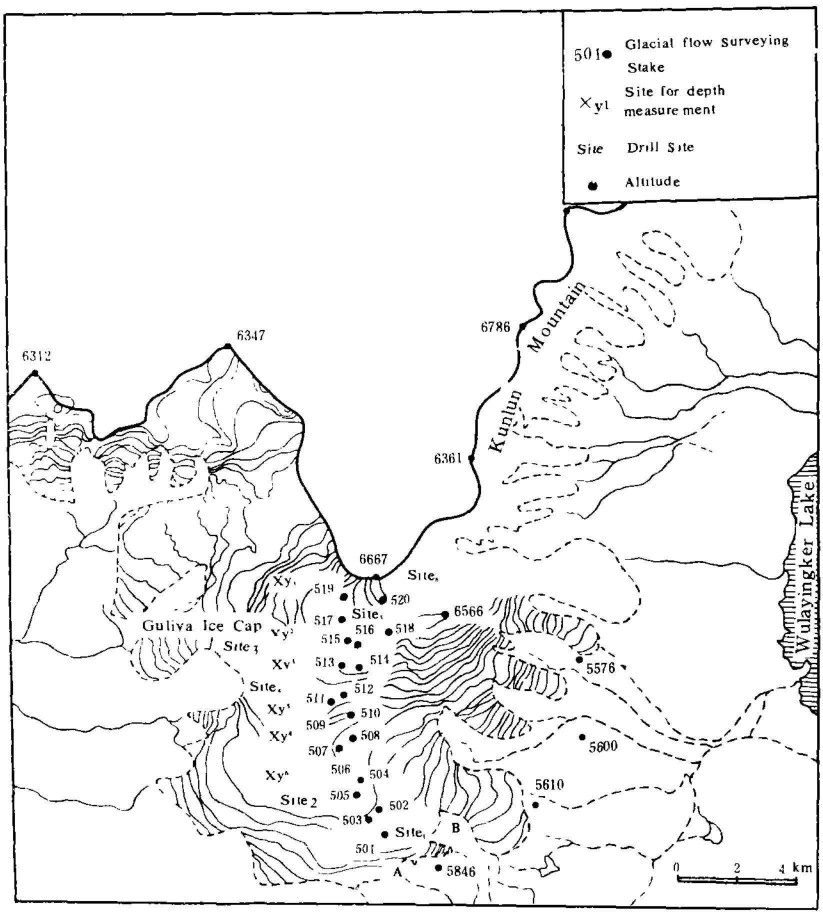

Fig. 1. Map of the Guliya Ice Cap.

1 Ice temperature

From 1991 to 1992, the glacial temperature was measured at many points along both shallow and deep boreholes from 6 180 m to 6 700 m a.s.l. on the Guliya Ice Cap. The equipment measuring the ice temperature is a multi-probe thermometer, with a precision of ±0.01℃.

Figure 2 shows the measured results of ice temperature at various boreholes in the Guliya Ice Cap. The ice temperature results at No. 1 and No. 2 were measured in May 1991 and those at No. 3 in August 1992. The measured results change with seasons in the upper 10 m ice due to the seasonal climatic variation. However, the ice temperature at 10 m depth does not change with seasons. It can be seen from fig. 2 that the distribution of the ice temperature at 10 m depth is closely correlated with altitudes. The ice temperature is −15.5℃ at No.1 (6 200 m a.s.l.) and −18℃ at No. 3 (6 700 m a.s.l.). There exsits a difference of −3.1℃, corresponding to 0.6℃/100 m of temperature gradient from 6 200 m to 6 700 m.

