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Evolution of permafrost in China during the last 20 ka

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Abstract: The formation and evolution of permafrost in China during the last 20 ka were reconstructed on the basis of large amount of paleo-permafrost remains and paleo-periglacial evidence, as well as paleo-glacial landforms, paleo-flora and paleofauna records. The results indicate that, during the local Last Glacial Maximum (LLGM) or local Last Permafrost Maximum (LLPMax), the extent of permafrost of China reached 5.3×10^6 km^2~5.4×10^6 km^2, or thrice that of today, but permafrost shrank to only 0.80×10^6 km^2~0.85×10^6 km^2, or 50% that of present, during the local Holocene Megathermal Period (LHMP), or the local Last Permafrost Minimum (LLPMin). On the basis of the dating of periglacial remains and their distributive features, the extent of permafrost in China was delineated for the two periods of LLGM (LLPMax) and LHMP (LLPMin), and the evolution of permafrost in China was divided into seven periods as follows: 1) LLGM in Late Pleistocene (ca. 20,000 ~ 13,000-10,800 a BP) with extensive evidence for the presence of intensive permafrost expansion for outlining its LLPMax extent; 2) A period of dramatically changing climate during the early Holocene (10,800 ~ 8,500-7,000 a BP) when permafrost remained relatively stable but with a general trend of shrinking areal extent; 3) The LHMP in the Mid-Holocene (8,500-7,000 ~ 4,000-3,000 a BP) when permafrost degraded intensively and extensively, and shrank to the LLPMin; 4) Neoglaciation during the late Holocene (4,000-3,000 ~ 1,000 a BP, when permafrost again expanded; 5) Medieval Warming Period (MWP) in the late Holocene (1,000 ~ 500 a BP) when permafrost was in a relative decline; 6) Little Ice Age (LIA) in the late Holocene (500 ~ 100 a BP), when permafrost relatively expanded, and; 7) Recent warming (during the 20th century), when permafrost continuously degraded and still is degrading. The paleo-climate, geography and paleopermafrost extents and other features were reconstructed for each of these seven periods.

Key words: Permafrost evolution, cryogenic wedge structures, local Last Glacial Maximum (LLGM) (local Last Permafrost Maximum, or LLPMax), local Holocene Megathermal Period (LHMP) (local Last Permafrost Minimum, or LLPMin), China

1. Introduction

In China, the local Last Glacial Maximum (LLGM, 26-16 ka BP) was the coldest period and the local Holocene Megathermal Period (LHMP, 8.5-7 ~ 4-3 ka BP) was the warmest period since the end of the Late Pleistocene (Shi, 1998, 2006, 2011; Zheng *et al.*, 1998; Shi *et al.*, 2000). During these two periods, climate fluctuations, in different cold-warm and dry-wet combinations, directly controlled the distribution of glaciers and permafrost and their changes. Therefore, understanding the past and present distribution, degradation rates, shrinking areal extents and volumes of permafrost is key to studying the source and sink effects of climate change and permafrost dynamics on the carbon pools in the atmosphere, soil and shallow permafrost.

Although the Last Glaciation Maximum (LGM) was the latest glaciation period, there was no a unified ice sheet, and snow and ice coverage was limited on the Qinghai-Tibet Plateau (QTP) and its peripheral mountains (Shi *et al*., 1990, 1995; Zheng, 1990； Shi, 2006, 2011; Heyman, 2010). Permafrost may have intensively developed, extensively expanded and reached the local Last Permafrost Maximum (LLPMax), establishing the framework of existing permafrost in China (Zhao *et al*., 2013). Later, it underwent the local Last Permafrost Minimum (LLPMin) in the local Holocene Megathermal Period (LHMP) and a series of evolutionary processes, forming the present distributive features of permafrost in China (Zhou *et al*., 1991; Qiu and Cheng, 1995; Zhou *et al*., 2000; Jin *et al*., 2007a, 2016; Chang *et al*., 2017).

At present, the areal extent of permafrost in China is 1.59×10^6 km^2, including an areal extent of plateau permafrost at 1.05×10^6 km^2 on the QTP, an areal extent of latitudinal permafrost at 0.24×10^6 km^2 in Northeast China, an areal extent of mountain permafrost at 0.30×10^6 km^2 mainly in West and Central China (Ran *et al*., 2012). The areal extent of seasonally frozen ground in China at present is 5.36×10^6 km^2, mainly found in North and Central China. In addition, at the beginning of the last 20 ka, permafrost may have occurred in most regions in Northwest, North, and Northeast China and on the Qinghai-Tibet Plateau. Rising sea levels permitted the East Asian Monsoon to re-develop, resulting in a change from very cold, dry conditions to warmer, more humid conditions marked by the rise and decline of ice-wedges, leaving behind a large amount of evidence and landscapes of Quaternary permafrost and periglacial phenomena. In this paper, the evolution processes and distributive features of permafrost in China since the last 20 ka were reconstructed on the basis of clarifying and using those numerous reported and recently identified evidence and proxies for inferring the past permafrost and periglacial environment. This study aims at providing a basic understanding and key scientific baseline for rebuilding the cold regions environment and carbon turnovers and their change rates among the glacial and interglacial periods in China and beyond.

2. Study Methods

2.1 Research method for Quaternary paleo-permafrost

Under the dry cold conditions at ca. 20-21 ka BP (21±2 ka BP), there was negligible water supply so that ice-wedges could not form. With the onset of the East Asian Monsoon due to rising sea levels, the warm precipitation entered the soil, producing ice wedges and bodies of ice. The heat, brought with the precipitation, plus the heat emitted during crystallization, resulted in warming the surrounding permafrost. The resulting ground ice is the evidence for past permafrost and paleo-periglacial geomorphology. However, their evidence is often subject to various interpretations (e.g., Vandenberghe, 1992; Vandenberghe and Pissart, 1993; Murton and Kolstrup, 2003; Harris *et al*., 2017; French, 2018). The formation, development, areal extent and evolution of past permafrost are estimated and reconstructed on the basis of Quaternary geology and paleo-biology, -climatology and -environmental proxies and data, and related dating techniques, under the principle of "the present as the key to the past", often aided by numerical model reconstruction (*e.g*., Liu *et al*., 2002; Jiao *et al*., 2015, 2016).

2.2 Evidence and criteria for past permafrost

The evidence for the occurrence of permafrost can be classified into two categories: direct and indirect indicators. Direct indicators include primary and secondary wedge structures, deeply buried permafrost and massive ground ice, past permafrost tables, pingos and pingo scars, lithalsas and palsas, to just name a few. Indirect indicators can be cryoturbations or cryogenic involutions, soil wedges and cryogenic polygonal structures, active or paleo-rock glaciers (*e.g*., Schmid *et al*., 2015); sorted and patterned ground, block fields, as well as pollen records in soil strata, such as *Picea* and *Abies* or other indicators of cold floristic communities, paleosols; glacial tills and landforms; periglacial flora and fauna (such as mammoths, wooly rhinos, and hardy plants), and characteristic combinations of clay minerals in soil strata. Some of these indicators are subject to multifaceted interpretations. Reliable conclusions can only be reached by comprehensive studies using multi-proxy combinations and cross-examinations.

The response of permafrost to climate change has a substantial time lag. On the ground surface, the relics of previous permafrost stages are often buried or erased by the next or new evolution events, only to increase the challenges for reconstructing a more detailed sequence of permafrost evolution. In another word, the closer to the present, the richer and more detailed the identified relics of permafrost. Therefore, various permafrost relics since the last 20 ka have been relatively better preserved. In recent decades, continuous and rapid advancement in sediment dating, more sophisticated and accurate dating methods, and continuous enrichment of various experimental and geoscience data have enabled more systematic approach and methods, and have resulted in more reliable results. In order to draw better conclusions in the formation and development of the permafrost environment, it is necessary to combine and validate with the results from Quaternary glaciology, desert research, periglacial studies, and paleo-climatology, -geography and -environment. These processes can largely overcome the multiplicity in the interpretations for some periglacial phenomena and eliminate as possible the false understanding.

