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Abstract

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Keywords

Quaternary; cryospheric change; human development

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Quaternary Cryosphere—Study on Global Change in Long Terms

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Abstract: The Quaternary is marked by the Great Ice Age. The basic characteristics of this great ice age are the alternating of glacial-interglacial period in orbital scale and changes of stadial-interstadial in suborbital scale. Present is a relatively warm interglacial period, with glaciers covering only 10% of the land area. The glacial maximum was characterized by the coverage of about 30% by glaciers on the global land area, spreading permafrost, dry climate with prevalence of dust, sea level reduction of 130–150 m, vegetation contraction of more than 10° to low latitudes, and downward movement of vertical band spectrum by more than 1 000 m. The astronomic theory of ice ages has successfully explained the glacial-interglacial cycles. However, there are still a lot of problems needing studies in detail. Quaternary is also the period of ancient human development. Ancient human was born in East Africa and spread to Eurasia only on a limited scale about 2 Ma ago. The spread on a large scale started during the last interglacial and they spread to America and Australia by means of land bridges during Last Glaciation Maximum (LGM). After the younger Dryas, the climate became warm and the human entered the Neolithic Period and gradually transited to the agricultural society. After the Industrial Revolution, human development has been profoundly affecting the natural process of the Earth, leading to global warming, heralding the arrival of the Anthropocene.
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The goal of research on the Quaternary cryosphere is to reconstruct the evolutionary history of the cryosphere over the past 2.6 million years, to understand its evolutionary pattern, and to reveal the main driving force. Therefore, the science of Quaternary cryosphere includes the changes of core cryospheric elements such as glaciers, permafrost, and permanent snow during the Quaternary. Besides, it involves the physical, chemical, and biological sedimentary records that reflect the changes of cryosphere and related mechanisms, as well as the astronomical and geological studies causally related to cryosphere evolution. This is determined by the interdisciplinary nature and long timescale of the cryosphere overlapping the other four spheres (lithosphere, atmosphere, hydrosphere, and biosphere).

1 Research significance

The Quaternary is a glacial period characterized by the alternating of glacial-interglacial period. The changes in cryosphere, which is the fifth sphere relatively independent and closely related to the other four spheres, have significant impacts on other spheres and even the earth system. In particular, it determines the major modification of Earth's surface processes, the decline and prosperity of the biosphere, and even the succession and evolution of species. We are now in a relatively warm and humid period of the Holocene, which is a continuation of the evolution of the entire Quaternary climate and environment. The research on the Quaternary cryosphere allows us to understand the magnitude, frequency, causes, and consequences, of changes in the Quaternary climate and environment, which helps to observe the current and predict the future trends of climatic and environmental variations. In particular, in the context of continued global warming, where the Earth, our "Noah's Ark" in the universe, is heading? The research on Quaternary cryosphere can at least give the ranges of changes on different time scales. Further, the Last Interglaciation, the interstadial of the Last Glaciation, and the Holocene Climate Optimum can be taken as references for prediction by paleo-analogue to help us cope with the current situation. Human originated in the Pliocene or the Miocene, and the period of rapid human evolution roughly corresponds to the Quaternary with repeated emergence of the European and American ice sheets in the Northern Hemisphere. When and how primitive humans originated in Africa and later *Homo sapiens* spread out of

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Africa to the whole world, and how the evolution of human figure, organs, brain, and intelligence is related to the expansion and contraction of the cryosphere are major scientific issues that imply the truth of human–earth relationship and thus have far-reaching academic significance for anthropology and human geography. CO_2 emissions have received unprecedented attention in the context of global warming, which, together with the unrestricted expansion of human living space, damage and pollution to the natural environment, and the resulting accelerated extinction of biological populations, force scientists to propose the new concept of Anthropocene. What Anthropocene will be and to what extent human beings will break the laws of nature need to be studied in the background of the entire history of the Quaternary. Therefore, the research on the Quaternary cryosphere not only has the scientific significance of knowing the late geological history but also provides background coordinates for predicting the future climatic and environmental changes.

2 Research topics

The studies on Quaternary cryosphere can be broadly categorized into the following seven topics.

