



# **Quaternary Permafrost in China: Framework** and Discussions

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Abstract: The framework of Quaternary permafrost in China was reconstructed for the first time on the basis of available periglacial, glacial, and other proxies. During the Early Pleistocene (2.68–0.80 Ma BP), permafrost advanced southwards to 47–50° N in northern China and possibly occurred in alpine regions in western China. During the Middle Pleistocene (800-130 ka BP), permafrost occurred extensively on the Qinghai-Tibet Plateau (QTP) and in alpine or mountainous regions of northern, western, central, and northeastern China. The Great Interglacial occurred afterward and before the Last Glaciation, but the evidence of permafrost for this period has been seldom found. Permafrost evolution of the Last Glaciation (72-19 ka BP) in China is divided into: Expansion (72~50 ka BP), degradation (50-26 ka BP), and intensive expansion during the Last Permafrost Maximum (LPMax, 26–19 ka BP) with a permafrost extent of  $5.3 \times 10^6 \times 5.4 \times 10^6$  km<sup>2</sup>, and when major features of present permafrost took shape. Permafrost fluctuated during the Younger Dryas (12.9–11.7 ka BP). Since the Holocene, permafrost in China expanded and retreated to lesser extents, forming the current permafrost environment. The Holocene evolution of permafrost was divided into: Unstable climate but stable permafrost during the early Holocene (11.7~8.5–7.0 ka BP); permafrost degradation during the Last Permafrost Minimum (LPMin, or the Holocene Megathermal; 8.5-7.0~4.0-3.0 ka BP) and the Medieval Warm Period (MWP; 1.0~0.5 ka BP); permafrost expansion during the Neoglaciation (4.0–3.0~1.0 ka BP) and the Little Ice Age (LIA; 0.5~0.1 ka BP); and recent permafrost degradation (20th century to the present). However, this review paper only provides the framework of Quaternary permafrost in China and some preliminary discussions. Many key questions await further investigations.

Keywords: permafrost evolution; periglacial remains; climate changes; permafrost extent; China

## 1. Introduction

In the Quaternary (ca. 2.6 Ma BP to present), multi-cycles of changes in glacial–interglacial climates and environments occurred in China [1–6]. These climatic fluctuations controlled the cyclic aggradation, stabilization, and degradation of permafrost [7–11]. In western China, in the Early

Pleistocene, glaciers started to occur in some alpine and high-plateau regions, and permafrost and periglacial phenomena also began to develop, initiating the development of the cryosphere in China [12].

Formal studies on permafrost evolution have been carried out in China ever since the late 1950s–early 1960s. Based on the divisions of Quaternary glaciations, Zhou (1965) preliminarily estimated that the existing permafrost on the Qinghai-Tibet Plateau (QTP) was the result of the Last and Penultimate glaciations [13]. In the 1960s–1980s, additional data accumulated on the evidence for the remains of Quaternary permafrost (e.g., [14–18]). However, by then, no data established the survival of earlier permafrost through the Last Interglacial [7,9,11,19]. Since the 21st century, with rapidly improving dating technologies and their applications, more reliable and accurate data on past permafrost have greatly facilitated the development of Quaternary geocryology in China. Chinese geocryologists have studied the formation, aggradation, stabilization, and degradation of permafrost in different parts of China in various Quaternary periods (e.g., [9,11,12,20–24]).

The Last Glacial Maximum (LGM, 26~19 ka BP) is regarded as the latest period of massive glaciations in China (e.g., [8,12,25–29]). Thus, permafrost extensively developed and expanded in China, resulting in the Last Permafrost Maximum (LPMax), shaping the main body of existing permafrost in China [7,9,11,13,19,30–32]. Later on, permafrost degradation in the Holocene Megathermal Period (HMP, 8.5–7.0~4.0–3.0 ka BP) resulted in the Last Permafrost Minimum (LPMin) [9,11,19]. In addition, a series of post-LPMin evolutionary processes have reshaped the permafrost in China, forming its present distributive patterns [9,11,30,33–35].

In this paper, for the first time, the framework of formation and evolution of permafrost and changes in periglacial environments in China during the Quaternary are preliminarily reconstructed and briefly discussed on the basis of spatiotemporal distributive patterns and regional differentiations of soil strata and ages of paleo-permafrost and periglacial remains, in addition to glacial geology and landforms (Table S1 in Supplementary). Based on large amounts of periglacial remains and past permafrost, together with references to glacial landforms and deposits, loess, ice- and lake-cores, and other paleo-climatic and -environmental proxies, the framework of Quaternary permafrost history in China is proposed and discussed. This may provide a starting point for rebuilding and elaborating the history of past permafrost and some support for related studies in China and beyond.

#### 2. Study Methods and Region

## 2.1. Study Methods for Quaternary Permafrost

The presence of permafrost is generally indicated by the formation and preservation of ground-ice, although permafrost is defined as a thermal state of the ground. At present, the time of ice formation is generally regarded as the age of permafrost formation. However, under a fluctuating climate, ground-ice is vulnerable to melting, forming some unique structures and textures, i.e., cryostratigraphy, and associated periglacial micro-reliefs and landforms and their pseudomorphs or casts, which may be preserved to a varying degree. In the meantime, most climatic and environmental indications of past periglacial remains are not well known, challenging even the most experienced Quaternary geocryologists (e.g., [36–38]).

In the field, researchers always need to estimate the timing of permafrost formation and thaw based on many geo-environmental variables, such as elevation, latitude, geomorphological positions, and modern air and ground temperatures. Thus, for Quaternary geocryologists, extensive and in-depth understanding and experience for fieldwork are necessary for properly judging the remains of past permafrost or periglacial environments, in addition to the data from Quaternary glacial and periglacial landforms and deposits, and hosting and adjacent strata and relative positions, ice-cores and lacustrine sediments, ground-ice isotopes, proxies for Quaternary geology, paleo-fauna, -flora, -climate and -environments, as well as dating data of soil strata. In addition, numerical models can be used for paleo-reconstruction and integration of permafrost and periglacial environments (e.g., [39–44]), in order

to better evaluate the formation time, development states, areal extents, and evolutionary processes of Quaternary permafrost.

#### 2.2. Criteria and Indicators for Quaternary Permafrost

The criteria and indicators for the presence of former permafrost can include active and inactive ice wedges and their casts, deeply buried (residual) permafrost and layered or massive ground-ice, paleo-permafrost tables, pingo scars, cryoturbations or involutions, sand, soil, and gravel wedges, and cryogenic polygons, inactive or relic rock-glaciers (e.g., [45]), and block fields, among others. They can also include mineralogical and paleo-floristic or -faunistic proxies and inversion methods from accurate permafrost temperatures at depths. However, these indicators or criteria produce multiple results. Thus, reliable conclusions can only be achieved through comprehensive synthesis and systematic integration of all available criteria and indicators, as well as spatiotemporal inter-comparisons and model simulations and prognosis at various spatiotemporal scales (e.g., [37,46]).