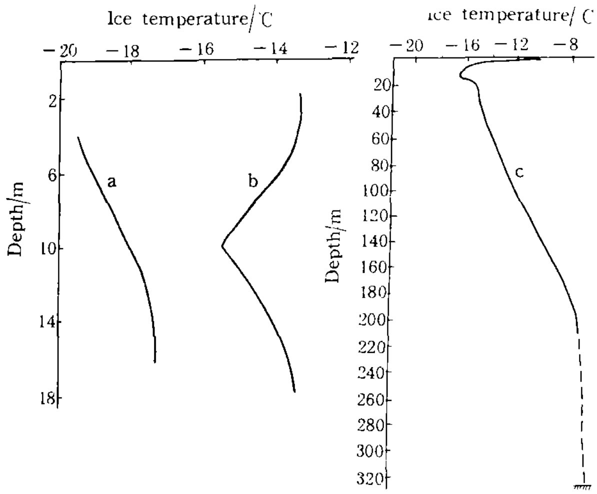

Fig. 2. Ice temperature in the Guliya Ice Cap. a, No.1 (measured in May 1991), b, No.2 (measured in May 1991); c, No.3 (measured in August 1992).

The measured ice temperature results in the Guliya Ice Cap suggest that the Guliya Ice Cap has some features similar to polar ice sheets. First, at the bottom of the 308-m ice core drilled at the thickest site of the ice cap in 1992, the ice is still frozen to its bedrock. It is calculated from the temperature measured along the upper 200 m that the ice temperature at the bottom would be about −2℃ — −3℃. Secondly, the ice temperature of about −19℃ measured at 10 m depth at 6 700 m a.s.l. of Guliya Ice Cap is the lowest ice temperature measured not only in Chinese glaciers but also in glaciers outside polar glaciers up to now. Thirdly, there is a dry-snow zone at the top of the Guliya Ice Cap. The ice temperature and dry-snow zone on the Guliya Ice Cap will be discussed in another paper.

2 Oxygen isotope

The study of the temperature variations by the oxygen isotope ratios is still at the beginning stage in the mid-latitude Qinghai-Tibet Plateau and our understanding is getting better and better. For instance, L. G. Thompson[2] and the author[3] thought that the oxygen isotope ratios in precipitation would be negatively correlated with the temperature in this region according to the measurement of precipitation samples collected during a short period, namely winter is characterized by high $\delta^{18}O$ value and summer by low $\delta^{18}O$ value. It has been found later in the systematic research of the relationship between the $\delta^{18}O$ in precipitation and air temperature in the Tanggula Range that $\delta^{18}O$ value in summer is related to the intrusion of marine air masses[4]. In order to study the relationship between the oxygen isotope ratio in precipitation and temperature (detailed results will be presented in another paper), long-term sampling sites were set up at Tuotuohe, Delingha and Xining in the Tibet Plateau in 1991. The latest results indicate that the oxygen isotope ratio in precipitation in the plateau is also characterized by high value in summer and low value in winter, i.e. $\delta^{18}O$ in precipitation is positively correlated with the air temperature when precipitation is formed, the same as in Arctic and Antarctic.

Oxygen isotope is characterized spatially by the obvious decrease with altitudes (fig. 3) due to bare old ice. Because the air temperature rises with the decrease of altitudes, the characteristic that the oxygen isotope ratio rises with decreasing altitudes reflects the effect of climatic changes.

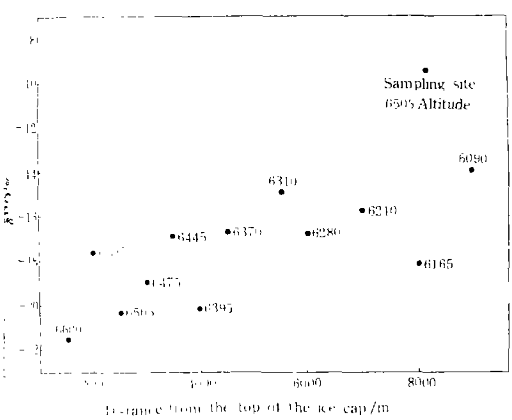

Fig. 3. Spatial variations of $\delta^{18}O$ on the Guliya Ice Cap.