The estimation of paleo-ground-temperature is important in understanding the occurrence and developmental conditions of past permafrost. It can be achived by using the paleo-air-temperatures, or interpretations from various paleo-cryogenic wedge structures. On the basis of field observations and lab experiments, Н. Н. Романовский (1977) summaried and pointed out that cryogeneic wedge structures, such as soil/ground, sand and ice wedges, as well as ice-wedge pseudomorphs (casts), as a result of cryogenic polygonal cracking, were closely related to the properties of soil sediments, soil moisture contents, and ground temperatures. The finer the soil grains, the lower the temperatures for the formation of cryogenic wedge structures. To grow soil wedges in fine-grained soils, such as fine sands, silts, sandy loams, clay, peat and humic soils, a mean annual ground temperature (MAGT) of –2 ~ –1 °C, or lower, is needed, whereas those in the coarse-grained soils, such as medium and coarse sands and sandy gravels, would need an MAGT of –5 ~ –3 °C, or lower, while ice wedges in coarse soils would mandate an MAGT of –6 ~ –5°C or lower. Up to date, this method of using cryogenic wedge structures for inferring paleo-temperatures have been widely adopted as a traditional method in rebuilding the Quaternary permafrost environment in China (*e.g.*, Cui, 1980; Liang and Cheng, 1984; Pan and Chen, 1997; Cui *et al*., 2002, 2004; Jin *et al*., 2007a, 2011a, 2011b, 2016; Chang *et al*., 2011, 2017), and beyond (*e.g*., Harris *et al*., 2017; French, 2018).

3. Statistics on paleo-permafrost and criteria for southern/lower limit of permafrost

3.1 Statistics on paleo-permafrost

The ages for the formation and thawing of paleo-permafrost are key in statistics and analyses of various paleo-permafrost relics and data. The authors of this paper have extensively collected, varified and extended the dating data on the basis of Quaternary glacial periods in China provided by Shi (2006), in addition to the statistics of related age data for past permafrost in China (see Supplementary materials). These data serve as the baseline for the divisions of chronological sequences of permafrost evolution in China. They were further elaborated with several representative profiles of wedge structures and some photos of typical cryogenic structures (Figure 1).

a) Ice wedges in Wuma, northern Da Xing'anling Mts.

b) Cryoturbations in Dishaogou Valley, Salawusu, Inner Mongolia. cryoturbations in yellowish fine sand with grayish silts

c) Sand wedges in Huang'he Village, Madoi, Qinghai

d) Pingo scars northwest of the Ngöring Lake, SAYR

e) Cryoturbations on the first terrace of the Datong River near Huangchengzi, Menyuan, Qinghai: 150×5 m, location at 37°38′25.2″N, 101°9′43.3″E; 3,148 m asl

f) Frost-cracking sand wedges at Yixing Logistics Co. in Dongsheng, Ordos, Inner Mongolia

Figure 1. Photos of typical cryogenic structures in China (only 6 sites are listed)

3.2 Delineation of paleo-permafrost boundaries

Paleo-permafrost remains, e.g., ice wedge pseudomorphs (casts) and rock, sand, soil and primary ice wedges in particular, are key indicators for rebuilding the paleo-environment and Quaternary boundaries of permafrost. Large numbers of wedge structures with various shapes and geneses have been identified. They can only be indicative of paleo-permafrost when they are clarified and verified as groups of cryogenic sand, soil and rock wedges closely related to frost cracking polygons and permafrost. By using the relationships of wedges to the host strata, ice wedges and ice wedge pseudomorphs (casts), and sand, soil and rock wedges can be recognized. Ground temperatures for the formation of wedge structures are related to wedge structure types and soil strata. Due to rapid tectonic uplifts in recent geohistory, it is necessary to make elevational and latitudinal adjustments for estimated air or ground temperatures: 6°C/km (elevation) and 1°C/°N (Zhou *et al*., 2000).

Since the Late Peistocene, the QTP has been uplified by about 1,000 m. Due the short time period involved in this discussion, an elevation of 500 m, as justified in Zhou (2007), is assumed in this paper. In addition, the adjustments have to take into account the tectonic units of these identified cryogenic structures, such as those of the Tianshui'hai Lake region in the relative uplift zone in the West Kunlun Mountains, and Nachitai along the Qinghai-Tibet Highway (QTH) in the Eastern Kunlun Mountains, the Gong'he Basin on northeastern QTP, and the Lenghu Basin on northern QTP in the relative subsidence zone. The southern/lower limit of permafrost (SLP/LLP) and distributive features, as well as paleo-geography, can then be delineated on the basis of adjusted air or ground temperatures.

4. Results and discussions

Many paleo-permafrost and paleo-periglacial remains of different ages since the Middle Pleistocene have been identified in China (*e.g.*, Pan and Chen, 1997; Zhou *et al*., 2008; Qi *et al*., 2014). However, the main body of the existing permafrost in China was formed during the LLGM in the Late Pleistocene (Zhou *et al*., 1965, 2000; Zhao *et al*., 2013; Jin *et al*., 2016; Chang *et al*., 2017). Since the Late Glacial period in the early Holocene, permafrost has undergone many expansions and retreats, forming the present distributive patterns of permafrost in China.

Taking into account of lagged responses of permafrost to climate changes, the LLPMax occurred about 20 ka BP (ca. 21±2 ka BP). Later, many major climatic and environmental changes, such as the LLGM and LHMP, have reshaped the distributive features of permafrost (Zheng *et al*., 1998). The LLPMax and LLPMin in China also took place (Figure 2) (Zhao *et al*., 2013; Harris *et al*., 2016; Jin *et al*., 2016; Chang *et al*., 2017).

Permafrost evolution in China since 20 ka BP can provisionally be divided into seven major periods on the basis of the distribution of existing permafrost in China and analyses of spatiotemporal differentiations of paleo-permafrost and -periglacial remains listed in the Supplementary materials, in addition to cross-correlations with Quaternary glacial, paleo-climatic and -environmental records. Among them, the LLGM/LLPMax and LHMP/LLPMin are the most important periods for the development, growth and evolution, as well as the distribution, of the existing permafrost in China. In those above-mentioned seven periods, some sub-tier changes in climate, permafrost and periglacial environments occurred. However, the responses of permafrost to these second-tier changes have been overlapped or erased by these seven major climate climaxes (the coldest or warmest). Therefore, under these complex circumstances, only distribution of permafrost under those longer-term climate extremes, *i.e*., the maxima or minima of permafrost extent, can be rebuilt.

On the studies and integration of paleo-permafrost in the periphery or bordering states and/or regions, an attempt is made for merging the reconstruction of LLGM permafrost in China with some other regions (Figure 2). It seems that the boundaries of permafrost in China merge with those in Kazakhstan, Central Asian states, and western Asia. However, it still needs data from Russia, Mongolia and Korean Peninsula to integrate the paleo-permafrost map with Eurasian permafrost body during the LLGM. In the meantime, it should be pointed out that due to large amplitudes of sea level drop as much as 120-150 m during the this LLGM, the general circulations and distribution of land-ocean, as well as some major landscapes and vegetation, were affected, complicating the reconstruction of paleo-permafrost in China and bording states. In particular, these mosaicked distributions of permafrost and talik in deserts have been discussed, but still lack reliable evidence for mapping these regions.