In general, responses of permafrost to climatic and glacial changes exhibit a delay with depth. In the meantime, the relics left on the ground surface by the preceding permafrost evolution processes or events could be damaged or removed by the next greater event, increasing the difficulty for past permafrost rebuilding. Thus, more remains and evidence of past permafrost and periglacial environments are found in more recent time. Thus, paleo-reconstruction is increasingly more accurate with proximity to the present.

As a key indicator for judging the presence and thermal state of past permafrost, paleo-permafrost temperature, or paleo-mean annual ground temperature (Paleo-MAGT), can either be deduced by the paleo-mean annual air temperature (Paleo-MAAT) or be inversed by various cryogenic wedges. Through field observations and laboratory studies, Romanovskii (1977) summarized the relationships between the types of hosting soils, soil moisture contents, and ground temperatures with cryogenic wedge structures: The coarser the grains and the drier the soils, the lower the maximum paleo-MAGT for the formation of cryogenic wedge structures [47]. These traditional methods of inversing paleo-MAGT by using cryogenic wedge structures have been extensively adopted in Quaternary geocryology in China (e.g., [9,11,17,20,30,48–51]). However, they only provide data on the maximum values of MAGT during wedge formation. The actual values of MAGT could have been much lower.

#### 2.3. Existing Permafrost in China

Existing permafrost in China can be divided into the latitudinal and elevational (alpine, high-plateau, and mountain) permafrost (Figure 1). The existing permafrost in the Da and Xiao Xing'anling Mountains in Northeast China can be roughly grouped into latitudinal permafrost because of generally low elevations. Because of the strong influences of local factors, this latitudinal permafrost is widespread, ecosystem-protected permafrost in the Xing'anling Mountains in Northeast China and the Outer Baikal region in Eastern Siberia, thus it is also dubbed as the Xing'an–Baikal permafrost [10]. It shares the common features of both latitudinal and mountain permafrost.

The main features of permafrost in China are described as follows:

- (a) Latitudinal permafrost. In China, it occurs mainly in the northern Da and Xiao Xing'anling mountains and northern Songhua-Nen rivers plain (46°30′~53°33′ N). Permafrost is mainly controlled by latitude and longitude (or continentality/aridity), as well as elevation in mountainous regions, extending southwards along the directions of the northern Da and Xiao Xing'anling mountains; it is also strongly influenced by local geo-environmental factors, such as snow and vegetation covers. As a result, the southern limit of latitudinal permafrost (SLLP) winds across the northern part of Northeast China at the MAAT isotherms of −1 °C (west)~0 °C (middle)~ +1 °C (east) [10,30,52].
- (b) Elevational permafrost occurs extensively in mountainous regions of West China. In particular, the QTP and periphery mountains host the most extensive elevational (alpine or high-plateau) permafrost in the world [53] (Figure 1).

- i. High-plateau permafrost. Permafrost of various types occurs extensively on the QTP and the Pamir Plateau in western China, displaying a distinct 3-dimensional zonality of elevation, latitude, and longitude/aridity [53,54], in regions with a MAAT of -3.5 ~-2.0 °C or lower [7,55–57].
- ii. Alpine permafrost. Alpine permafrost is mainly found in the Altai, Tianshan, and Qilian mountains in western China, as well as the periphery mountains of the QTP. Isolated patches of alpine permafrost also occur in high mountains in Central and East China, such as the Taibai, Qinling, Wutai, and other mountains. Elevation controls the distribution of alpine permafrost, generally with a northward and eastward declining lower limit of alpine permafrost (LLAP) [9,34,55–57].
- iii. Mountain permafrost. Permafrost in the southern Da Xing'anling and Changbai mountains is classified as mountain permafrost because of relatively lower latitudes and higher elevations (1000–3000 m above mean sea level (amsl)), but not yet reaching the elevations of alpine or high-plateau (generally >3000 m amsl) regions [7].



**Figure 1.** Distribution of permafrost in China during the local Last Glaciation Maximum/Last Permafrost Maximum (local LGM/LPMax) versus that of the present (existing permafrost) (updated from [11]). Note: The areas of northern deserts were left blank (grey) because of the paucity of evidence for past permafrost.

The areal extent of existing permafrost in China is  $1.59 \times 10^6$  km<sup>2</sup>, mainly including high-plateau permafrost,  $1.05 \times 10^6$  km<sup>2</sup>; latitudinal permafrost,  $0.24 \times 10^6$  km<sup>2</sup>, and; alpine permafrost,  $0.30 \times 10^6$  km<sup>2</sup> [11,23,30,55,58,59]. Large parts of North China are now in the zone of seasonal frost. However, these regions were once occupied by Quaternary permafrost or glaciers, which expanded

and retreated under fluctuating climates, leaving behind a large amount of remains of past permafrost and periglacial landforms and deposits [9,11,30].

#### 2.4. Estimation of Quaternary Permafrost Extents

It is essential to reliably judge the types of cryogenic wedges. Particularly, the most reliable evidence comes from inactive ice-wedges or ice-wedge pseudomorphs and sand wedges. Paleo-reconstruction of permafrost and periglacial environments would rely on climate conditions and elevation for the formation of various types of cryogenic wedges, spatial relationships of these evidence, soil strata, and their positions, among many others.

Only a few evidence or remains of permafrost and periglacial environments and processes of the early Quaternary have been reasonably preserved and discovered in some rare cases. Thus, the division of permafrost development in the early Quaternary has to rely heavily on glacial and interglacial stages and paleo-stratigraphy (e.g., [1]). After the inversions of paleo-MAGTs from cryogenic wedges, corrections or adjustments are deemed necessary for the elevation/uplifts of the QTP and rising latitudes. At present, the MAGT declines by 6 °C/km with rising elevation and 1 °C/°N with northern latitude [7]. This translates into an elevational compensation for present latitudinal change of 160–165 m/°N, which is substantially smaller than the approximation of 309–385 m/°N during the LPM as estimated by [32]. Since the Late Pleistocene, the QTP has uplifted by 1000–1500 m, and by 500 m since the Last Glaciation. In addition to the SLLP or LLAP, and on the basis of corrected or adjusted paleo-MAATs or -MAGTs, Quaternary permafrost extents in China can be determined.

We have reviewed and summarized more than 300 ages for paleo-permafrost and -periglacial landforms, including those of our research team, and have selected 122 crucial data in Table S1 as the basis for dividing the stages of formation and development of permafrost and periglacial environments.