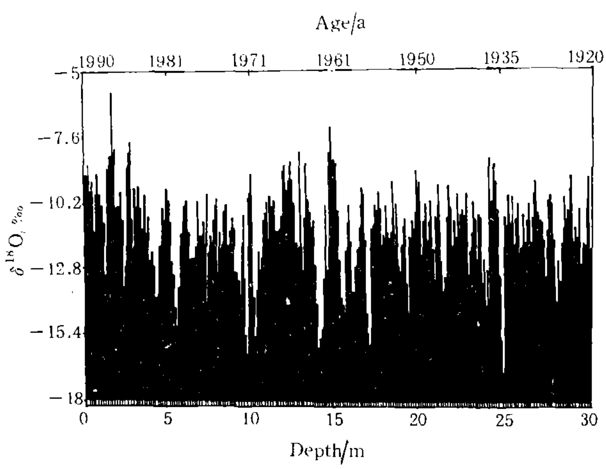

Fig. 4. Variations of oxygen isotope in ice core of the Guliya Ice Cap versus depth.

Figure 4 shows $\delta^{18}O$ variations with depths in ice core. It can be seen from fig. 4 that the oxygen isotope ratios in Guliya Ice Cap have regular variations, reflecting the seasonal variations of $\delta^{18}O$ based on the study of snow stratigraphy. The oxygen isotope fractionation feature in the vapour is closely related to the air temperature. Air temperatures rise in summer, and as a result, the oxygen isotope ratio in precipitation increases; while in winter, air temperatures decrease, and oxygen isotope in precipitation decreases. Year after year, the regular variations in snow layers will be formed due to the seasonal variations of the oxygen isotope ratio. There exsit distinct seasonal variations of oxygen isotope ratios in the Guliya Ice Cap, on which we can base to count the annual layers and establish time series of ice core.

Another feature presented in fig. 4 is the abrupt increase of oxygen isotope ratios in recent years, reflecting the rapid rise of air temperature. From the top of the ice core corresponding to 1990 to 3 m depth corresponding to 1985, the five-year mean oxygen isotope ratio is $-11.4‰$, $1.9‰$ greater than that from 1981 to 1985, which was probably caused by air temperature increase. Actually, this warming event began as early as in the 1970s, and at least in the Tibet Plateau, the affected area is extensive. Similar temperature rising trend can be found from the analysis of ice cores extracted in the Tanggula Range, eastern part of the Tibet Plateau[5,6]. Both the Guliya ice core and the Tanggula ice core show that the warming event beginning from the 1970s and becoming intensive in the 1980s is one of the strongest events in this century.

3 Chemical characteristics of snow and ice

Retrieving the related environmental information from various chemical elements in snow and ice is an effective method to study the chemical composition changes in the atmosphere, a reliable indicator to monitor the human impact on the environment, also an important means to distinguish the environmental diversities in different areas and under different climates. Because it is very clean, snow and ice are very sensitive to either atmospheric variations or environmental difference in different areas and under different climates. Chemical components, especially K^+, Na^+, Ca^{2+}, Mg^{2+}, NO_3^-, SO_4^{2-}, Cl^-, etc. are analysed.

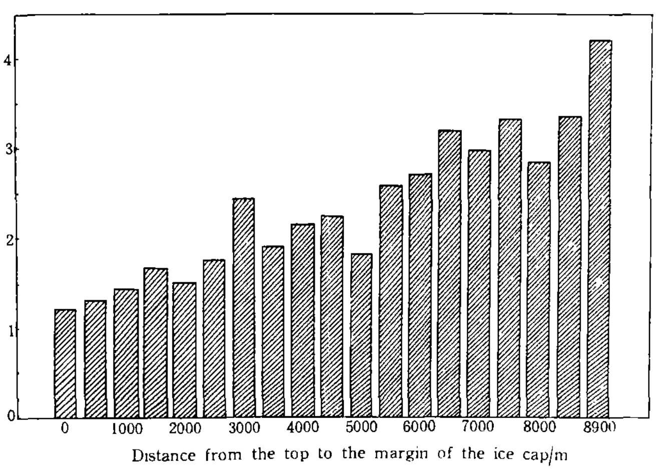

Fig. 5. Spatial distribution of Ca^{2+} in the Guliya Ice Cap. Ordinate shows $Ca^{2+}(\times 10^{-6})$.

All the components analysed except Cl^- have an increase trend from the interior to the margin of the ice cap (fig. 5).