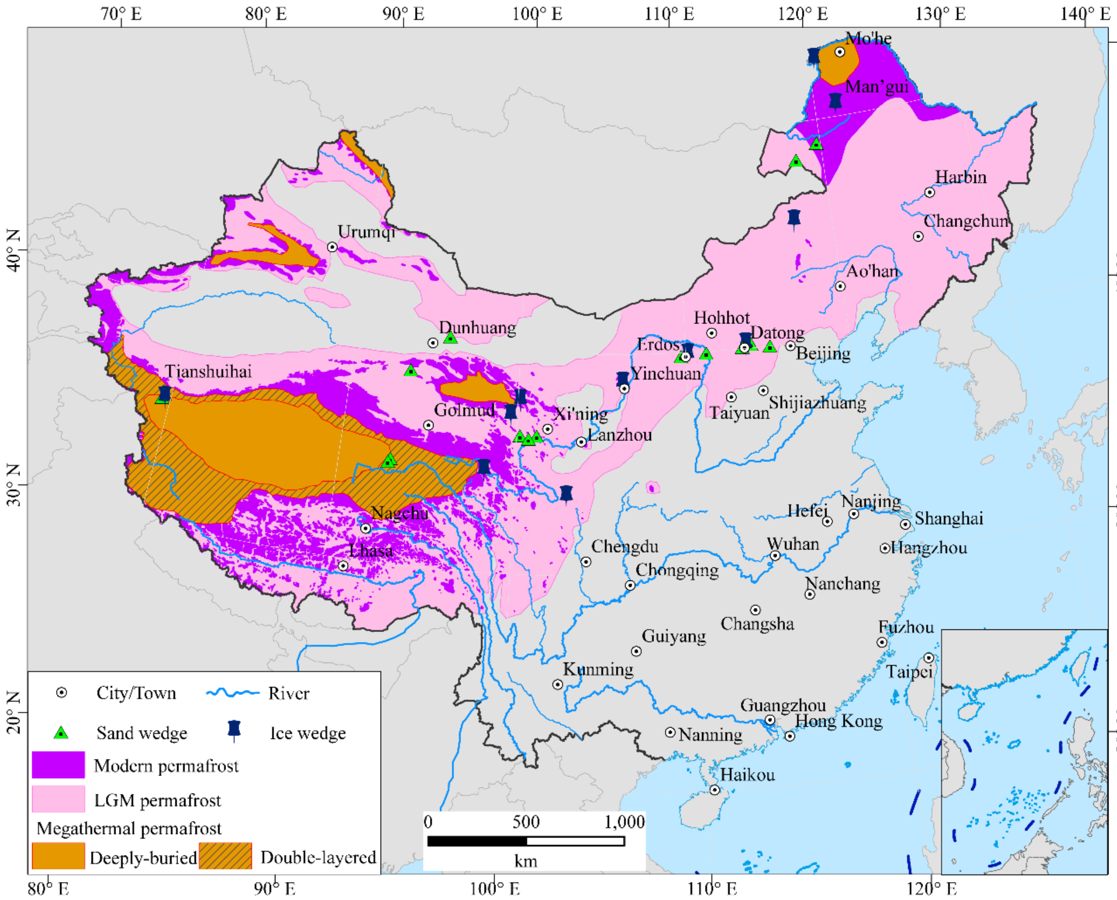

Figure 2. Distribution of permafrost in China during the LLPMax/LLGM, LLPMin/LHMP, and at present

4.1 Permafrost expansion during the LLPMax in the end of the Late Pleistocene (LLGM，~20 to 13~10.8 ka BP): permafrost was extremely well developed and intensively expanded

The climax of LGM (26~16 ka BP) witnessed the latest large-scale glaciations, with a massive cooling in the Northern Hemisphere (Shi, 1998; Shi *et al*.,1990, 1995, 1997; Zheng, 1990; Wang and Sun, 1994; Zheng *et al*., 1998). In the meantime, glaciations expanded in North China and on the QTP; however, the spatial scales of glaciations were limited on the QTP and in its periphery mountains, and mountains in Central Asia, and Northeast, North and Central China (Sun *et al*., 1985; Li *et al*., 1991; Shi *et al*., 2000; Shi, 2006; Heyman, 2010). Therefore, it could have been the LLPMin in China. Many paleo-permafrost and -perlglacial remains have been well and extensively preserved (Supplementary materials). In particular, large numbers of cryogenic wedge structures, especially those extensively identified sand and soil wedge groups, formed during the LLGM, have been found in China. In addition, numerous cryogenic wedge structures have also been discovered and archived in most regions of what is seasonally frozen ground at present, such as the Ordos (Loess) Plateau, QTP, North China and southern part of Northeast China (*e.g*., Zhang, 1983; Xu and Pan, 1990; Wang and Bian, 1993; Pan and Chen, 1997; Cui *et al*., 2004, 2004; Vandenberghe *et al*., 2004, 2016; Cheng *et al*., 2006； Jin *et al*., 2006a, 2006b, 2007a, 2016; Zhou, 2007; Zhou *et al*., 2008; Chang *et al*., 2011, 2017; Harris and Jin, 2012; Wang *et al*., 2013; Xu *et al*., 2015; Harris *et al*., 2016, 2018). These wedges were generally formed at the margins of lacustrine or river terraces, and covered by sediments of 1~2 min thicknesses. In profiles of some of those wedge structures, falling textures and blocky and gravelly infills can be identified, which can be related to the melting of ground ice.

A very cold and dry climate prevailed on the QTP during the LLGM until 14 ka BP. Afterwards, climate warmed up intermitently, and the growth of some wedges stopped due to the rising air temperatures. According to the ice-core records from the Gulia Ice Cap in the West Kunlun Mountains, a warming of about 2~3°C occurred during 14~12 ka BP, although there were still appreciable ups and downs in air temperatures (Shi, 2011). By the end of the Late Peistocene, the major distributive patterns of existing permafrost on the QTP were already established (Jin *et al*., 2007a; Chang *et al*., 2017).

On the basis of the interpretations for numerous wedge structures, there was a cooling of about 7~9°C on the QTP at ca. 20 ka BP (Jin *et al*., 2007a; Chang *et al*., 2017). Shi *et al*. (1995, 2000) concluded that, on middle and eastern QTP, it was 6.8°C colder than today. On the Zoîgé Peat Plateau, a cooling of 5.8~7.9°C occurred, as inferred from an 1,200-m lowering of the upper timberline. Based on pollen records, the deduced paleotemperatures at the LLGM were about 6~7°C cold than today (Shen *et al*., 1996). On the basis of paleo-periglacial landforms, Cui (1980) estimated a cooling of 5.5~6.4°C for the Tanggula Mountains in the Interior of the QTP. By comparing the changes in the lower limits of paleo-permafrost, Yang and Wang (1983) estimated a cooling of 5~6°C for the plateau regions south of the Tanggula Mountains. Zheng (1990) believed that because of the large areal extent and massive relief of the QTP, there should be a marked differentiation in climate cooling during the LLGM: a cooling of 5~7°C in the Interior and alpine regions of the QTP, but the cooling could be as much as 8~10°C in the peripheries. On the basis of surface pollen records in Rencuo, Basu County, Tibet Autonomous Region, Tang *et al*. (1998) deduced that the mean January air temperature at ca. 18 ka BP was 10°C lower than today, *i.e.* a cooling of about 6°C. On the basis of large cryoturbations and glaciofluvial sediments in Menyuan, Qinghai Province, Wang *et al*. (2013) estimated an LLGM cooling of at least 7°C, resulting in glaciers advancing to the foothills of the Qilian Mountains. Vandenrberghe *et al*. (2016) and Harris *et al*. (2016) also have similar notions.

Numerical climate model reconstruction on the QTP indicate an LLGM cooling of 2~13°C (Liu *et al*., 2002), 6°C (Böhner and Lehmkuhl, 2005), and 1.8~6.4°C (Ju *et al*., 2007). Mark *et al*. (2005) estimated an LLGM cooling of 7.5°C on the QTP according the changes in snowline, or the equilibrium line altitude (ELA). In a word, most scholars more or less have reached similar conclusions on the LLGM magnitude of the cooling on the QTP. Thus, it is reasonable to assume an LLGM cooling of 7~9°C. However, Heyman (2010) and Owen *et al*. (2003, 2006) suggested that the glacial expansion was very limited on the basis of their latest studies on the QTP and adjacent regions with an LLGM of cooling (2~4°C). There was no unified QTP or regional icesheet; most of plateau glaciers were formed long time ago and with ony limited expansions during the LLGM (Heyman *et al*., 2008, 2009; Stroeven *et al*., 2009).