(1) Geomorphology and deposit of cryosphere. This is the basis for reconstructing the spatial scope and scale of cryosphere evolution, including glacial erosion landform and glacial deposit, periglacial landform and deposit, and fossil permafrost. Such geomorphological relics have been discovered in high-latitude and high-altitude areas, as well as marine sediments.

(2) Environmental records. Reconstruction of the change ranges and environmental characteristics in the entire Quaternary cryosphere is based on records in deep-sea sediment cores, polar ice cores, continental loess-paleosols, lake sediment cores, stalagmites, and tree rings. The environmental information is marked by indicators such as multiple isotopes, sediment grain size, CO_2, pollen, dust, calcium carbonate, magnetic susceptibility, organic carbon, diatoms, and weathering index. These indicators are used to reveal the long-term climate changes in the Quaternary, which are confirmed by the information from cryospheric geomorphology and sediments to obtain insights of the change pattern.

(3) Quaternary chronology. Dating is the technical basis for revealing the geomorphological, sedimentary, and environmental changes, including isotope dating (uranium-series dating, potassium-argon dating, rubidium-strontium dating, and C4 dating), palaeogeomagnetic dating, electron spin resonance dating, luminescence dating, and cosmogenic nuclide dating. These dating methods have their own strengths and weaknesses and are suitable for testing different sediments and different time periods. Their applicability and accuracy are being explored, developed, and refined.

(4) Modeling and simulation. There are conceptual models, physical models, and mathematical models. Simulation is widely used in studies of ancient snow line, lower limit of permafrost, the rise/fall of ancient forest line, the increase/decrease of continental ice, the fluctuation of sea level, and the prediction of future.

(5) Biological evolution. Biological evolution is bound up with the changes in cryosphere, and animal and plant fossils allow understanding of the climate and environment in ancient times. For example, pollen and mammoth/woolly rhinoceros fossils suggest that Siberia was once a vast permafrost tundra during the Last Glacial Period, and the permafrost tundra extended southward into northern China.

(6) Human survival/evolution and cryosphere. Since humans evolved primarily in the Quaternary, the study of human–earth relationship in the Quaternary is of great academic significance. Such studies are still limited by the number of paleoanthropological sites and have much room for development.

(7) Causes and driving force of changes in cryosphere. This is the inevitable progression from record excavation to theoretical understanding. The relevant studies focusing on the extraterrestrial space involve the movement of the solar system in the galaxy, changes in Earth orbital parameters, and sunspot activity. The studies focusing on the internal earth involve crustal movement, vulcanian eruption, ocean–atmosphere energy transport, bioclimatic effects, and human disturbance.

The research on the Quaternary cryosphere involves a wide range of topics and mysteries, and related questions have long been debated, which not only is in line with the general law of science development, but also reflects the great internal driving force of this discipline.

3 Progress in the research on the evolution and its causes of cryosphere during the Pleistocene

Cryosphere is a relatively new concept, while the basic research on it has a long history. At the beginning of the 18th century, some geographers paid attention to Alpine glacial relics. After nearly a century of investigation and exploration, glaciology was developed in the early 19th century and the classic model of the Quaternary glacial period in the Alps was proposed in the 20th century. Meanwhile, glacial astronomy has been greatly developed. Subsequently, deep-sea drilling, core records, and geochronological techniques have advanced rapidly. Now we have a relatively clear understanding of the changes in the Quaternary cryosphere.

(1) An unstable ice sheet formed on the Antarctic continent at ~35 Ma and stabilized at 14 Ma. Covered glaciers initiated in the Northern Hemisphere at 8 Ma and stabilized at 2.6 Ma during the glacial period, marking the beginning of the Great Ice Age [1,2]. Therefore, the Quaternary is defined at 2.6 Ma by international community.