Ca^{2+} is mainly derived from crust. The characteristic that the concentrations of these elements increase from the interior to the margin of the ice cap indicates that, towards the margin of the ice cap, components coming from the

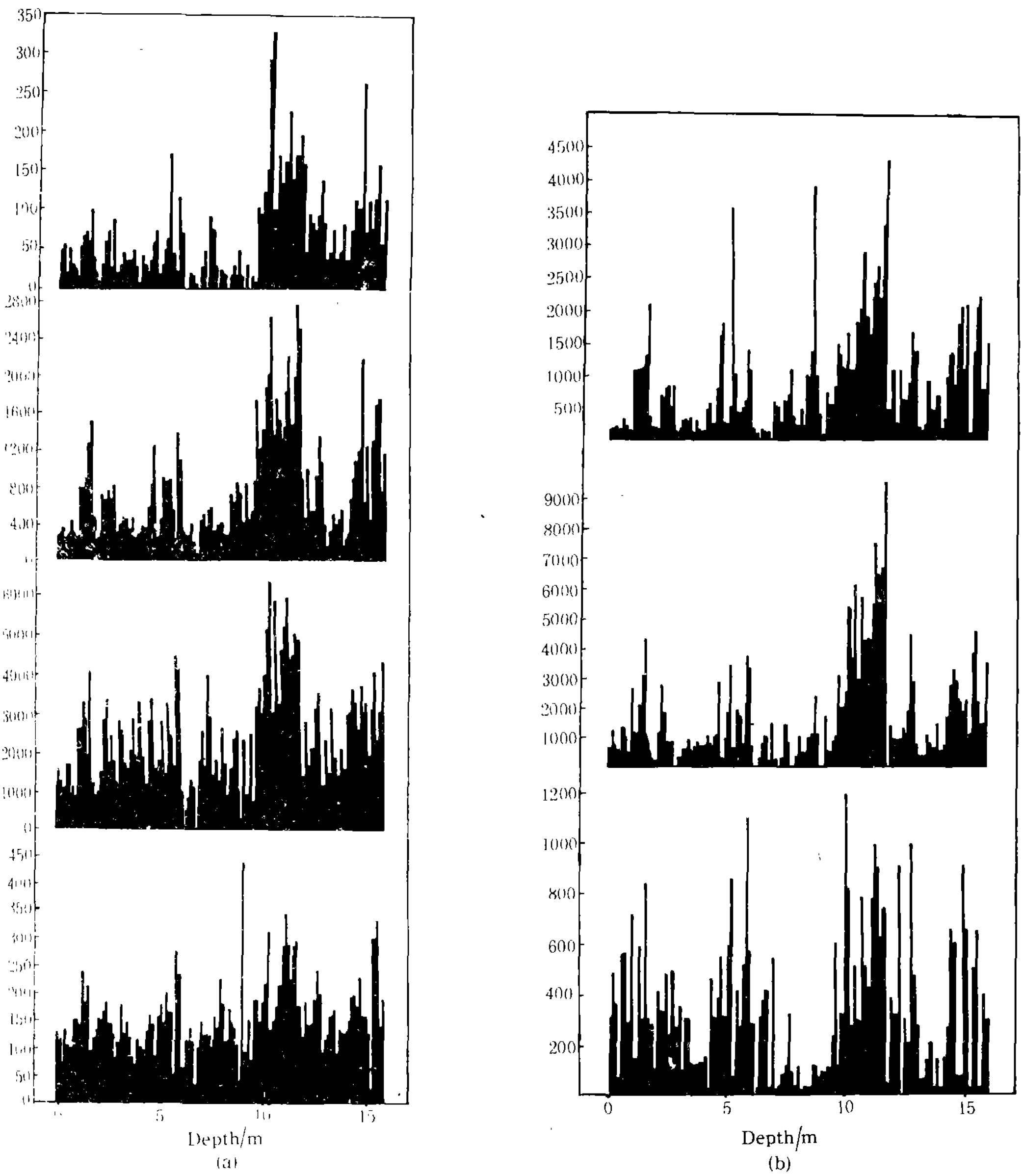

Fig. 6 Variations of chemical components in the Guliya Ice Cap versus depth. (a) Variations of cations versus depth; ordinates showing $K^+(\times 10^{-9})$, $Na^+(\times 10^{-9})$, $Ca^{2+}(\times 10^{-9})$, $Mg^{2+}(\times 10^{-9})$ from the upper to the lower. (b) Variations of anions versus depth; ordinates showing $Cl^-(\times 10^{-9})$, $SO_4^{2-}(\times 10^{-9})$, $NO_3^-(\times 10^{-9})$ from the upper to the lower.

atmosphere relatively decrease, while those from ice-free zones increase comparatively.