Groups of inactive ice wedges were also found in Wuma (52°45′N, 120°45′E), northwestern corner of the Da Xing′anling Mountains, Northeast China (Tong, 1993). On the basis of AMS-^{14}C dating of ambient and overburden soils of the ice wedges, they were formed during 14,475±304~10,668±257 a BP. It would need a mean annual air temperature (MAAT) of about −7 ~ −5°C for forming ice wedges in the sandy soils (Nomanovskii, 1977). The observations indicate that the present MAGT is 3.8~4.3°C higher than the MAAT in the northern Da Xing'anling Mountains (Chang *et al*., 2015; Jin *et al*., 2016). Therefore, it is estimated that, when these ice wedges were formed, the local paleo-MAAT was about −10 ~ −9°C (Tong, 1993). The present-day MAAT in this region was about −5°C (in the 1990s). Therefore, the northern Da Xing′anling Mountains was about 4~5°C colder during the ice wedge growth period than today (Jin *et al*., 2016). To the south in the middle-western part of Northeast China, the Hulun Buir High Plain was sparsely vegetated under a dry continental climate during 22~11 ka BP (Yang *et al*., 2006).

In the arid regions in North China, Yu *et al*. (2013) rebuilt the paleoclimate during the LLGM (ca. 26~16 ka BP) on the basis of a large amount of paleodata, with a climate cooling of about 5~11°C and a variability (uncertainty) of 60%~200%; the concurrent decline in annual precipitation was about 180~350 mm. In the end of the Late Pleistocene, the present-day topography, geomorphology and topography were largely formed in the arid regions in Northeast and North China. Therefore, the SLP at the LLGM can be largely determined by the 0°C isotherms of MAAT (Jin *et al*., 2007b). In Northeast China, assuming an MAAT of 4~5°C colder than today and a northward cooling rate of 1°C/°N (Zhou *et al*., 2000), the SLP at the LLGM could have extended southwards by 4°~5°N, *i.e.*, reaching 41°~42°N (Figure 2). The LLGM SLP and LLP met in the Liupanshan and Hua′jialing mountains on the Longdong Plateau (near Lanzhou) at elevations of 2,200-2,300 m asl (Zhou *et al*., 2000; Jin *et al*., 2007a, 2016; Zhao *et al*., 2013; Chang *et al*., 2017). This estimation was later confirmed by discoveries of many frost-cracking wedges on the Ordos (Loess) Plateau and reconstructed the latest coldest paleoevironment in the LLGM of about 10~12°C colder than today during 25~13 ka BP, when permafrost expanded southwards to south of 37°~38°N (Cui *et al*., 2004; Vandenburghe *et al*., 2004).

On the QTP and in alpine regions in Central and West China, the MMAT at the LLP generally ranges from −4 ~ −2°C. There the LLP decreases by about 160-170 m for every 1°C cooling in MAAT (Wang and Bian, 1993). The LLP during the LLGM was 1,200-1,400 m lower than that of today, inferred from the combined evidence from the 7~9°C cooling of MAAT on the QTP and in alpine regions, the distribution of cryogenic wedge structures and other periglaical remains, and the lowering of the upper timberline (Jin *et al*., 2007a; Zhao *et al*., 2013; Chang *et al*., 2017). The plateau permafrost expanded and descended into the periphery inland basins, such as Xinghai, Gong′he, Zoîgé, Chaidam and Tarim basins, with an areal extent of continuous permafrost at about 2.2×10^6 km^2. Sporadic and isolated patches of permafrost were also extensively distributed in mountainous areas in West China. Thus, the LLP could be estimated as follows:

1) On western and northwestern QTP, the LLP was at 2,800-2,900 m asl in western section of northern slopes of the West Kunlun Mountains, at 2,400-2,500 m asl on eastern section of northern slopes of the West Kunlun Mountains, and at 2,900-3,100 m asl in the southern margin of the Tarim Basin;

2) On eastern QTP, the LLP was at 2,300-2,400 m asl in the Gong’he Basin, 2,600-2,800 m asl in the Chaidam Basin, 2,700-2,800 m asl on the Zoîgé Plateau, 3,000-3,200 m asl on the Chuanxi (West Sichuan) Plateau, and 3,800-4,000 m asl in the Hengduan Mountains; on southern QTP, it was at 3,600-3,800 m asl in the middle- and down-streams of the Yarlong Zangpo River Basin in southern Tibet Autonomous Region;

3) On northern QTP, the LLP was at 2,200-2,300 m asl on northern slopes (Lenglongling Mountains) of Qilian Mountains and mountainous regions south of the Jiayuguan Pass, Gansu Province and;

4) The LLP was at 2,100-2,200 m asl on southern slopes and at 1,900-2,000 m asl on northern slopes of the Chinese Tianshan Mountains, and 1,400-1,500 m asl on southern slopes of the Chinese Altai Mountains.

In summary, except for taliks in some deserts and lowland basins, the majority parts of North China and QTP were in permafrost zones (Figure 2), with a total permafrost extent at 5.3×10^6~5.4×10^6 km^2, or three times of the present permafrost extent.

During the LLGM, periglacial landforms were extensively developed, leaving behind many relics, such as those primary sand wedges in medium and fine sands (Q_3 Gong′he Group sediments) on northeastern QTP reported by Xu (1984), Pan and Chen (1997), with a formation time prior to 20,403±430~19,430±360 a BP. Numerous sand wedges and ice wedge pseudomorphs have been identified and studies in the Source Area of the Yellow River with a formation age at 12,300±100~16,340±250 a BP (Pan and Chen, 1997; Cheng *et al*., 2006). The soil wedges in Nachitai on northern slopes of the Kunlun Mountains along the QTH were formed during 14,041±339~15,377±292 a BP; those sand wedges in the Fenghuoshan Mountains in the Interior of the QTP were formed at 23,500±1200 and 15,340±770 ~9,218±189 a BP. Sand wedges in Lenghu of the middle and northern parts of Qinghai Province were TL-dated at 18,510±2,220 a BP (Ma, 1996). Inactive ice wedges and primary sand wedges on the terrace of the Tianshuihai North Lake in the West Kunlun Mountains were formed during 21-12 ka BP (Li and He, 1990; Li and Jiao, 1990; Chang *et al*., 2011). In a 5-m-high roadcut close to Huangchengzi, Menyuan Hui Prefecture, Qinghai Province, on the southern flank of the Qilian Mountains, very large load castings developed during the OSL 20~30 ka BP (Vandenberghe *et al*., 2016; Harris *et al*., 2016).

Due to the extremely cold and dry continental climate, the plateau vegetation severely degraded during the LLGM. The majority of the plateau surface reverted to desert, steppe, or tundra environments: lakes shrank and deserts expanded. Steppes extended eastwards to Linxia, Gansu Province and to the Zoîgé Plateau, Sichuan Province, and southwards to Basu County to the Yarlung Zangpo River Basin, southeastern Tibet Autonomous Region. Forests retreated to the eastern and southern edges of the QTP, with only some small patches of alpine shrublands and mountain needle- and broad-leaved mixed forests on the Western Sichuan and south of the Yarlung Zangpo River (Tang *et al*., 1998).

In Northeast China, a rich pollen assemblage of *Picea* and *Abies* have been found in the strata of the Guxiangtun Group in the Late Pleistocene in Huangshan, Harbin, Heilongjiang Province and Yushu County, Jilin Province, indicating for a forest-steppe landscape. Based on incomplete statistics, fossils and remains of Mammoths *(Mammuthus)*-wooly Rhino (*Coelodonta*) fauna, an indicator for cold climate, have been excavated in many places in southern part of Northeast China and in the northern part of North China, concentrated in areas north of 42°N (Qiu, 1985; Zhang, 2009; Wei *et al*., 2010). By integrating the evidence from the extensive occurrences of the dark needle-leaved forests and Mammoths *(Mammuthus)*-wooly Rhino (*Coelodonta*) fauna in these regions, it is evident that in the end of the Late Pleistocene, cold climate prevailed in northern and mountainous parts of Northeast China, as well as the Songhuajiang-Liao′he Plain in Northeast China (Guo and Li, 1981), even in the lately exposed extensive continental shelves as a result of lowering sea level (Zhao *et al*., 2013; Jin *et al*., 2016). Since the 1970s, many megafauna, such as *Mogaloceros ordosianus* and *Mammuthus*, have been excavated in primary strata of the Late Pleistocene in the Bay of Bo'hai Sea. This at least can serve as concrete evidence for cold climate in Northeast China.