(2) During the Quaternary, the so-called Middle Pleistocene transition (MPT) occurred at 0.8 Ma. The MPT was preceded by a 41-ka cycle dominated by the Earth's obliquity, and glacier extents were generally smaller during glacial period. This was followed by an eccentricity-dominated 0.1-Ma cycle with larger glacial extents. At the glacial maximum, the global glaciers covered an area of 45×10^6 km^2 (30% of the global land area), which were dominated by the North American ice sheet, Eurasian ice sheet, and Antarctic ice sheet. During the interglacial period, glaciers accounted for only ~10% of the global land area, mainly including the Antarctic ice sheet and the Greenland ice sheet (Figure 1). At the Last Glacial Maximum (~20 ka), the area of permafrost in the Northern Hemisphere reached 33.5×10^6 km^2 (Figure 2), and the sea level declined by 135 m. However, glacial extents varied during the 0.1 Ma glacial period of the cycle. For example, among the glacial periods represented by even marine oxygen-isotope stages (MISs), MIS2, MIS6, MIS12, and MIS16 were characterized by large glacial extents while MIS8, MIS10, and MIS14 by small glacial extents (Figure 3).

(3) The glacial period occurred during the time of low orbital eccentricity, when the average annual Sun-Earth distance increased because the orbit tended to be round and the long axis remained unchanged, resulting in a 0.8% reduction in surface solar radiation [3,4]. This effect, together with reduction in axis inclination, facilitated the extension of the continental ice sheet at high latitudes, and the axial precession tended to be zero. The axial precession was prominent during interglacial period with high eccentricity, such as the last interglacial period and most odd-numbered MISs.

(4) A series of short timescale climate change records were collected during and after the last glacial period, i.e., the alternating stadial-interstadial periods. These records cannot be explained by changes in orbital parameters and are referred to as suborbital scale changes. Notable records included the Dansgaard-Oeschger (D-O) event, Heinrich (H) events, the Dryas, the Bølling-Allerød (BA), the 8.2 ka cold event, the neoglaciation, and the Little Ice Age cooling. The D-O event was a cold-warm cycle recorded by the Greenland ice core, and each warm period was followed by a cold period, with temperature changes ranging from 5 °C to 8 °C for hundreds of years to 2 ka (1.5 ka on average). In the D-O cycle, the coldest period was evidenced by the moraine deposited by the ice blockage effect in the North Atlantic Ocean, and this period was called the H event. A total of six periodical sedimentations were found, dating from 60.0 ka to 16.9 ka. The H event was thought to cause decreases in sea surface temperature and salinity, blocking the North Atlantic thermohaline circulation and further exacerbating widespread cooling. Both H event and D-O cycle were considered climate events of global significance. At the end of the last glacial period, a Dryas cooling event occurred in 18.0–11.7 ka, which is divided into the oldest Dryas, older Dryas, and younger Dryas. The three cooling events were separated by two warm periods in 14.7–12.9 ka which referred to as the BA events. The cooling during the younger Dryas was 50%–75% of that during the glacial period. After the younger Dryas, the Earth entered the post-glacial period, and thus the end of younger Dryas was defined as the beginning of the Holocene.

(5) Although the Holocene is in an interglacial period, there have been frequent fluctuations in the cryosphere. Western researchers in the late 19th century divided the Holocene into Pre-Boreal, Boreal, Atlantic, Sub-Boreal, and Sub-Atlantic climate periods based on pollen data in North Europe. In the mid-20th century, Hypsithermal Interval, Climatic Optimum, and Thermal Maximum were used to define the warmest climate periods in the Holocene. It was estimated that the temperature at that time was 2 °C–3 °C higher than that today. Further studies revealed that nine cold events occurred in the North Atlantic region in the Holocene at 10.3, 9.4, 8.2, 5.9, 4.2, 4.0, 2.8, 1.4, and 0.4 ka, respectively [7,8]. These events occurred in cycles of (1 470 ± 500) a, with the maximum cooling in the 8.2 ka event and a temperature 2 °C–3 °C lower than that today. Besides, the cold periods in the Holocene led to the advance of mountainous glaciers and the formation of small-scale moraine ridges, while the glacier advance at this scale was highly regional (Figure 4) [9], which occurred in the Northern Hemisphere in Late Holocene and in the Southern Hemisphere in Early Holocene. This conclusion needs to be evidenced by more accurate chronological data.

(6) The astronomical theory of glacial period predicts that the next great ice age will occur 60 ka after present without human disturbance, and the maximum ice extent in the Northern Hemisphere may reach 27×10^6 m^3.