#### 3. Results

In the Quaternary, there have been many cyclic climatic and cryospheric changes, resulting in the formation, expansion, and retreat of permafrost and great hydrological, ecological, and other impacts. Glaciers and permafrost in China also underwent numerous advances and retreats, substantially shaping landscapes, ecosystems, and hydrogeology and flow systems, particularly on the QTP and other high mountains. For example, in the Zanda Basin, Ngari Plateau on the western QTP, involutions, periglacial deposits, and cold-climate paleo-flora and -fauna fossils have been extensively discovered in the upper part of the alluvial-fluvial sediments of the Early Pleistocene at 2.68–2.45, 2.45–2.11, 2.11–1.49, and 1.49–1.36 Ma BP, indicating at least 20 evident climate fluctuations of various amplitudes and durations [60]. It should be noted that all those phenomena are not indicative of permafrost themselves, but of cold climate conditions. After the collision of the Indian and Asian plates, the Himalaya uplift started at the Late Eocene to the Early Oligocene, the QTP and a series of huge mountain ranges have been formed at the high-elevations in Asia. Since the late part of the Early Pleistocene, glaciers have started to build up above the snowline, preluding the Quaternary glaciations in China. During 800–600 ka BP, the Antepenultimate Glaciations occurred above 3000–3500 m amsl on the QTP and in other high mountains in West China. During the Pleistocene, the climate was intermittently cooling with large fluctuations, and severe periglacial climates prevailed in North and West China, resulting in the formation and evolution of permafrost, and subsequently many archives of permafrost and periglacial remains and landforms.

The evolution of permafrost in China can be roughly divided into four major epochs as the Early, Middle, and Late Pleistocene and the Holocene. Because of very limited available data for paleo-permafrost during the Early Pleistocene (2.68–0.80/0.78 Ma BP), only relative development and distribution of permafrost can be briefly estimated on the basis of glacial geology. During the Middle Pleistocene (800/780–130 ka BP), four major glaciations and the Great Interglacial occurred, among which the late stages of the Penultimate Glaciations may have seen the largest glaciations in China during 300–130 ka BP, possibly even greater than the Last Glacial Maximum (LGM; 26–19 ka BP).

Relatively, in China, there are richer data on past permafrost since the Late Pleistocene. Thus, more stages of permafrost evolution can be further divided and better quantified. During the Late Pleistocene, six periods of climatic evolution can be distinguished as follows: (1) Last Interglacial (ca. 130 to 72 ka BP); (2) Early Stadial of Last Glacial (72–60 ka BP); (3) Last Glaciation Interstadial (60–26 ka BP); (4) LGM or LPMax (26–19 ka BP); (5) Last Deglacial (19–12.9 ka BP); and (6) Younger Dryas (12.9–11.7 ka BP). With the largest impacts on the formation, development, and patterns of existing permafrost in China, the LGM formed the major body of current permafrost in China. Since the start of the Holocene (since 11.7 ka BP), relative to the LPMax, permafrost in China has been degrading in general, although with some expansion periods under cold climate fluctuations, such as the Neoglaciation and Little Ice Age (LIA).

#### 3.1. Early Pleistocene (2.58~0.78 Ma BP)

Based on results from paleo-glacial and paleontological records (e.g., [8]), cold climates prevailed on the QTP and in high-mountainous regions in West China, and the northern part of Northeast China during the Early Pleistocene, when the QTP rose to average elevations of 2000–2500 m amsl, with some high peaks above 4000 m amsl. Under strong influences of monsoonal climates, small-scale glaciations occurred on the tops of some major mountains.

#### 3.1.1. Cold-Climate at the Beginning of the Early Pleistocene (2.68~1.17 Ma BP)

Zhu et al. (2006) revealed extensive occurrences of cryoturbations and cryogenic wedges and alpine climate paleo-flora, -fauna, and -microsomes fossils in periglacial deposits and alluvial-fluvial sediments of 2.68–2.45 and 2.45–2.11 Ma BP (cool-dry climate), 2.11–1.49 Ma BP (drier climate), and 1.49–1.36 Ma BP (cold-dry steppe climate). Cryoturbations in the Zanda Basin and adjacent areas can be divided into four periods [60]. Those of the first period (upper layer), with cryoturbated wavelengths of 0.4~0.6 m, are identified in the first section of the lower Qangzê Formation of Early Pleistocene. Those of the second, larger in widths and heights, and with distortions, were occasionally seen in the second section of the middle Qangzê Formation. In the Shampa area at ~3400 m amsl, at the third section of the Qangzê Formation, wavy cryoturbations were well developed and occasionally seen with upturning and distortions in sandstone and silty fine-sandstone. In the fourth section of the Qangzê Formation, cryoturbations of smaller wavelengths (centimeter scale) are often mentioned, sometimes with more than ten layers of cryoturbations. In summary, in the Qangzê Formation, cryoturbations are visible from occasional to often, sparse to dense, from few to numerous, from widely occurring to occasional distortions, indicating a cooling climate. In the meantime, occurrences or records of pollens, ostracods, and rhino fossils and others in glacial-alluvial sediments also confirm the temperature decline. The pollen assemblage in the Qangzê Formation is dominated by herbs, mainly including Chenopodiaceae and Artemisia, occasionally with Picea and Quercus and tropical pollens, suggesting a dry-cold alpine tundra in the northern Himalaya Mountains at that time [60].

The formation of the Loess Plateau started at ca. 2.5 Ma BP in association with the uplifting of QTP and resultant climatic and environmental changes [61]. However, only trace glacial evidence was found in some high mountains in Central, North, and Northeast China, such as Qinling, Wutai, Changbai, and Huanggangliang mountains. In conclusion, the occurrence of the Early Pleistocene permafrost could be possible in China, but further studies will be necessary because most identified indicators for paleo-permafrost point to a later time.

3.1.2. Himalaya-Shishapangma (Xixiabangma) Glaciations (1.17~0.80/0.78 Ma; Marine Isotope Stage (MIS) 36~20)

On the northern flank of the Himalayas on the southern QTP and in the Kunlun Mountains on the northern QTP, some glacial tills and moraines were dated at 1.17~0.80/0.78 Ma BP (MIS 36~20) and regarded as the evidence of Himalaya-Shishapangma (Xixiabangma) and/or Wangkun-Kunlun Glaciations (e.g., [8,12,62–66]). Cryogenic involutions were also discovered in the lacustrine clayey soils

of the Early Pleistocene in the basin near the Kunlun Mountain Pass along the Qinghai-Tibet Highway from Golmud, Qinghai Province to Lhasa, Tibet Autonomous Region, China, where pollen records from these sediments and glacial snowline depression indicated a MAAT of ca. 7~8 °C lower than the present, suggesting possible permafrost development then [14,67]. However, only limited scales of morainic tills have been identified so far, suggesting small glaciations on some high peaks on the plateau margins during the Early Pleistocene, but most parts of the plateau remained un-glaciated [68]. Permafrost may have developed on the QTP at limited scales during the Early Pleistocene [33].

Periglacial remains were also discovered by Gravis et al. (1974) in the Early Pleistocene lacustrine sediments of the northern Khangai Mountains (47–50 °N) in Mongolia. In Northeast China, many cryogenic involutions have been extensively identified in soil strata of the Baishan Group of the Early Pleistocene [69–71]. An estimation based on the occurrences of these periglacial remains, in addition to latitudes and elevations of northern parts of Northeast China (>50° N) and the Khangai Mountains in Mongolia, suggests the possible occurrence of permafrost in cold periods of the Early Pleistocene [7].