Since coming into the Holocene, in comparison with the LLPMax/LLGM, the areal extent of permafrost was on a general decline. The history of permafrost evolution can still be divided into six distinct periods since the early Holocene starting at 10.8 ka BP.

4.2 Early Holocene with dramatic climate changes (10,800 a BP to 8,500~7,000 a BP): period of stable but relatively shrinking permafrost

The climate in the early Holocene was very unstable. A sharp cooling is indicated by the ice-core records from the Dunde Glacier, Qilian Mountains (38°06′N, 96°24′E; 5,200 m asl): at 8,700 a BP, δ^{18}O reached −12.75‰, the lowest in the Holocene, whereas −9.60‰ at 8,500~ 8,400 a BP, the highest in the Holocene, indicating a spike in climate warming (Yao and Shi, 1992). Accordingly, the diatom records in the Angren Co (Lake) in southern Tibet Autonomous Region indicate a lower lake temperature and a rising lake water salinity, *i.e.*, a cold and dry period, prior to 8,700 a BP (AMS-^{14}C), but during 8,700~ 8,600 a BP, the records suggest a very high lake temperature, with lowered lake water salinity and large input of glacier-melt (Li and Jiao, 1990).

The climate in early Holocene was cold and dry, but it was gradually changing to cool and moist climate. On the basis of remains of paleo-permafrost, the northern LLP was at 3,400~3,500 m asl to the north of Nachitai along the QTH, the southern LLP was at 4,200~4,300 m asl between Yangjiajing and Damxung, northern Tibet Autonomous Region; the LLP then was about 600~700 m lower than today. Permafrost was continuous and thermally stable, but overall it was degrading from the LLPMax, with a declining areal extent of permafrost, but the permafrost extent was still 40%~50% greater than today.

Song and Xia (1990) reported 150 pingo scars on the Sanjiang Plain (47°10′~48°43′N, 133°~135°E) in the northern part of Northeast China. They are generally accompanied by pingo-thawed lakes in round or oblong shapes, with a diameter of about 10~100 m. The outer margins of pingo scars generally have a wall of about 23 m in height, with an outlet. Generally, inside the walled lakes, water bodies can be found, or they have gradually developed into wetlands. Most of these pingo scars were formed during 10~8 ka BP (Li, 1990; Song and Xia, 1990). Therefore, it is evident that permafrost still occurred on the Sanjiang Plain in the early Holocene, but permafrost to the south had largely vanished.

On the basis of pollen records from 20 lakes on the QTP, Tang and Shen (1996) synthesized the environmental features of the plateau in the early Holocene as follows. During ca. 10,000~9,100 a BP, meophytic deciduous broad-leaved and needle-leaved forests dominated on eastern QTP; during ca. 10,800~8,000 a BP, *Artemisia* and *Chenopodiaceae* dominated in the subalpine steppe in the region of the Qinghai Lake on northeastern QTP, in which at 9,500~8,800 a BP, there was an evident spike of arbor species pollens of more than 50%, indicating a sudden warming and wetting (Du *et al.*, 1989). During 10,000~7,700 a BP, *Artemisia* dominated steppes on the western QTP under a cold and moist climate.

In summary, the plateau climate was wetting and warming, forming wetlands in basins and valleys and depositing peat and thick layers of humus. For example, the thick-lyered peat at the bottom of soil profiles in Wumaqű, Damxung and Qinongga, Yangbajing, in the Tibet Autonomous Region is AMS-^{14}C-dated at 8,175±200~9,970±135 a BP, indicating a starting period of peat formation (Li, 1982). For another example, dark silty sand clay is found at depths of 2.5~3.0 m in the Borehole CK80 at Qingshui'he Riverside along the QTH. A soil sample at depths of 2.7~3.0 m is dated at 8,800±305 a BP. Meanwhile, the lithology changes upward from yellow sand clay and medium-fine sand with limestone blocks and carbonate nodules at the bottom to dark silty sand clay deposits at the upper part. This transition is a result of climate warming and wetting and subsequent enrichment of organic matter. In addition, humic silt and sand at the upper part of sand wedges on the second terrace of the Zuomoxikong Qű (River) in the Fenghuoshan Mountains along the QTH is dated at 9,218±189 a BP, while that at the Highway Maintenance Squad Station (HMSS) 82 along the QTH at the southern piedmont of the Fenghuoshan Mountains was dated at 9,160±170 a BP. They all indicate an ameliorating climate and no growth of frost cracks and sand wedges. Warming climate was conducive to plant growth; as a result, some sand dunes formed during the end of the Late Pleistocene were (semi)fixed. For example, buried plant roots and stems in the sand ridges 2 km southeast of Wudaoliang along the QTH is ^{14}C-dated at 9,716±270 a BP (Wang, 1989).

4.3 Local Holocene Megathermal Period (LHMP) (8,500~7,000 to 4,000~3,000 a BP: intensive permafrost degradation

The mid-Holocene is the optimal climate period in the Holocene, so it is also called the hypsithermal period, or LHMP. According to Shi *et al.* (1992), the LHMP in China occurred during 8,500-3000 a BP, with a stable warm and wet climax at 7,200~6,000 a. During the LHMP, it was 1~2°C warmer than today in South China and in the middle- and down-streams of the Yangtze River Basin, 3°C warmer than today in North, Northeast and West China, 4~5°C warmer than today on the QTP in Southwest China, and the warming in winter was much more pronounced. For example, in the ice-core record from Gulia Ice Cap, at the climax of the LHMP, δ^{18}O was 3‰ higher than the average of the δ^{18}O during the last millenium, *i.e.*, a warming of about 4~5°C (Shi, 2006). The climate warming in the arid regions in North China could have been about 1.0~3.5°C in MAAT (with an uncertainty of 20%~130%); annual precipitation increased by 30~400 mm (with an uncertainty of 10%~120%). The increase in annual precipitation also had a trend of inland increasing from Southeast China to Northwest China (Yu *et al.*, 2013).

The field surveys indicate that the ice wedges in Wuma in northern part of the Da Xing′anling Mountains were formed during the LLGM and were preserved well before the last inpsection in 2007. There were thawed concaves on the top 0.7 m of the ice wedges, an evidence for the lowering permafrost table. This implies that in spite of a warming climate during the LHMP, the periglacial environment still prevailed in the area (Tong, 1993; Jin *et al.*, 2016). In addition, in the Amu′er in northern part of the Da Xing′anling Mountains (52°51′N, 123°11′E), analysis on the light and heavy mineral contents of Quaternary deposits indicate low contents of unstable and relatively stable minerals, and even less stable minerals (<5%); in contrast to 75%~92% in the gravels (Guo *et al.*, 1981). This also indirectly demonstrates that the northern part of the Da Xing′anling Mountains have never undergone a long-term warm and wet climate. The above-mentioned two areas are now still in the continuous permafrost zone.

With rising temperature in the LHMP, permafrost in China retreated extensively, and latitudinal permafrost disappeared from eastern Inner Mongolia, eastern Xinjinang, and North China. Most latitudinal permafrost in Northeast China also disappeared, or retreated to the northwestern corner (north of Amu′er-Mangui) of the Da Xing′anling Mountains to the north of 51°~52°N (Figure 2). Because of the northward retreat of the SLP by 3~4°N, the climate warming could be about 3~4°C warmer than today.

The age data on the formation of thick peat and humus layer on the QTP, as listed in the Supplementary materials, are largely grouped in the LHMP, indicating a warm and wet climate. Along the QTH, the ^{14}C-age of the humus soil at the depth of 4.4 m in the Borehole No. 8 at Xidatan is 7,530±300 a BP, and that of ash-like humic sand on the first terrace of Nachitai is 4,910±100 a BP; anthropic fire-used ash sites have been found in many places from Nachitai to Xidatan along the Kunlun River, indicating a suitable climate and environment for human activites; the age of humus layer at the HMSS 109 on the southern slopes of Tanggula Mountains is 5,058±443 a BP, and that at HMSS 120 is 4,313~4,576 a BP; the completion time for the continuous deposition of thick peat was 3,050±120 a BP at Qinongga, Yangbajiang, Tibet Autonomous Region and 3,575±80 a BP at Wuma Qű (River), Damxun, Tibet Autonomous Region.