4 Quaternary cryosphere and lithosphere movement

There is a close interaction between cryosphere and lithosphere. All of the great ice ages in geological history were coupled with the distribution patterns of continental and oceanic plates. Although the global continental plate distribution did not change greatly during the Quaternary, the uplift of thousands of meters in the areas with active neotectonics changed the water and heat circulation, thus significantly affecting and responding to the cryosphere. Studies have shown that the Alps in Europe reached 2 500–3 000 m in the Eocene. Since 3.5 Ma, glaciers began to develop in some high mountains. By MPT, the majority of Alps had entered the cryosphere and developed ice sheets. In the central Andes of South America, paleobotanical evidence indicates that the mean elevation at 20 Ma was less than one-third of that (3 700 m) today, with an average uplift of (1 705 ± 695) m since 12–9 Ma. With mountain uplift, the climate was getting colder, and these two effects together led to the glaciation in

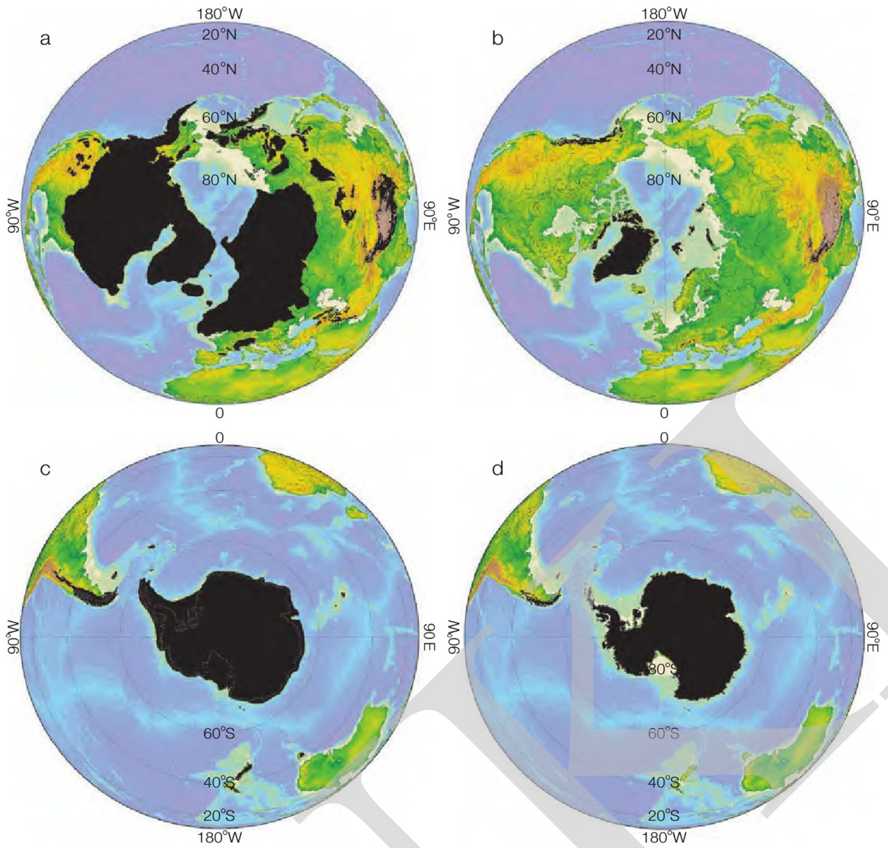

Figure 1 Comparison of glacial extents during glacial period and at present [5]

(a) and (c): glaciers in the Northern Hemisphere and the Southern Hemisphere in glacial period, respectively; (b) and (d): glaciers in the Northern Hemisphere and the Southern Hemisphere at present, respectively.