On the Ordos Plateau in North China, a series of deposits consisting of aeolian sands, loess and upward thinning paleosols, and weakening percolation indicate an evident temperature decline since the beginning of the latter half of the Early Pleistocene (ca. 1.1 Ma BP) and a transition of the landscape to windy and cold-dry (semi)arid deserts, alternating many times with steppes, meadows, and shrublands, with shortening and less intensive warm periods [72]. The Ordos Plateau witnessed 11 stages of sand-dune mobilization under extremely cold-dry climates, seven stages of dune fixation, and eight stages of loess deposition under dry-cold climates [73].

In addition, Chen et al. (1990) reported cryogenic involutions and ice-wedge casts from the end of Early Pleistocene to early Middle Pleistocene on the third terrace of a tributary of the Hanjiang River at Zhongxiang on the Jiang (Yangtze)-Han (Hanshui) Rivers Plain in East-Central China [74]. Wedge-like thick-layered sands and gravels were thrust into the upper part of the Early Pleistocene strata, with a TL-dating at 1.106 Ma BP in the ferromagnetic crust and the interlayer in between. Cold-climate fauna fossils, such as oriental saberdon (*Stegodon orientalis*), Chinese rhinoceros (*Rhinoceros sinensis*), and molar teeth of Yunnan horse (*Equus yunnanensis*), key elements of the Liucheng Fauna of South China, were identified in these gravely sand layers. Relative warm interglacials occurred during 1.2–0.9 Ma BP [75]. Permafrost should have disappeared then. Unfortunately, up to now, direct and indirect evidence of permafrost and periglacial remains are still grossly inadequate to draw reliable conclusions on the distribution and other properties of permafrost in China in the Early Pleistocene.

#### 3.2. Middle Pleistocene (800/780~130 ka BP)

In the Middle Pleistocene (800/780~130 ka BP), the climate was characterized by significant and frequent glacial–interglacial transitions [76]. Thus, climatic and cryospheric changes were also dramatic, with large-scale advances and retreats of glaciers and permafrost.

## 3.2.1. Wangkun-Kunlun Glaciations (800/780~620 ka BP; MIS 18/20~16) and possibly concurrent Antepenultimate-Naynayxungla (Nieniexiongla) Glaciations (720~500 ka BP; MIS 18~16)

At the beginning of the Middle Pleistocene (800/780–600 ka BP), the climate was cold, and the blockage of the QTP to the Southwest Indian Monsoon started to show up. In China, the largest Quaternary glaciations occurred on the QTP and high mountains in West China, with a glacier extent of >500,000 km<sup>2</sup>, as represented by the Antepenultimate-Naynayxungla (Nieniexiongla) (800/780~620 ka BP; MIS 16~18/20), generally identified by morainic platforms in U-shaped glacial troughs, such as those at the Kunlun Mountain Pass, at Damxung in the Nyénqên Tanggula Mountains, at Yushanping in the Yulong Snow Mountains, and at Daocheng in Western Sichuan Province [8].

Cao et al. (1989) discovered ice-wedge casts and associated cold-climate paleo-flora, -fauna, and -microsomes fossils in soil strata of 900~730 ka BP at Zhoukoudian, Beijing [77]. This was at a time when the QTP rose to ca. 3000 m amsl in average elevation [78,79], with the Antepenultimate Glaciations

under a cold plateau climate (MAATs at  $-17 \sim -14$  °C) [14,67]. However, until now, direct evidence or remains of Middle Pleistocene permafrost have seldom been discovered in the naturally exposed profiles, such as that discovered on the northern shore of the Qinghai Lake on the northeastern QTP [80]. Primary sand wedges were discovered in eastern Gangcha County-town and Quanji Village, Gangcha County, Qinghai Province, with wedge-filled sands at the bottoms of three wedges Electron Spin Resonance (ESR)-dated at 774 ± 70, 773 ± 70 and 229 ± 20 ka BP in Quanji Village and only 197 ± 18 ka BP in the eastern Gangcha County-town. The first two primary cryogenic wedges were formed during the Kunlun Glaciations (780~620 ka BP; MIS 18/20~16), implying a harsh permafrost environment under a cold climate and cryospheric environment (MAAT <-10 to <-7.5 °C) on the northern QTP at the beginning of the Middle Pleistocene, or at least 9–12 °C colder than the present.

Fotiev et al. (1974) found ice wedges in the Lena-Viliuyi lowlands (64° N) in Central Yakutia, Sakha Republic, Russia formed during the cold periods of the Middle Pleistocene, which have survived until the present day [81,82]. Ice-wedge casts of the same period are extensively distributed as far south as 56° N. Gravelly ice-wedge casts of similar ages were also excavated at the Tianchi Forest Farm of the middle Da Xing'anling Mountains (48° N) [7]. This serves as an indicator for the expansion of permafrost from Siberia into Mongolia and further to Northeast and North China, as far as the Songhua-Nen rivers plain at 45~46° N.

#### 3.2.2. Zhonglianggan Glaciations (480~420 ka: MIS 12)

As a major glaciation of ca. MIS 12 with an ESR date at 462.9 ka BP [83,84], the Zhonglianggan Glaciations were widely recognized in many mountains in West China, such as in the Gaowangfeng moraines, with ESR ages at 471.1 and 459.7  $\pm$  46 ka BP, in the headwater area of the Urumqi River in the middle Chinese Tianshan Mountains [83,85,86]; glacial till at the Tumor Mountains (ESR ages at 440.6  $\pm$  41.7 and 418.9 ka BP) in the southern part of the Chinese Tianshan Mountains [87,88], and Ganhaizi glacial till in the Yulong Snow Mountains in Yunnan Province in South China (ESR age at 530~450 ka BP) [89]. Unfortunately, until now, no permafrost or periglacial remains of MIS 12 have been reported in China.

#### 3.2.3. Penultimate-Guxiang Glaciations (300~130 ka; MIS 6)

During the late part of the Late Pleistocene (300–130 ka BP), cold climates resumed above 3000 m amsl on the QTP [78,79]. Evidence has revealed the greatest glaciations on the QTP, i.e., the Penultimate Glaciations, at ca. 300–130 ka BP, with glacial extent possibly larger than that of the LGM. In particular, a cool and moist climate prevailing on the eastern QTP concurred with the Gong'he Movement, characteristic of rapid uplifts [90,91], facilitating the glaciations. The Guxiang Glaciations in the eastern Nyénqên Tanggula Mountains are typical of the Penultimate Glaciations on the QTP, with a CRN-<sup>10</sup>Be till age of  $136.5 \pm 15.8 \sim 112.9 \pm 16.7$  ka BP (i.e., MIS 6) [92]. Penultimate glacial landforms also have been identified and dated in many other regions, such as the Gongger, West Kunlun, western Nyéngên Tanggula, Tanggula, Diancangshan, Qilian, and Chinese Tianshan mountains. The MAAT was lowered to -17~-14 °C as inferred by pollen records and lowered paleo-snowline [67]. Permafrost should have extensively developed on the QTP. This deduction was further supported by extensive wedge-like structures on the northeastern QTP, such as those in the sand and gravel layers at Da'heba (3500 m amsl), Xinghai County, southern Qinghai Province, where sand and gravel wedges have been identified in groups together with intensively deformed cryoturbations. Fine sands filling in the wedges was TL-dated at  $135.7 \pm 10.5$  ka BP [49]. The maximum paleo-MAGT for ice wedges in sands and gravels wedges should be no higher than  $-8 \sim -7 \degree C$  [47]. Thus, the paleo-MAAT should be at least ca.  $-11 \sim -10^{\circ}$ C, or  $10 \sim 9^{\circ}$ C lower than the present, implying well-developed plateau permafrost.