Figure 6 shows the variations of the concentrations of K^+, Na^+, Ca^{2+}, Mg^{2+}, NO_3^-, SO_4^{2-} and Cl^- in ice core versus depths. It can be seen from fig. 6 that the concentrations of the chemical components are characterized by regular variations. Analyses of snow pit data indicate that the variations are actually seasonal. According to the analysed results of the shallow ice cores drilled in 1990 and 1992, the concentrations of chemical components reach the highest in spring on the Guliya Ice Cap. The regular seasonal chemical variations, the same as oxygen isotope, are the base to establish the ice core time series correctly. The regular variations of chemical components in snow and ice exsit, in fact, not only in the Guliya Ice Cap, but also in the whole Tibet Plateau[7]. The concentrations of Ca^{2+}, Mg^{2+}, especially Ca^{2+}, account for a great part of chemical composition in snow and ice, suggesting that the terrestrial composition (formed in dry and cold conditions in the interior of the Tibet Plateau) greatly affects the chemical feature of snow and ice in the plateau. The ratio of Cl^-/Na^+ is a substantial indicator to study the contributions of elements with different origins. The ratio of Cl^-/Na^+ from sea water is 1.8. In the Guliya Ice Cap and other regions of the plateau, almost all the ratios of Cl^-/Na^+ are greater than 1.8, indicating that the terrestrial composition contributes a lot to Cl^-. This phenomenon provides a unique opportunity and question to study the environmental information of snow and ice in the Tibet Plateau. On one hand, through analysing the components affected by terrestrial composition, we can reconstruct the evolution of paleoenvironment in the Tibet Plateau; on the other hand, the effect of regional environmental characteristics should be considered first before any environmental information with global significance is studied.

Figure 6 shows not only the regular seasonal variations of chemical components, but also several abrupt events corresponding to extraordinary peaks of various components. They are mainly at 4 m (corresponding to 1982), 14 m (corresponding to 1960—1962), 19 m (corresponding to 1951—1952) and 23 m (corresponding to 1926—1927) respectively. According to data available, 1982—1983 is in El Niño period and abrupt volcanic activity took place in the vicinity of the Guliya Ice Cap in 1951. These events should be recorded in ice cores and it is estimated that the recorded abrupt changes of chemical compositions happening in 1982 and 1951—1952 may be related to those two events.

Another important discovery is that all the peaks of various chemical components correspond to low values of oxygen isotope (from one year to several years) and the concentrations of K^+, Na^+, Ca^{2+}, Mg^{2+}, NO_3^-, SO_4^{2-} have the decreasing trend in warmer periods. This is also discovered in the Tanggula ice cores drilled in 1989. This relationship is actually very important in interpreting the long-term climatic changes and environmental changes recorded in ice cores.

4 Microparticles

The variation of insoluble microparticles in ice cores is an important factor in retrieving envivonmental characteristics.

The microparticles in ice samples collected in the Guliya Ice Cap have been measured in different sizes from 0.2 μm to 40 μm. The results indicate that the variations of microparticle contents in different sizes are generally simultaneous. Two features can be seen from fig. 7. First, the variations of microparticles are regular and seasonal, the same as that of oxygen isotope. What is different from chemical components is that the peaks of microparticles correspond to those of oxygen isotope values, while the peaks of chemical components correspond to low values o oxygen isotope. Secondly, the rapid changes of microparticles also suggest some abrupt events, which is the same as chemical components.

The microparticle content has an obvious decrease trend from 1980 to 1990, which agrees very well with the trend reflected by anions and cations mentioned above. Because the whole 1980s was characterized by warming, it is just the fact that the microparticle decreasing reflects the correspondence that the microparticle decreases when the climate becomes warmer. This correspondence is verified by ice core research in many regions, and will be served as a tool for interpreting the long-time series established in Guliya ice core.