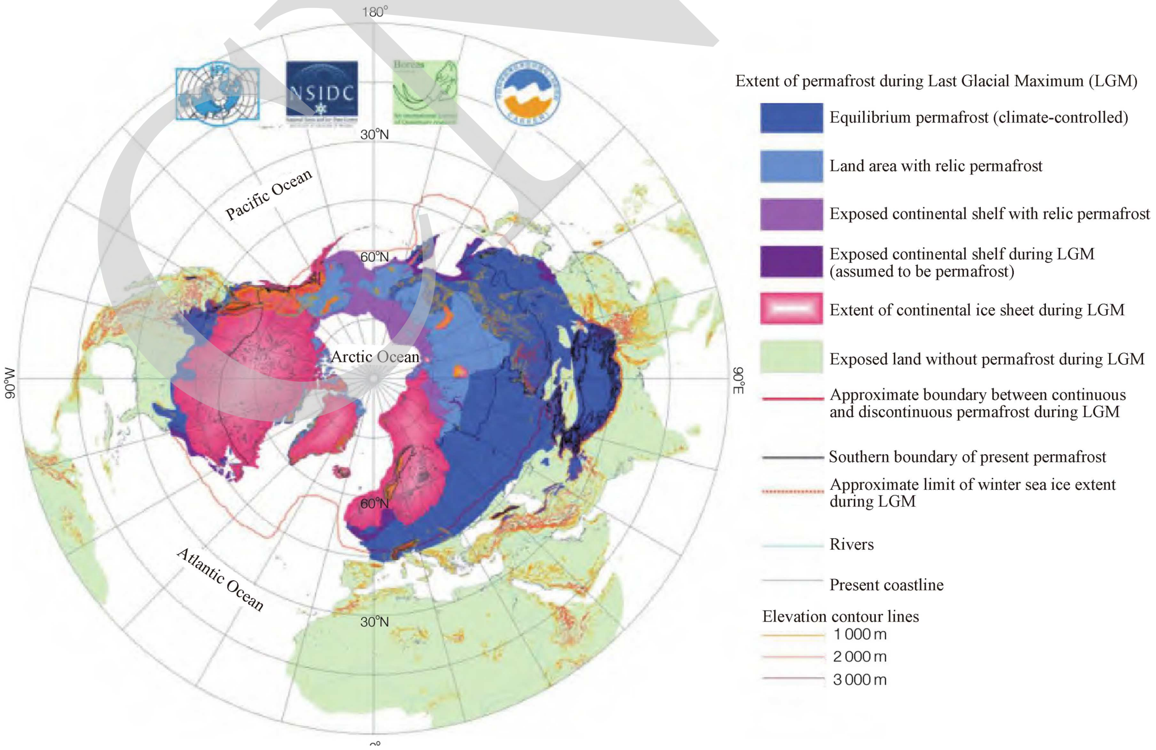

Figure 2 Distribution of permafrost in the Northern Hemisphere during the last glacial period [6]