On the northern shore of the Qinghai Lake, sand wedges were discovered in eastern Gangcha County-town and Quanji Village of Gangcha County, Qinghai Province, with wedge-filled sands at the bottoms of the three wedges ESR-dated at  $774 \pm 70$ ,  $773 \pm 70$ , and  $229 \pm 20$  ka BP in Quanji Village, but only  $197 \pm 18$  ka BP to the east of Gangcha County-town [80]. The latter two primary

cryogenic wedges ( $229 \pm 20$  ka BP in Quanji Village and  $197 \pm 18$  ka BP to the east of Gangcha County-town) were formed during the Guxiang Glaciations (300–130 ka BP), implying a harsh permafrost environment under a very cold (<–10.0 to –9.5 °C) climate at the beginning of the Middle Pleistocene, i.e., a paleo-MAAT of at least 11–12 °C colder than the present. However, we should be cautious with the two older datings, since they oppose the other much younger datings of 229 and 197 ka BP, as discussed in the previous Section 3.2.1. The occurrence of the two datings of 774 and 229 ka BP in wedges at the same stratigraphic position might be due to contamination of sampling, such as those of sediments falling down from the wedge wall.

Ice-wedge casts were also identified in loess layers at Yangsigezui ( $39^{\circ}59'$  N,  $111^{\circ}18'$  E; 1231 m amsl) in the Zhunger Banner, Inner Mongolia Autonomous Region in North China, with an ESR-dated wedge-filled sand at 132.0 ± 1.3 ka BP [24]. This suggests the possible development of permafrost on the Loess Plateau during the late part of the Middle Pleistocene, with a LLAP at  $36^{\circ}33'$  N between  $105-118^{\circ}$ E and  $40^{\circ}20'$  N to the east of  $118^{\circ}$  E (the Tai'hang Mountains) because of lowered elevation by 600 m and with a LLAP at 3100 m amsl at 29°N on the southern margin of the QTP and 2000 m amsl at  $36^{\circ}$ N on the northern margin [11]. Thus, latitudinal and alpine permafrost joined in the vicinity of Lanzhou (the Liupanshan Mountains), indicating a decline in air temperature by about 10–15 °C, taking into account the plateau uplift of about 1000–1500 m since the Late Pleistocene [78].

#### 3.3. Late Pleistocene (130~11.7 ka BP)

The climate fluctuated dramatically during the Late Pleistocene (130~11.7 ka BP). As shown in Table S1, the majority of existing permafrost and periglacial remains in China was formed and evolved since the Late Pleistocene [9,11,30–32,93]. Based on these data and climate fluctuations, six evolutionary periods of permafrost and periglacial environments in China since the Late Pleistocene can be distinguished as follows.

#### 3.3.1. Early Glacial Stadial (ca. 72-50 ka BP) of Last Glaciation (LG): Permafrost expansion

During the Last Interglacial (130–72 ka BP), direct evidence for permafrost has not yet been found. Starting from 72 ka BP, the climate cooled sharply, resulting in the Last Glaciations (LG) in China. Alpine glaciers developed in western China, as evidenced by two sets of glacial tills at Yangbajing in the western Nyénqên Tanggula Mountains, with an ESR-dating of  $72.1 \pm 6.1$  ka BP for calcareous cement of morainic gravels. Additionally, glacial till was dated at 71.7~64.7 ka BP for the terminal moraines at the outlet of the Muzhart River valley in the southern part of the Chinese Tianshan Mountains. Based on the Gulia (Gulya) ice-core record in the West Kunlun Mountains, a MAAT of 12 °C colder than present occurred under a general cold and arid climate [8]. On the northeastern QTP, loess deposition and aeolian action prevailed, resulting in loess layers of 30–40 m in thickness in the Gong'he Basin, southern Qinghai Province. Loess and aeolian sand were also deposited extensively on the northern flank of the Kunlun Mountains, with an AMS-<sup>14</sup>C dating of 50 ka BP for calcareous concretions, in Wudaoliang and on the Chumarhe High Plain in the Interior of the QTP, and in Guide and Gong'he basins on the northeastern QTP [18].

Plateau permafrost was reformed and expanded, with its northern LLAP lowered to 3000–3200 m amsl near the Golmud Reservoir along the Qinghai-Tibet Highway and its southern LLAP to 3600–3700 m amsl near Yangbajing [9]. A buried paleo-palsa of 5 m in height and 25–30 m in length was discovered under layers of loess deposits at 2450 m amsl in the Songshantan Basin in the Lenglongling Mountains in the eastern Qilian Mountains, with the age of lower peat layers older than 50 ka BP [94]. Widespread permafrost occurred in the Qilian Mountains above 2200–2300 m amsl during the LG Early Stadial (ca. 80–50 ka BP) [9,11]. Thus, during the early LG, plateau LLAP was 1300–1400 m lower than the present, and permafrost occurred extensively. Large groups of sand wedges also occurred in the Wuhai Basin on the western Ordos Plateau at c.  $66.5 \pm 7.08 \sim 62.7 \pm 6.81$  ka BP [95]. In Dongsheng (~39° N), Ordos City, many sand-wedges have been discovered, with Optically stimulated luminescence (OSL)-dating at 57.9~51.2 ka BP [31,32,93]. Thus, the SLLP

then was found to the south of 36–37° N in North China [20,31,32,50,93]. In the meantime, pingo scars were extensively identified in the Songhua-Liao'he rivers plains (~44° N) in Northeast China [96], implying a permafrost expansion.

#### 3.3.2. Last Glacial Interstadial (ca. 50-26 ka BP): Permafrost Degradation and Thawing

Grayish or silty clayey soils of Late Pleistocene age (ca. 50–30 ka BP), with layered lamina, rich in organic matter and freshwater paleo-flora and -fauna remains, were revealed at depths greater than 5 m in Lindian, Daqing in southern Heilongjiang Province, Northeast China [97]. This implies seasonal frost on the Songhua-Nen rivers plain during this period. However, the climate fluctuated intermittently: (Semi) arid steppes or cold deserts dominated in North China [98–100], and loess deposits extended as far as the downstream Yangtze River Basin [101]. Sand polygons in the Left (East) Sunite Banner of Inner Mongolia Autonomous Region were developed in two stages (45~41 and 38~36 ka BP); desert steppes prevailed under a colder and drier climate, with a MAAT of at least 4~8 °C lower than the present [102]. On the Ordos Plateau, during the LG Interstadial, cryoturbations were extensively developed under a warming climate [93].