5 Conclusions

1 In the Tibet Plateau, low values of oxygen isotope correspond to colder periods and high values of oxygen isotope correspond to warmer periods. The oxygen isotope ratios have increased abruptly since the beginning of the 20th century, suggesting that the climate is warming. Chemical components, especially Ca^{2+}, and microparticles increased when the climate became colder, chemical components

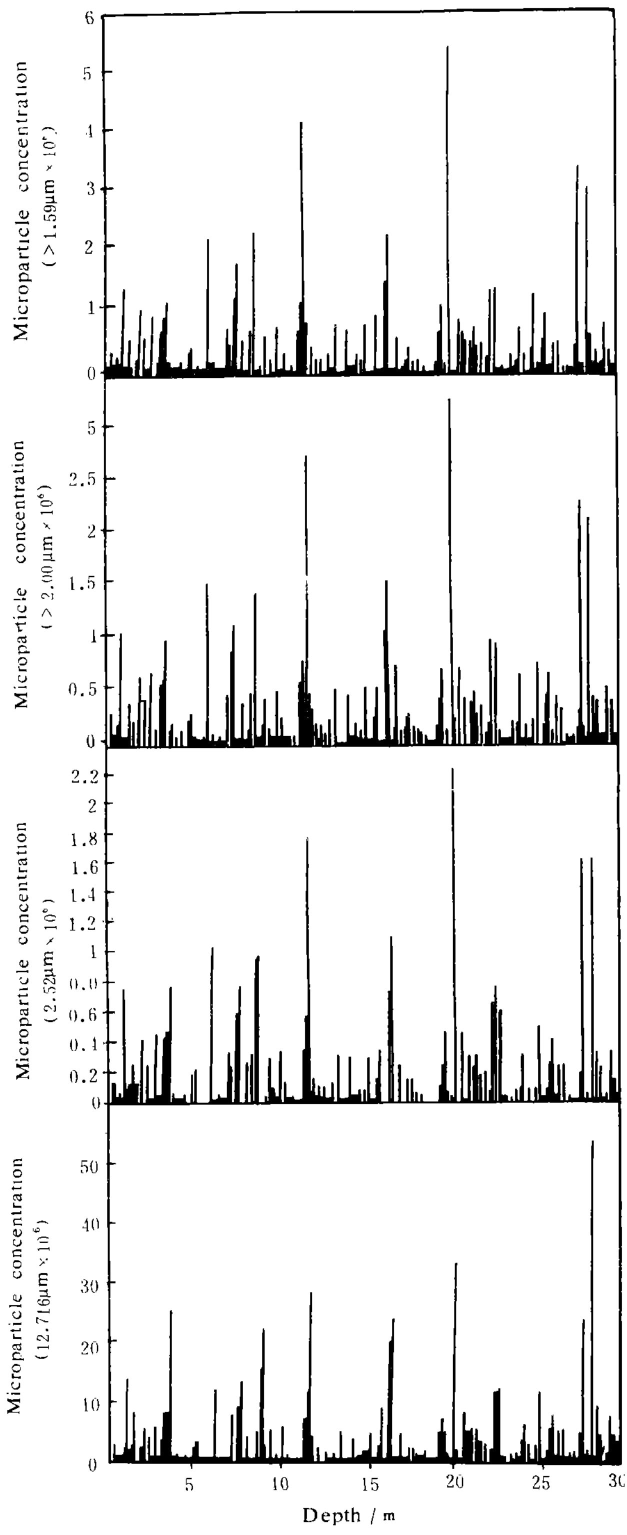

Fig. 7 Microparticle in the Guliya Ice Cap versus depth.

and microparticles in ice core decreased during the warmer period of the 20th century, and *vice versa*. Microparticles, anions and cations decreased obviously from 1980 to 1992, which can be compared to the warming period from 1980 to 1990 reflected by rapid increasing of oxygen isotope ratios. According to the records of the Guliya Ice Cap, the mean oxygen isotope ratio from 1985 to 1990 is 1.9‰ greater than that from 1981 to 1985.