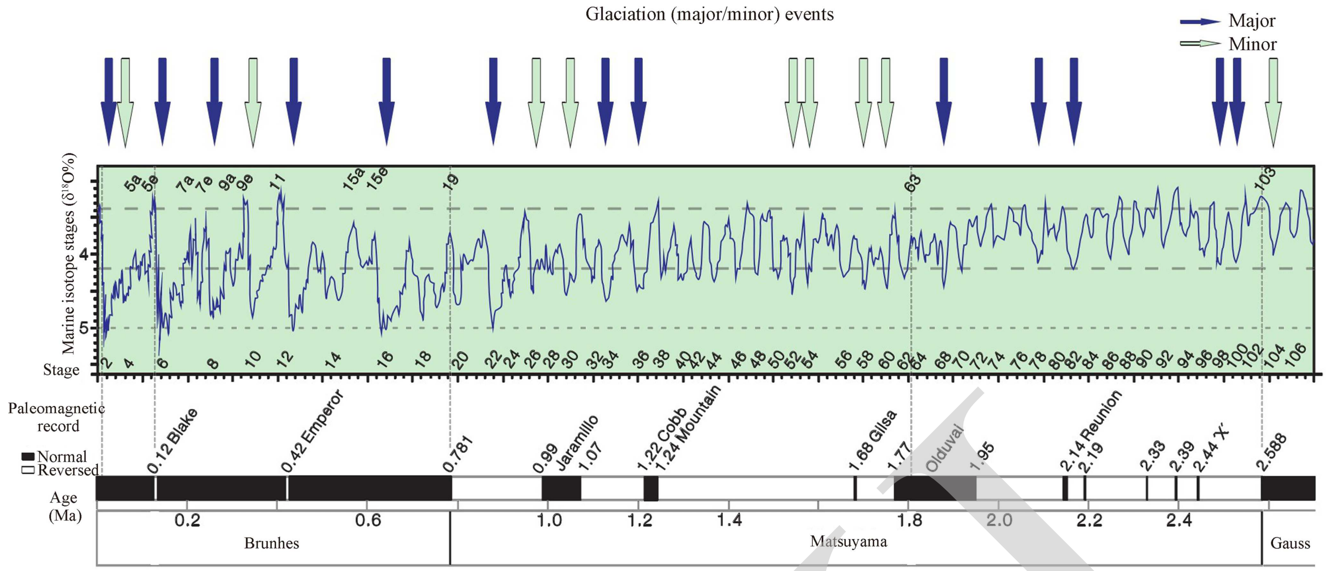

Figure 3 Quaternary cryosphere changes recorded by marine oxygen isotope [5]

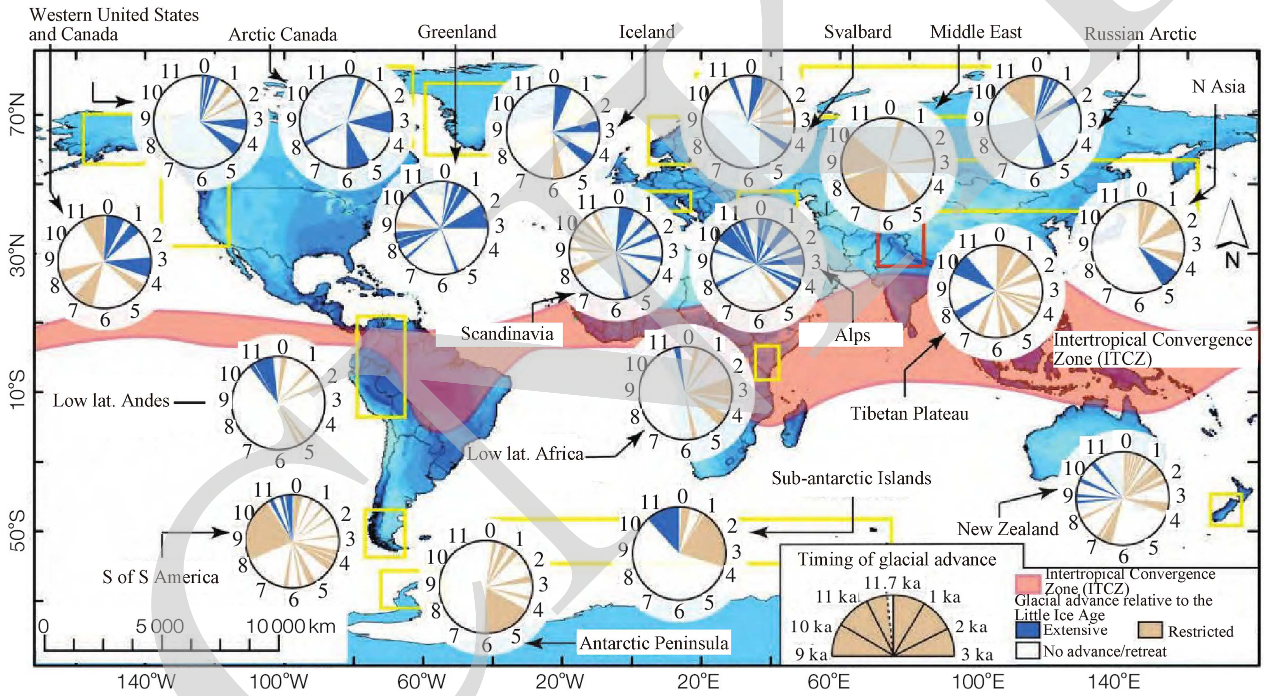

Figure 4 Ages of glacial advances since the Holocene [9]

the Patagonia region in 7.0–4.6 Ma. By 1.2 Ma, the largest ice sheet of the Pleistocene was formed in Patagonia. With further cooling and the gradual uplift of mountains, the middle and low latitudes of the Andes successively entered the cryosphere and developed glaciers, while the glacier development was much later in the northern Andes, with the greatest extent of glaciation at MIS8–MIS6.