The Gulia ice-core recorded a MAAT of 4 °C higher than present in the West Kunlun Mountains during 40–30 ka BP [12]. The  $\delta$ D and  $\delta^{18}$ O in water inclusions of salt rock from wellbores of the Charhan Salt Lake in the Qaidam Basin on the northeastern QTP also indicate a climate of 2 °C warmer than at present [103]. The climate on the western QTP was relatively cool and moist, with annual precipitation of about 400 mm and extensive expansion of lakes; hence, this time was also dubbed as the Great Lakes period [65]. Evident lowering of carbonate content was discovered at depths of 6.0–5.5 m (equivalent of 35–33 ka BP) in lacustrine sediments in the Tianshui'hai Lake in the western Kunlun Mountains; at the same depths, the assemblage of *Dolerocypris fasciata* Müller and *Leucocythere mirabilis* Kaufmann indicated a warm, freshwater lake environment [104,105]. Thus, the period from 50–26 ka BP had to be caused by a warm Interstadial, which is supported by rich evidence (e.g., [106]), permafrost did not survive through the LG Interstadial in most parts of the western QTP. However, we should be careful in judging the degrading permafrost from retreat glaciers, because glaciers or permafrost, such as those in the Canadian Rockies are retreating primarily due to reduced precipitation, as well as rising temperatures [107–109].

3.3.3. Last Permafrost Maximum (LPMax) at the Last Glacial Maximum (LGM, 26–19 ka BP): Very well-Developed Permafrost and Intensive Expansion

In China, after the Last Glacial Interstadial, the climate cooled sharply at c. 26 ka BP, resulting in the coldest climate of the Last Glacial Maximum (LGM) at 26–19 ka BP [11,28]. During the LGM, in comparison with the present, it was 7–9 °C colder (MAAT) and 30–70% drier (annual precipitation) on the QTP [8]. In arid regions in North China, it was about 5–11 °C colder (MAAT) and 180–350 mm drier (annual precipitation) than at present [31,110,111]. A climate of 4–5 °C colder in MAAT also happened in the Da Xing'anling Mountains in the northern part of Northeast China [30].

As a result, permafrost developed extensively and intensively, reaching the Last Permafrost Maximum (LPMax) (Figure 1) [11,19,30,35,112,113]. The major body of existing permafrost in China was largely formed during the LPMax, and in general, it was degrading afterward, resulting in many periglacial remains, such as sand and gravel wedges of 30–23 ka BP age discovered on the Ordos Plateau in North China, Northeast China and on northeastern QTP (e.g., [11,30,114,115].

Li et al. (1998) studied the lacustrine sediments in the Tianshui'hai Lake in the West Kunlun Mountains, revealing climate changes during 240~17 ka BP. The evolution of permafrost on the northeastern QTP during the past 150 ka was also investigated in more detail [14,49,116–118]. Zhou (2007) [118] and Zhou et al. (2008) [24] estimated a larger extent of permafrost during the LPMax, or greater than that of the Penultimate Glaciations in China. In alpine regions and on the QTP in West China, the LLAP generally coincided with the isotherms of -4~-2 °C in MAAT, and the LLAP lowered with MAAT at rates of 160–170 m/ °C) [7]. According to earlier estimates of LPMax climate cooling

of 7~9 °C, and based on distributive features of paleo-permafrost and -periglacial remains and other proxies (Table S1), in comparison with the present, a LLAP lowering of 1200–1400 m occurred during the LPMax (e.g., [9,11,19,32,35]). Plateau permafrost expanded into periphery basins, such as Tarim, Qaidam, Gong'he, and Zoîgé basins. Plateau permafrost was extensive and continuous, with an areal extent of permafrost at ~2.2 × 10<sup>6</sup> km<sup>2</sup> [9,11]. Similar to the present situation, the LLAP rose eastwards and southwards during the LPMax. For example, it rose southeastwards from 2600–2800 m amsl in the Qaidam Basin to 2700–2800 m amsl in the Zoîgé Plateau, and from 3600–3800 m amsl in the Yalu Zangpo River basin on the southern QTP to 3800–4000 m amsl in the Hengduan Mountains in the east [9]. In Xinjiang, it rose from 1400–1500 m amsl on the southern Chinese Altai Mountains to 1900–2200 m amsl in the Chinese Tianshan Mountains, and to 2200–2300 m amsl on the western and northern QTP [11].

Based on glacial landforms and deposits (diamicton records) and the toe-to-summit-altitude ratio method of Louis (1955) [119], the LGM snowline in North China rose westwards from ~2600–2700 m amsl in the Wutai Mountains [120] to 3000–3100 m amsl in the Helan Mountains [121], 3250–3300 m amsl in the Qinling Mountains [122,123], and ~4150 m amsl in the Laji Mountains on the northeastern QTP [119,124]. The snowline was depressed by ~900–1200 m in the Qinling, Wutai, and Helan mountains, in comparison with the lowering of LLAP by 1000–1100 m in the Qinling and Wutai mountains [33,125], and ~850 m in the Laji Mountains to the south of Xining city, Qinghai Province due to a westward rising in climatic continentality, implying a MAAT of LGM at least 5.5–8 °C colder than the present [120] and a zone of seasonal frost under 1500 m amsl in North China [126].

In Northeast China, the existing SLLP largely follows the 0  $(-1 \sim +1)$  °C-isotherms of MAAT, and SLLP moved southwards by 1° N at a decline in MAAT by 1 °C [7,9,11,30]. Thus, During the LPMax, SLLP should have moved southwards by 4°-5° N, to 41°~42° N (Figure 1). Recently, a large amount of data based on cryogenic wedges, polygons, and cryoturbations on the Ordos Plateau were applied for reconstructing past climate, permafrost, and periglacial environments [31,32,50,93,110]. It was estimated that during the LPMax (25–17 ka BP), MAAT was about 10–12 °C colder than the present; permafrost was very well developed, with the SLLP advancing southwards to somewhere between Yulin and Jingbian in northern Shaanxi Province to the south of 36–37° N, or slightly to the north between the Uxin Banner, Inner Mongolia Autonomous Region and the west–east trending Great Wall [31,32].

In summary, with exceptions in areas of possible seasonal frost or taliks in deserts and lowlands, most regions in Northwest, Southwest, North, and Northeast China were dominated by permafrost during the LPMax (e.g., [11,19,31,32,93]). The permafrost extent in China during the LPMax, including glaciated areas, reached  $5.3 \times 10^6 \sim 5.4 \times 10^6$  km<sup>2</sup>, or 3.5 times of the presently existing permafrost extent in China.