On the northeastern and eastern QTP, the middle part of a 2-m-thick humus soil profile on the eastern slope of Mount Ri'yueshan is dated at 4,920±80 a BP while the peat at the depth of 2 m in a 5-m-thick peat soil profile on southern slope of Heka South Mountains is dated at 4,625±117 a BP. A thick humus soil is dated at 4,395±215 a BP at a gelifluction tongue in the Wenbo South Mountains in Shiqu, Sichuan Province, while the peat is dated at 5,422±94 a BP in the lower part of a 4.15-m-thick peat deposit on the morainic platform in the Nianbao'yeze Mountains. A layer of 5.2 m of peat was deposited during 9,350~370 a BP in the Peat Farm soil profile in the outskirts of Hongyuan, Zoîgé Plateau, Sichuan Province, and a layer of 3.3 m peat was formed during 6,350~3,250 a BP (Sun, 1998).

The above-mentioned extensive and thick deposits are all products in the LHMP as long as 4,000~5,000 years. They appear to be an indirect indictor of large-scale and intensive degradation of permafrost. In the later LHMP (ca. 4,000~3,000 a BP), the LLP was 300~500 m higher than today; to the north of Kunlun Mountains and to the south of Tanggula Mountains, permafrost had been converted into seasonally frozen ground. In the Chumar'he High Plain between the Kunlun and Tanggula mountains, permafrost was thawing continuously for a long time, reaching to a depth of 14~16 m (Jin *et al*., 2007a) and resulting in a vertical detachment of permafrost from the active layer (Jin *et al*., 2006). In the meantime, a thick-layered ground ice was formed at depths of 14~16 m, *i.e*., the position of paleo-permafrost table (Xin and Ou, 1983). Due to the thawing of shallow permafrost and ground ice, numerous thermokarst lakes and depressions were formed, and ice wedge pseudomorphs were formed after ice melting, on the QTP.

During the LHMP, permafrost on the plateau was sporadic and isolated, or deeply buried (Jin *et al*., 2009). However, at high elevations, such as in the Kunlun, Fenghuoshan and Tanggula mountains, it was still dominated by continuous permafrost. In the meantime, permafrost degraded more intensely on eastern QTP as represented by that along the Qinghai-Kang (W Sichuan) Highway (QKH) than that in the interior QTP as reprsented by that along the QTH and western QTP. Along the QKH, permafrost was completely converted to seasonally frozen ground at elevations lower than 4,200 m asl; that at 4,200~4,400 m asl (Hua'shixia to Qingshui'he), permafrost thawed down to depths of 15~25 m, with a 3-dimensional thawing (vertical and lateral) (Jin *et al*., 2006, 2009; Chang *et al*., 2017). In the end, deeply buried permafrost was left at depths of 10~20 m in some well-preserved areas in the Bayan Har and Anemaqên mountains along the QKH, and in the Source Area of the Yellow River (Jin *et al*., 2006a, 2009). In some areas further to the east, permafrost was thawed completely at lower elevations, leaving behind only some isolated permafrost islands on the top of Bayan Har and Anemaqen mountains.

In mountainous areas in western China, such as in the Tianshan, Altain and Qilian mountains, if calculated by an elevation of the LLP by 300~500 m, permafrost could only be preserved on the top or upper parts of these high mountains. The Tarim, Turpan and Zhunger bains are at 41°~46°N, similar to that of Songhuajiang-Liao'he Basin in Northeast China. Thus, permafrost should have vanished in the major basins during the LHMP. Calculations based on Figure 2 indicate only an areal extent of 800,000~850,000 km^2 for the remained permafrost in China during the late LHMP, or about 50% of existing permafrost extent at present.

During the late LHMP, westward shifts of vegetation zones occurred under a warming and wetting climate; it was acompanied also by vertical and horizontal shifts as well. In the peripheries of high mountains and plateaux, timberline lowered, while in West China, steppes expanded and deserts shrank. The transition zone (meadowy steppes) between forest and steppe belts evidently moved westwards to northeast of Manzhouli-Buhat Banner-Hoh Hot-Helanshan South-Xi'ning, a westward movement of 3~5°E in comparison with today. In the meantime, the boundary between temperate forest-steppe and typical steppe also shifted westward by 3~4°E. Forest-steppe environment dominated the Altai and Tianshan mountains, while plateau steppe and forest dominated the QTP. The areal extent of semi-deserts and deserts dramatically shrank, with only some patches remaining in the middle Tarim Basin, middle and western Inner Mongolia Plateau and Chaidam Basin. Vegetation zones on southern and eastern QTP, such as in the Hengduan Mountains, also shifted to varied extents (Tang and Shen, 1996).

4.4 Neoglaciation in the late Holocene (4,000~3,000 to 1,000 a BP) : second major permafrost expansion

In the late Holocene (4,000~3,000 a BP), climate started cooling again. The ice-core record from the Dunde Glacier in the Qilian Mountains indicates a cooling started ca. 4 ka BP, and reached the coldest period during 2,800~2,700 a BP. Hence, the cooling fluctuated until 1,000 a BP. This is the so-called Neoglaciation period in the late Holocene. With the uplifting QTP, climate kept cooling, and mountain glaciers advanced extensively. Three to four terminal and lateral morains were left behind in the Kunlun and Tanggula mountains, such as the Neoglacial lateral moains dated at 3,983~3,522 a BP in the Congce Ice Cap in the Kunlun Mountains (Zheng, 1990).

A string of pinos were formed at 4,250~4,300 m asl along the fault in eastern Xidatan along the QTH; intensive cryoturbations were developed at about 3,800 m asl on the first terrace of the Kunlun River south of Nachitai along the QTH. The thick layer of humus formed during the LHMP near the HMSSs 100 and 120 on southern slopes of Tanggula Mountains were re-frozen. Pingo groups 40 km east of Shiqu County Town, Sichuan Province on eastern QTP were formed at 2,925±175 a BP; those at the northern side of K65 along the Maqên-Changma'he Highway were formed at 3,925±185 a BP. Large polygons, gelifluctions and stone circles, and othe periglacial phenomena were extensively developed during the Neoglaciation period, such those on the Mt. Ri'yueshan (>3,450 m asl), Öla Mountain Pass (>3,750 m asl) along the QKH and northern slopes of the Bayan Har Mountains (4,000~4,100 m asl). All these paleo-permafrost and periglacial remains prove a relatively cold climate, when a 20-m-thik permafrost was developed near the Borehole No. 8 in Xidatan along the QTH.

By comparing spatiotemporal variations in these periglacial remains, it can be deduced that the LLP was then 300 m lower than that of preesent, and the MAAT, about 2°C lower than today. On the basis of intensive degradation of permafrost during the LHMP, permafrost reappeared, and expanded radially from the interior QTP, and reached the maximum permafrost extent in the Neoglacial period by 1,000 a BP, which was about 20%~30% larger than today. In the Neoglacial period, along the QTH the northern LLP was at 3,700~3,800 m asl south of Nachitai, and the southern LLP was at 4,400~4,500 m asl in the Damxung Valley. On the Chmar'he High Plain between the Kunlun and Tanggula mountains (>4,500 m asl), permafrost refroze downwards, forming a layer of epigenetic permafrost 30 m in thickness (Ding and Guo, 1982). This layer was detached with the residual permafrost of the LHMP. Therefore, so far there has been no buried or double-decked permafrost found on the Chumar'he High Plain along the QTH.

This contrasts with many places on northeastern QTP, such as Hua'shixia to Qingshui'he along the QKH, and to the east where buried permafrost and thawed nuclei (talik) have been discovered. This might be attributed to the fact that these areas are on the eastern margins of the plateau permafrost zone, and downward thawing during the LHMP reached depths of 15~25 m, but the epigenetic permafrost of Neoglaciation was thinner than 15~25 m, resulting in vertical detachment of permafrost and resultant buried and/or double-decked permafrost layers. It is also possible that in some areas, due to secondary (second-tier) climate warming, the Neoglacial permafrost was thawed to certain depths, resulting a mosaicked distributive features of interwoven multilayered permafrost and taliks (Jin *et al*., 2006a, 2007a, 2009; Chang *et al*., 2017). Cold air drainage could possibly be involved.