Studies have shown that the Tibetan Plateau was in a peneplain state during the Pliocene, with an altitude of ~1 000 m [10,11]. The "Qingzang Movement" at 3.6 Ma in the late Pliocene initiated a new round of uplift. After A, B, and C phases of uplifts and Kunhuang movement, the plateau surface reached an altitude above 3 000 m at ~0.8 Ma. The plateau relic and surrounding mountains reached higher altitudes, and large-scale glaciation occurred in MPT, which marked that the plateau entered the cryosphere. The uplift continued thereafter. Glaciers extended in glacial periods and retreated in interglacial periods. Especially during the "Gonghe Movement," the plateau gradually approached the current altitude. Even in the interglacial period, a large number of mountain glaciers remained and represented the majority of low-latitude cryosphere on Earth. It is now established that the Pleistocene on the Tibetan Plateau saw the Shishapangma, the Kunlun, the Zhonglianggan, the Guxiang, and the Dali glacial periods, which corresponded to MIS22, MIS16, MIS12, MIS6, and MIS4–MIS2, respectively. In addition, the mountain glaciers responded actively to Holocene Neoglaciation and Little Ice Age.

The uplift of Tibetan Plateau has a feedback effect on cryosphere. Some scientists believe that the uplift of Tibetan Plateau enhanced chemical weathering and consumed CO_2 in the atmosphere. The "icebox effect" cooled the climate, which is likely related to the initiation of the Greenland ice sheet at 2.6 Ma [12,13]. Some others inferred that the Kunhuang movement raised the Tibetan Plateau to an altitude of more than 3 000 m, and possibly caused the MPT event. These striking deductions need to be explored further. However, they do suggest a possible link between the Quaternary cryosphere and the uplift of Tibetan Plateau. It is obvious that the uplift of Tibetan Plateau created the three tiers of topography in China, the powerful Asian monsoon climate system in the world, the typical three-dimensional zonality, and the three major natural regions of China, which have exerted profound impacts on the climate and environment in China and even in Asia.

In addition, the interaction between cryosphere and lithosphere is reflected by isostasy. Large ice sheet causes the subsidence of crust, which rebounds after ice sheet retraction. For example, during the glacial maximum in the Pleistocene, the isostatic subsidence of the central area of the Laurentide Ice Sheet exceeded 900 m [14]. The area covered with ice sheet generally rebounded after glacial period. For example, North America uplifted by ~300 m, and Fennoscandia by 307 m. At the southeast corner of Hudson Bay, the average uplift rate was more than 30 $m \cdot ka^{-1}$ during the Holocene and 13 $m \cdot ka^{-1}$ at present. The uplift rate in early Holocene should be much higher than 30 $m \cdot ka^{-1}$.

5 Adaptation of organisms and humans to cryosphere changes in the Quaternary

The Quaternary is a relatively short period in the history of biological evolution. However, compared with those in the Tertiary, woody plants decreased while herbaceous plants increased in the Quaternary. Among the woody plants, cold-tolerant deciduous, broad-leaved, and coniferous species increased, and angiosperms flourished unprecedentedly. Plant communities experienced multiple migrations, with the longitudinal variation > 10º and the vertical spectrum shifted > 1 000 m, which marked the ranges of contraction and extension of cryosphere in the Quaternary. In terms of mammals, the Quaternary was characterized by the extinction of *Hipparion*, *Zygolophodon*, *Stegodon*, and *Machairodus*, as well as the emergence of *Elephas*, *Equus*, and *Bos*. Some of the original populations migrated southward and survived. During the glacial period, specific biological populations developed to form new ecosystems. For example, the permafrost tundra in Siberia was the kingdom of woolly rhinoceroses and mammoths. In addition, a few species survived the extreme glacial environment and were called "living fossils," such as *Ginkgo biloba*, *Cathaya argyrophylla*, *Metasequoia glyptostroboides*, *Glyptostrobus pensilis*, *Taiwania cryptomerioides*, *Pseudolarix amabilis*, *Ailuropoda melanoleuca*, *Rhinopithecus*, *Alligator sinensis*, and *Lipotes vexillifer*. The Yangtze River Basin in China where these relict species are preserved is called shelter for animals and plants, which indicates that the glacial environment in the Yangtze River Basin was less extreme.