#### 3.3.4. Last Deglacial (19–12.9 ka BP; MIS 2)

In China, the period of 19–12.9 ka BP was called the Last Deglacial between the LGM and the Younger Dryas (YD), although its age interval is not clearly divided. The evidence for permafrost at that time is not rich, either. In China, it was typically represented by the terminal moraines at the Ronbus on the northern slopes of the Mt. Everest, with a cosmic rays and nuclides (CRN)-dating of  $16.6 \pm 4.1$  ka BP and OSL-dating of  $14.2 \pm 0.9 \sim 16.32 \pm 0.8$  ka BP [127]. The cold and dry plateau climate persisted until 14 ka BP, and in comparison, with LGM, it was followed by a warming climate with intermittent cold events (Shi, 2011). As a result, most cryogenic wedges stopped growth, and cryoturbations, as evidence for permafrost degradation, started to dominate periglacial landforms. According to the Gulia ice-core record, a warming of 2-3 °C occurred at 14–12 ka BP [12].

Tong (1993) first discovered a series of inactive ice-wedges with their truncated/eroded tops buried at about 1 m in depth at Wuma ( $52^{\circ}45'$  N,  $120^{\circ}45'$  E; 350 m amsl) in the northern Da Xing'anling Mountains in Northeast China [128]. The <sup>14</sup>C-dating of hosting strata and overburden soils indicate the formation ages of these ice-wedges at  $14,475 \pm 304 \sim 10,668 \pm 257$  a BP [128]. The MAAT for the

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formation of ice-wedges in sandy soils should be lower than  $-8 \degree C$  [47]. The MAAT at Wuma is about  $-5.0 \degree C$  at present. Based on statistics for the existing permafrost environment in Northeast China, MAGT is generally ~4 °C warmer than MAAT [10,30,129], local paleo-MAAT for ice-wedge formation would be at~-9 °C [128], or ~5 °C lower than the present [30]. Based on the OSL-dating of ice-wedge casts in Wuhai, Inner Mongolia, North China, the wedge ice melted in the Late Deglacial (MIS 2) [95].

### 3.3.5. Younger Dryas (YD) cooling (12.9–11.7 ka BP)

The age of the start of the Younger Dryas (YD) is well established by Greenland ice-core data and terrestrial vegetation/climate patterns (e.g., [130]). In contrast to Greenland ice-core dating, we prefer to keep a chronology (12.2–11.7 ka BP) generally used in China. The YD episode occurred at 12.2~11.7–10.9 ka BP and was characterized by a sharp decline in air temperature by 12 °C. It was followed by a marked warming of 4.5 °C at c. 10.9~10.8 ka BP [131]. The evidence for the YD glacial advance included many terminal moraines with glacial boulders formed during the Last Deglacial (e.g., [132,133]), which was CRN<sup>10</sup>Be-dated at 11,590 ± 490 ka BP (e.g., [134]). The YD environment deteriorated, vegetation retreated, and dust events increased under a prevailing cold and dry climate, resulting in a tundra-like environment on the eastern QTP [135]. However, on the northern Loess Plateau, it was a fluctuating cool-wet and cold-dry climate [84].

There is also evidence of YD permafrost development. In Wuma ( $52^{\circ}45'$  N,  $125^{\circ}45'$  E; 350 m amsl) in the northern Da Xing'anling Mountains, inactive or buried (ice still present) ice wedges were first discovered by Tong (1993), with <sup>14</sup>C ages of 10,653~14,475 ka BP [128]. Small cryogenic wedges were discovered in a service area ( $39^{\circ}49'59''$  N,  $110^{\circ}09'04''$  E; 1526 m amsl) of the National Highway 109 in Dongsheng District, Ordos City, Inner Mongolia, with an OSL age of  $11,600 \pm 600$  ka BP [31,93]. Sand-wedges with TL-dating at 11,000~14,500 ka BP were found in Xinzhaizi Town, Ekto Banner, Ordos City [11,30]. YD permafrost remains are rare on the QTP, such as sand-wedges on the northern terrace of the Tianshuihai Lake in the West Kunlun Mountains ( $35^{\circ}32'$  N,  $79^{\circ}31'$  E; 4847 m amsl) (<sup>14</sup>C ages at 11,533~13,888 ka BP) [51]. By the end of the Pleistocene, the framework and patterns of permafrost distribution in China were largely formed.

### 3.4. Holocene (Since ~11.7 ka BP)

Since the beginning of the Holocene, permafrost in China has been degrading in general in comparison with the LPMax. Based on detailed data on past permafrost and periglacial remains (Table S1), as well as climate proxies, six distinct Holocene permafrost periods are divided as follows: (1) Early Holocene (ca. 11.7~8.5–7.0 ka BP); (2) Holocene Megathermal Period (HMP, 8.5–7.0~4.0–3.0 ka BP); (3) Neoglaciation, 4–3~1 ka BP; (4) Medieval Warm Period (MWP, 1~0.5 ka BP); (5) Little Ice Age (LIA, 500~100 ka BP); and (6) recent warming in the 20th~21st centuries. It is necessary to stress here that although different phases have been distinguished, they are in fact only representing slight temperature fluctuations. However, these fluctuations are characterized by distinctive features of permafrost growth or decline.

## 3.4.1. Unstable Climate in the Early Holocene (ca. 11.7 to 8.5–7.0 ka BP): Relatively stable but Shrinking Permafrost

The climate was very unstable in the early Holocene (ca. 11.7 to 8.5–7.0 ka BP). The Plateau climate in the early Holocene was cold and dry, with alternating cool and warmer periods. Based on periglacial remains, the northern and southern LLAPs on the interior QTP were at 3400~3500 and 4200~4300 m amsl, respectively, about 600–700 m lower than those of the present. Plateau permafrost was thermally stable and areally continuous [11,35]. However, in comparison with that of the LPMax, Plateau permafrost degraded in general, with a shrunk permafrost extent (but still 40~50% greater than at present). At the end of the early Holocene, many wetlands had been developed, resulting in peat accumulation [9,115]. Some mobile sand-dunes formed during the LGM were becoming fixed, indicating a warming-wetting climate [136,137].

About 150 pingo scars, dated at about 10~8 ka BP, identified on the Sanjiang Plain (47°10′~48°43′ N, 133°~135° E) in Northeast China [96], suggest the occurrence of permafrost [30]. However, permafrost later vanished in most places to the south of the Sanjiang Plain, except at the top or upper parts of high mountains. On the southern Ordos Plateau in North China, periglacial landforms were dominated by sand wedges, small frost cracking polygons, and some cryoturbations [20]. In general, cryoturbations suggest permafrost degradation [29,31,32,93].

## 3.4.2. Last Permafrost Minimum (LPMin) at the Holocene Megathermal Period (HMP, 8.5–7.0 to 4.0–3.0 ka BP): Intensive Permafrost Degradation

In China, the Holocene Megathermal Period (HMP) occurred at 8.5–7.0 to 4.0–3.0 ka BP, with its climax of warm-humid climate at 7.2~6.0 ka BP [11,12,28,138]. In comparison with the present, the MAAT of the HMP was possibly 3 °C higher in North, Northeast, and Southwest China, and in particular, 4~5 °C warmer on the southern QTP [28]. In arid regions in North China, it was about 1.0~3.5 °C warmer, with a variability of 20–130%, and with a distinct wetting trend in Northwest China [111]. Layers of peat were formed on the QTP (Table S1), indicating a warm-wet HMP/LPMin climate, with the extensive presence of large thicknesses of peat blanket or peat bog, exhibiting the continuous extent of peat deposits and extensive permafrost degradation.