On the first terrace south of Yituli'he (50°32′N, 129°29′E) in the northern Da Xing'anling Mountains, Neoglacial ice wedges have been discovered and ^{14}C-dated at 3,600-1,600 a BP, indicating three cooling periods of 2,800 a BP (2.1 °C), 2,300 a BP (1.1°C) and 1,900 a BP (1.3°C) (Yang and Jin, 2010; Yang *et al*., 2015). It thus concluded that there was a cooling of about 2°C, and a southward shift of the SLP by about 2°N.

4.5 Medieval Warming Period (MWP) (1,000 to 500 a BP): relative Permafrost degradation

After the Neoglaciation, China experienced serveral small-scale climate fluctuations, among which the Sui and Tang dynasties (AD 581-907) were in warm periods. The warming started in Shang Dynasty (ca. 1,600 BC to 1,046 BC), reached maxima in Zhou (ca. 1,46 BC to 221 BC), Han (202 BC to AD 220) and till Tang dynasty (AD 618-907), with a warming of about 1.5°C for centuries, but there were also cooling in the Sui Dynasty (AD 581-618), and cooling kept to South and North States (AD 420-589) when it was cooler than today (Zhu, 1972). Because of short history to date, most paleo-periglacial landforms of this period were well preserved and the remains of paleo-permafrost were distinct on the QTP.

Pingos formed in Xidatan, K40 East of Shiqu, West Sichuan Province and K65 along the Maqên-Changma'he Highway during the Neoglaciation were thawed, forming pingo scars. The humus soils in the center of thawed depressions were dated at about 720~625 a BP, when permafrost had been thawed at these locations.

This was a period for regional permafrost degradation on the QTP. Downward thawing of permafrost reached the depth of about 10 m at lower elevations. For example, the lower layer of permafrost, as revealed at depths of 9.7~12.3 m in Borehole CK1 in Dinaran northeast of Huashixia and at depths of 11.6~15.2 m in Borehole ZK8 in Changma'he, was the residual permafrost during the MWP (Jin *et al*., 2006a, 2007a).

Accordingly, the upper layer of permafrost as found at depths of 7.5~9.0 m on the Chumar'he High Plain, and in the Fenghuoshan Mountains in particular along the QTH, was formed during the MWP. For example, there were two positions of paleo-permafrost tables in the Borehole CK224 on the Chumar'he High Plain: the upper one of the MWP at 8.4 m in depth, and the lower one of the LHMP at 16 m. Thick-layered ground ice were all identified under these permafrost tables (Xin and Ou, 1983). The degradation of permafrost during the MWP resulted in a higher LLP of about 150~250 m above the present LLP, while the SLP moved northwards by 1~2°N. As a result, the permafrost extent in China during the MWP was about 20% less than today.

4.6 Little Ice Age (LIA, 500 to 100 a BP) in the late Holocene: Relative permafrost expansion

The Little Ice Age (LIA) is the cold period in the 15th ~ 19th century, with the latest permafrost expansions and glacier advances, which was recorded in ice-cores and glacial deposits. In the ice-cores from the Dunde Glacier No. 1 in the Qilian Mountains, the three coolings occurred in AD 1420~1520, 1570~1680, and 1770~1890. The second cold period (16th and 17th centuries) was the coldest among the three, with a cooling of about 1.5°C colder than today.

It was a time when the QTP was drying and cooling, which was accompanied by permafrost expansion and thickening, and new permafrost islands were formed in the peripheries of the QTP. Along the QTH, a permafrost layer was formed by the downward freezing, which was re-attached with the upper paleo-permafrost (table) formed during the MWP in the late Holocene. For example, the humus layer at the HMSS 121 along the QTH formed since the last 780 a BP was refrozen. On eastern QTP, the thin permafrost of the LIA was unable to attach to the underlying permafrost layer, such as the permafrost layer found at depths of 1.5~8.0 m in Borehole ZK6 on the northern bank of the Ngöring Lake and at depths of 5.3~8.2 m in the water well in the Qingshui'he Town on the southern slope of the Bayan Har Mountains along the QKH (Jin *et al*., 2006a, 2006b)

Active rock glaciers, block fields, stone stripes, or other similar sorted patterned ground or ice-contained permafrost can indicate the occurrence of permafrost (Tian, 1981; Gao, 1983). Barsch (1978) first pointed out that rock glaciers could indicate the LLP of discontinuous alpine permafrost. Therefore, Jakob (1992) estimated the LLP of discontinuous alpine permafrost at about 5,560-5,360 m asl (sunny slopes) and 4,959-5,050 m asl (shadowy slopes) in the Kunbu Himalayas, Nepal on the basis of active rock glaciers and seismic geophysical data in the vicinity ogf Poklade Cliff (27°55′N, 86°50′E), whereas the lower limit of active rock glaciers there is at about 5,000~5,300 m asl. These results agree well with the calculated result from the Gauss curve for the location (≥ 5,080 m asl, 25°22′N) (Cheng and Wang, 1982). On the basis of the distribution of protalus and morainic rock glaciers, Owen and England (1998) deduced that the LLP of discontinuous permafrost should be higher than 4,000 m asl in western Himalayas and Karakurums in northern Pakistan and India. Similarly, it can be deduced that during the LIA, (inactive) stone fields and (inactive) stone stripes were above 4,130 m asl along the road side of Rizha Village, Darag County, Qinghai Province. At the lower limit of these stone fields and stripes, the underlying humic soils are dated at 422±85 a BP, which should be older than the overlying stone streams or stripes. Therefore, those inactive stone fields and stone stripes/streams were formed during the LIA. At present, the LLP at this location is at 4,300 m asl. Thus, the LIA had a cooling of about 1.0~1.5°C, a lowering of LLP by 150~200 m, and with a permafrost extent of 1.5×10^6 km^2, or about 15%~20% greater than today.

During the LIA, plateau lakes shrank continuously, and some small and medium lakes dried up. Most of the lakes became saline and salt lakes, such as the salt lake behind the HMSS 69 along the QTH, where silty soil under a 60-cm-thick salt crust was dated at 1,094±433 a BP; the silt under a 50-cm-thick salt layer in the Hajiang Salt Lake to the east of Ngöring Lake was dated at 1,080±260 a BP. In the meantime, those (semi)fixed sand dunes were re-activated on the surface, and covered by aeolian sand, result in worsening land desertification.

4.7 Recent warming (since 100 a BP, i.e., the 20th century): persistent permafrost degradation

During the last century, especially the last few decades, the effect of greenhouse gases may have caused and sustained climate warming. Large amounts of data indicate a global warming of about 0.3~0.8°C since AD1880; in particular, the climate since the 1980s has been the warmest since the meteorological record was commenced. During the last four decades, the MAAT in the permafrost regions on the QTP has risen by 1.12°C, at a warming rate of 0.025~0.030°C/a, much greater than that of the periphery non-permafrost regions (0.017~0.019°C/a) (Jin *et al*., 2011a). Particularly, since the 21st century, the climate warming has been accelerated, and mean annual ground surface temperature has risen by 1.34°C. The climate in Northeast China has risen by 1.7°C during the last 100 years, in which the Da Xing'anling Mountains has experienced the most pronounced warming: the last three decades in the 20th century have witnessed a rise in MAAT by 1.4~2.0°C. It is evident that during the last six decades, there have a clear patten in changes in ground surface temperatures. There was a cold period during the 1950s to 1970s, followed by a warming since the 1980s; the coldest occurred in the 1950s, with a departure of −0.8°C; the warmest occurred in the 2000s, with a departure of +1.1°C. However, the climate warming again was the most pronounced in the Da Xing'anling Mountains, with a warming rate of 0.038~0.040°C/a in the MAAT during the last 30 years (Luo *et al*., 2014). Climate warming has resulted in persistent permafrost degradation, and particularly since the 21st century, permafrost degradation has been accelerating. Areal extent of permafrost in China has been reduced to 1.59×10^6 km^2 from 1.59×10^6 km^2 (Zhou *et al*., 2000; Ran *et al*., 2012) .