Ancient human originated in Africa and spread to limited areas in the early Quaternary. Sporadic fossils or stone tools have been discovered in Georgia, Turkey, Israel, Indonesia, Vietnam, Germany, Hungary, Czech Republic, Algeria, Morocco, and China (Lantian Man, Yuanmou Man, and Peking Man). Large-scale spread occurred until the last interglacial period of the Late Pleistocene. The sea level decreased during the last glacial period, and humans spread to America and Australia through land bridges. The Neanderthals perished while the Cro-Magnons survived and became the ancestors of present human. Human migration and natural selection are related to the evolution of cryosphere in glacial-interglacial cycles. It is particularly interesting that the living and production skills such as broad-spectrum revolution ①, fine stone tools, cultivation, domestication, textile, and pottery emerged successively and were associated with climate warming after the Younger Drays. Since then, the agricultural society developed vigorously.

Since the industrial revolution, humans have quickly released into the atmosphere the organic energy accumulated in the lithosphere over the past hundreds of millions of years, and the global warming has led to a rapid degradation of cryosphere. Human production and living activities have caused widespread pollution in lithosphere (soil), hydrosphere, and atmosphere, which, coupled with competition for living space, have resulted in the mass extinction of species at a speed and a scale far exceeding any natural extinction event in geological history. The influence of human on the earth system is so severe that it forces scientists to put forward the concept of Anthropocene as a warning—where exactly are we steering this "Noah's ark"?

6 Reflections and recommendations

China has made great progress in the research of Quaternary cryosphere. Specifically, the distribution patterns of

① It refers to the period from the Late Paleolithic to the Early Neolithic (the beginning of the production and economy), when human livelihoods gradually shifted to exploiting animal and plant resources that had been unused or neglected in the early and the middle Paleolithic.

Quaternary glaciers and permafrost on the Tibetan Plateau and the surrounding mountains have been basically clarified; the glacial period cycles have been reconstructed; the coupling of the high-Asian cryosphere with the global glacial periods and the uplift of Tibetan Plateau has been expounded. Nevertheless, such basic research still needs to be actively promoted. We believe that the following three topics need to be studied urgently in the near future.

(1) Establishment of aerial photographic databases of glaciers and glacial landforms on the Tibetan Plateau and surrounding mountains. The drone aerial photography technology, well developed for high-resolution landform identification, is suitable for the aerial photography of landforms in areas without vegetation and covered with ice and snow. Therefore, it is urgent to make use of this new method for aerial photography of glaciers and glacial landform and to establish a basic map database. This is essential for not only the dynamic monitoring of modern glaciers and permanent snow but also the study of glacial/periglacial landforms and refinement of Quaternary glacial period cycles. The establishment of such a set of basic data will greatly promote research and prediction. We suggest that the National Natural Science Foundation of China and the Chinese Academy of Sciences set up major projects to complete this work.

(2) Surveying and mapping of periglacial landform relics. This work has not been systematically conducted, and the knowledge of periglacial relics is usually a "by-product" of other studies. The paleo-periglacial relics widely distributed on the Tibetan Plateau and surrounding mountains as well as Northeast and North China are of great significance for understanding the environment in the Quaternary, especially the last glacial period, and predicting the future. They are also helpful to further authenticate the hypothesis of ice sheet on the Tibetan Plateau and the so-called low-altitude glaciers in eastern China. Now that transportation, equipment, and talents are available, we suggest that this work should be carried out as soon as possible.

(3) Clarifying the suspected paleoglaciers in some famous mountains in eastern China that may mislead the public. The research on the Quaternary cryosphere involves the so-called low-altitude Quaternary glaciers in eastern China. As a result of early misconceptions and the persistence of a few people, as well as the need for the development of tourism, some famous mountains use the specious "glacial relics" to attract tourists, greatly misleading tourists and the public. It even happened that the Pengzhou in Sichuan Province of China mistakenly renamed "Bajiao Town" to "Bingchuan (meaning glacier) Town" and refused to correct this mistake. It is recommended that the China Association for Science and Technology brings together a panel of experts to cooperate with the local government and tourism department to address similar problems, correct the mistakes, and lead the public to a scientific understanding of this issue.

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