2. As ice temperature is concerned, the Guliya Ice Cap is an ideal place for ice core research found so far outside the polar regions. The ice temperature is −19℃ at 10 m depth in the Guliya Ice Cap, close to that of southern Greenland Ice Sheet and Antarctic Peninsula. The bottom ice temperature where the ice cap is the thickest is still below zero, and ice is frozen to bedrock. This is a real polar-type ice cap. From the viewpoint of glaciology, if the Tibet Plateau is the "Third Pole" of the earth, the Guliya Ice Cap and its surroundings will be the "pole point" of the "Third Pole".

3. All the measured parameters including oxygen isotope ratios, chemical components and microparticles are of climatic and environmental significance and distinct seasonal cycles. Using the climatic environmental indicators revealed by various measured parameters, we can not only understand the general characteristics of the modern climate and environment, but also reconstruct the variations of the climate and environment in the past. Using the seasonal cycles of various measured parameters, we can accurately establish the high-resolution time series, and precisely calculate the net accumulation during different times.

4. On the surface of Guliya Ice Cap, all the measured parameters are characterized by spatial variations. The concentrations of K^+, Na^+, Ca^{2+}, Mg^{2+}, NO_3^-, SO_4^{2-}, Cl^- and microparticles of surface samples increase from the margin to the interior of the ice cap, so does the oxygon isotope. The former increase mainly reflects the effect of terrestrial composition. The closer it is to the margin of the ice cap, the greater the terrestrial composition provided by ice-free zone, and the larger the above-mentioned parameters. The latter mainly reflects the effect of altitudes. The closer it is to the margin of the glacier, the lower the altitude, the higher the air temperature, and the greater the oxygen isotope values in snow.

The characteristics of spatial variations are of great importance to the research of temporal variations (the recovery of paleoclimate and paleoenvironment). First, because cations, like Ca^{2+}, Mg^{2+}, mainly reflect the changes of terrestrial composition, the reconstruction of these cations is also the reconstruction of terrestrial composition changes. Additionally, the temperature implication of oxygen isotope with altitudes is another evidence that the variations of oxygen isotope ratios reconstructed from ice core can be used to interpret the climatic changes.

5. The correct interpretation of special events recorded in the Guliya Ice Cap will help us to reconstruct various climatic and environmental events and abrupt events recorded

in the deep ice cores. The reconstruction of these events, especially El Niño and volcanic events, and the study of the relation between these events and climate will be very important to predict the climatic change in the future.

References

1 Yao Tandong, Jiao Keqin, Zhang Xinping *et al.*, Glaciologic studies on Guliya Ice Cap, *J. of Glaciol. and Geocryol.* (in Chinese), 1992, 14(3): 233.

2 Thompson, L. G., Thompson, E. M., Davis, M. E. *et al.*, Pleistocene climate record from Qinghai-Tibetan Plateau ice cores, *Science*, 1989, 246: 474.

3 Yao Tandong, Xie Zichu, Wu Xianling *et al.*, The Little Ice Age as recorded in the Dunde Ice Cap, *Science in China*, Ser. B(in Chinese), 1990, (11): 1196.

4 Yao Tandong, Ding Liangfu, Pu Jianchen *et al.*, The $\delta^{18}O$ features in the snowfall and the relation to water vapor sources in Tanggula Range, Qing-Zang (Tibet) Plateau, *Chinese Science Bulletin* (in Chinese), 1991, 36(20): 1570.

5 Yao Tandong, Yang Zhihong, Liu Jingshou, Qing-Zang (Tibet) Plateau warming revealed from ice cores, *Chinese Science Bulletin* (in Chinese), 1994, 39(5): 438.

6 Yao Tandong, Pu Jianchen, Liu Jingshou, *Climatology Study* on *Tanggula Ice Core, Glacial Climate and Environment in the Qinghai-Tibetan Plateau* (in Chinese), Beijing: Science Press, 1993.

7 Yao Tandong, Sheng Wenkun, Yang Zhihong, *A Study on Ice and Snow Chemistry in Qing-Zang (Tibet) Plateau, Glacial Climate and Environment in the Qinghai-Tibet Plateau* (in Chinese), Beijing: Science Press, 1993.