4.8 Changes of permafrost in China during the last 20 ka: patterns, processes and trends

In summary, since the LLGM although there have been occasional permafrost expansions in cold periods, such as the Neoglaciation and LIA, the areal extent of permafrost in China in general has been on the decline under a fluctuatively warming climate (Table 1). The areal extent of permafrost during the LLGM was close to its maximum at 20 ka BP and the LHMP could have reached its minimum, despite the substantial expansions during the Neoglaciation and LIA. During the MWP and since the last century, China has witnessed the most intensive, rapid and extensive permafrost degradation since the LHMP, and this trend is currently being enhanced. Because of these changes, the areal extent of permafrost in China has shrunk from 5.30×10^6~5.40×10^6 km^2 at the LLGM/LLPMax to 0.80×10^6~0.85×10^6 km^2 at the LHMP/LLPMin, and then back to the present 1.59×10^6 km^2.

Table 1. Summary of changes in permafrost in China during the last 20 ka

Climate period	Absolute age	Changes in pf features	Climate & cooling（°C）	Change in SLP (°N)	Change in LLP (m)	Pf extent (10^6 km^2)	Percentof today (%)	Major direct evidence	Mjor indirect evidence	Major references
Local Last Glacial Max (LLGM) in Late Pleistocene	~20 to13~10.8 ka BP	Ice-wedges developed over the entire permafrost area	Cold/dry, 4-5 (NE China), 3-11 (N China), 7-9 (QTP)	S ↓4-5 (NE China)	↓1200-1400	5.3-5.4	>300	Cryogenic wedges of all types	Glacial landforms,ice cores, paleo-timberline, pollen, sandland.cold climate fauna & flora, models	Zhang, 1983; Xu & Pan, 1990; Wang & Bian, 1993; Tong, 1993; Pan & Chen, 1997; Cui *et al.*, 2004; Cheng *et al.*, 2006; Jin *et al.*, 2006a, 2007a, 2016；Chang *et al.*, 2011, 2017; Zhao *et al.*, 2013
Dramatic climate changes in early Holocene	10.8 to 8.5~7 ka BP	Relative stable & degrading permafrost	Drying/ cooling, then warming/ wetting, very unstable	Retreat, started to disappear on Sanjiang Plain	↑600-700	2.2-2.4	140-150	Pingo scars,sand wedges	Ice core, diatom, pollen, peat, sand dunes, …	Li，1982；Wang，1989；Li & Jiao，1990；Song & Xia，1990；Yao & Shi，1992；Tang & Shen，1996
MidHolocene Megathrmal Period (LHMP)	8.5~7 至 4~3 ka BP	Intensive degradation	Wet/warm，2~3 (most parts)，4~5 (QTP)，1.0~3.5 (N China)	↑N 3-4 (NE China)	↑300-500 (QTP, mts. in W China)	0.8-0.85	50	Ice wedges, buried pf, ground ice, thermokarst lakes, paleopf gelifluctions, pingo scars	Mineral analysis, peat, ice-core (δ ^{18}O), sand dunes, human fire use, timberline, pollens	Guo *et al.*，1981；Xing & Ou，1983; Tong, 1993; Tang & Shen，1996；Sun，1998; Jin *et al.*, 2006a, 2007a; 2009, 2016; Shi *et al.*, 2006；Yu *et al.*, 2013
Late Holocene cold period (Neoglaciation)	4~3 to 1 ka BP	2nd expansion	Fluctuatingly cooling −2 ~ −1 (NE China, QTP)	S↓2 (NE China)	↓~300（青藏）	1.9-2.1	120-130	Pingo scars, cryoturbations, polygons, gelifluctions, ice wedges	Ice core, glacial till,peat, detached or buried pf	Ding & Guo, 1982; Zheng, 1990; Jin *et al.*, 2007a, 2009, 2011b, 2016; Yang & Jin, 2010；Yang *et al.*, 2015; Chang *et al.*, 2017
Late Holocene warm period (MWP)	1~0.5 ka BP	Relative retreat	Wet/warm, 1.5	↑N 1~2	↑~150-250	1.4-1.5	80	Pingo scars, buried pf, ground ice	Phenology, humus	Zhu, 1972; Xing & Ou, 1983; Jin *et al.*, 2006a, 2007a
Little Ice Age (LIA)	500~100 a BP	Relative expansion	Fluctuatingly cooling −1.5~ −1	S↓1~1.5	↓~150-200	2.1-2.2	115-120	Paleopf, detached pf, stone fields & streams	Ice-core, till, humus, silt in salt lake, sand land	Jin *et al.*, 2006a
Recent warming	100~0 a BP	Persistent degradation	Warm/dry 0.3~0.8	↑N 0.5-1.5	↑50~100	1.59	100	Ground temp, LLP/SLP, areal extent survey abd measurement	Measurement and thermokarsts	Jin *et al.*, 2006a, 2011b, 2016; Ran *et al.*, 2012

5. Conclusions and prospects

Since the last 20 ka, China has experienced many major climatic, environmental and geocryological changes, such as the LLGM/LLPMax at the end of the Late Pleistocene and the LHMP/LLPMin in mid-Holocene. On the basis of paleo-permafrost and periglacial remains, in combination with glacial, palentological and other records, it is estimated that during the LLGM, in comparison with today, the MAAT was about 7~9°C colder on the QTP, 4~5°C colder in the Da and Xiao Xing'anling Mountains, and 5~12°C colder in arid regions in North China; during the LHMP/LLPMin, in comparison with today, the MAAT was about 4~5°C warmer on the QTP, 3~4°C warmer in the Xing'anling Mountains, and 1~3.5°C colder in arid regions in North China. Accordingly, permafrost has changes substantially. The latest data indicate a present extent of permafrost in China at 1.59×10^6 km^2, shrinking from 5.3×10^6 ~ 5.4×10^6 km^2 during the LLGM/LLPMax, or three times of today. However, during the LHMP/LLPMin, that was reduced to 0.80×10^6 ~ 0.85×10^6, or about 50% of the current permafrost area. That in other periods falls in between the LLPMax and LLPMin.

According to the ages and distributive features of paleopermafrost in China, after the delineation of permafrost patterns in the LLPMax/LLPMin, the evolutionary processes of permafrost in China can be divided into seven periods: (1) LLGM/LLPMax in the Late Pleistocene (~20 to 13~10.8 ka BP); (2) Dramatic changes in climate and permafrost in early Holocene (10.8 to 8.5~7 ka BP); (3) local Mid-Holocene Megathermal Period (LHMP, 8.5~7 to 4~3 ka BP); (4) Late Holocene cold period, or Neoglaciation (4~3 to 1 ka BP); (5) Late Holocene warm period (Medieval Warm Period, MWP, 1,000 ~ 500 aBP); (6) Late Holocene cold period (Little Ice Age, LIA, 500~100 a BP), and; (7) Recent warming period (118~0 a BP, 20th century upto date). Paleo-climate, -geography and -environment, and permafrost features were reconstructed for the seven periods.

The formation, development and changes of permafrost in China are complicated due to the combined influences from climate changes of varied spatiotemporal scales and human activities and subsequent interwoven impacts. They have resulted in concurrent processes of permafrost formation and development as well as degradation at the same time in different regions and at different depths. This is particularly true for shallow permafrost and the permafrost layer in the peripheries of permafrost zones where climatic fluctuations of different amplitudes and intensity have induced repreated freezing and thawing, forming mosaicked distributive patterns of permafrost and talik. As a result, the dating of permafrost remains a major challenge in Quaternary geocryology in China. In particular, rapid, large-scale and intensive economic development have tremendous adverse impacts on Quaternary permafrost and periglacial landforms, it deems necessary to timely rescue and study these precious evidence and records.

Permafrost should have developed in Tarim and Zhunger basins in Xinjiang, West China during the LLGM/LLPMax taking into account of their latitudes and elevations. However, so far no reliable paleo-permafrost and -periglacial evidence has been discovered in the interiors of the two basins. Was there permafrost in history? This is also true for other sand lands and deserts/gobi in North China and adjacent regions or countries. The relationships between permafrost and deserts in China and bordering regions await for reliable data and further investigations.

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