During the late LPMin, plateau permafrost degraded to seasonal frost to the north of the Kunlun Mountains and to the south of the Tanggula Mountains; on the interior QTP, permafrost degraded downwards in the ground to depths of 14~16 m, detaching the permafrost table from the active layer [9,11,21,35]. Accordingly, thick-layered ground ice was formed at depths of 14~16 m slightly beneath the relatively stable former permafrost table [139]. Numerous thermokarst lakes and cryoturbations developed. As a result, the remaining high-plateau or alpine permafrost survived either by preservation in favorable locations and conditions, or are deeply buried [115]. However, continuous permafrost persisted in alpine regions, and permafrost degraded more intensively on the eastern QTP because of stronger influences from monsoonal climate [9,21,115]. During the late LPMin, Plateau the permafrost extent was reduced to 40–50% that of the present. In West China, alpine permafrost only survived at the upper parts of Altai, Tianshan, Kunlun, and Qilian mountains, with an uplift of LLAP by 300~500 m.

During and shortly after the HMP, permafrost degraded extensively in China [11,30,35]. The SLLP retreated to Amu'er-Mangui (>51–52° N) in the northwestern Da Xing'anling Mountains (Figure 2). Thus, except for some mountain tops, permafrost vanished in North China, and the SLLP retreated to the north of 46° N on the Inner Mongolia Plateau [11]. The areal extent of LPMin permafrost in China was reduced to 800,000~850,000 km<sup>2</sup>, or c. 50% of the present area (Figure 2).

#### 3.4.3. Neoglaciation (4-3 to 1 ka BP): Permafrost Re-Expansion

The climate started cooling at 4~3 ka BP during the late Holocene, resulting in the Neoglaciation in China. Plenty of evidence for Neoglacial permafrost has been identified [9,11]. The Neoglacial LLAP and MAAT were about 300 m and 2 °C lower than those of the present, respectively. Thus, on the basis of the intensive degradation of permafrost during the LPMin, epigenetic permafrost was formed by refreezing of HMP taliks and expanded radially from the interior QTP, until reaching the largest extent of Neoglacial permafrost at ~1.0 ka BP, about 20–30% greater than that of the present. On the interior QTP (>4500 m amsl), taliks refroze downwards, forming a 30-m-thick epigenetic permafrost [140]. This new permafrost re-attached with the residual permafrost of LPMin and became part of the present permafrost [9,11,115]. However, buried permafrost or taliks have been extensively found on the northeastern QTP [115]. This might be attributed to the limited downward thawing of permafrost by 15~25 m on the eastern margins of the QTP during the HMP, while the Neoglacial permafrost was thinner than the burial depth of LPMin permafrost (15~25 m), resulting in vertical detachment [9,11,35,115].



Figure 2. Last Permafrost Minimum (LPMin) in China and at present (end of the 20th century).

In Yitulihe (50°32′ N, 129°29′ E; 731 m amsl) in the northern Da Xing'anling Mountains in Northeast China, Neoglacial inactive ice-wedges were unearthed and AMS-<sup>14</sup>C dated at 3.6~1.6 ka BP. Wedge-ice  $\delta^{18}$ O records indicate three cold snaps of 2.1, 1.1, and 1.3 °C at 2800, 2300, and 1900 ka BP, respectively [141,142]. Neoglacial MAAT in the Da Xing'anling Mountains should have been 1~2 °C lower than the present, and the SLLP, 2° N more southerly.

### 3.4.4. Medieval Warm Period (MWP, 1000-500 ka BP): Relative Permafrost Degradation

Warm climate dominated during 1000–700 ka BP, i.e., the Medieval Warm Period (MWP: AD 900–1300). Post-Neoglacial climate in China was warming but in fluctuations [143]. On the QTP, the MWP consisted of three warm periods and three cold periods. Paleo-periglacial landforms have been well preserved. The downward thawing of permafrost might have reached depths of 10 m at lower elevations [9]. On the Chumar'he High-plain in the interior of the QTP, two visible positions of paleo-permafrost tables were identified: The upper paleo-permafrost table at 8.4 m depth and the lower one at 16.0 m, possibly formed during the MWP; in addition, thick-layered ground-ice was identified beneath the paleo-permafrost tables [139]. To the south of the SLLP in Northeast China, island permafrost was discovered [97]. In comparison with the present, degradation of permafrost during the MWP resulted in a rise of the LLAP by about 150~250 m, a northward shift of SLLP by  $1-2^{\circ}$  N, and a reduction of permafrost extent in China by about 20% [11,30].

#### 3.4.5. Little Ice Age (LIA, 500-100 ka BP): Relative Permafrost Expansion

The Little Ice Age (LIA) refers to the cold period during the 16th~19th centuries (AD 1550–1850), with the latest permafrost expansion in China. On the QTP, the climate cooling-drying resulted in expanded and thickened permafrost during the LIA, and in the formation of some new permafrost

islands. Taliks were refrozen, re-attaching with the buried MWP permafrost table [9]. The newly formed humus soils since 780 ka BP refroze, but they were too thin to attach with the buried permafrost, as exemplified on the northeastern QTP [115]. Permafrost at depths were 1.5~8.0 m near the Ngöring Lake and at depths of 5.3~8.2 m in Qingshui'he town in the southern Bayan Har Mountains on the northeastern QTP [9,11,115]. Jakob (1992) concluded the lower limit of discontinuous alpine permafrost was at 5560~5360 m amsl on sunny slopes and 4959~5050 m amsl on shadowy slopes in the Himalayas [144]. The lower limit of active rock glaciers was at ~5000–5300 m asml in the Nepal-Kunbu Himalayas based on the distributive features of active rock glaciers and seismic geophysics near the Poklade Cliff ( $27^{\circ}55'$  N,  $86^{\circ}50'$  E). These results agree reasonably with the calculations of Cheng and Wang (1982) ( $\geq$ 5080 m amsl at  $25^{\circ}22'$  N). Owen and England (1998) estimated a lower limit of discontinuous alpine permafrost at approximately more than 4000 m asml in the Western Himalayas and Karakorums in northern India and Pakistan [145]. On the QTP, during the LIA, there was a decline in air temperature by about 1.0~1.5 °C, a lowering of LLAP by 150~200 m, and an expansion of permafrost extent by  $15\sim20\%$ .

#### 3.4.6. Recent Warming in the 20th–21st Centuries: Persistent Permafrost Degradation

Since the 20th century, the climate has been warming persistently in China. The MAAT in permafrost regions on the QTP has increased by 1.1 °C during 1970–2010 at rates of 0.025~0.030 °C/a, greater than in regions of seasonal frost (0.17~0.19 °C/decade) [23]. As a result, permafrost in China warmed by 0.2–0.4 °C [23], resulting in a reduction of permafrost extent in China to  $1.59 \times 10^6$  km<sup>2</sup> [58]. The depth of the burial of the permafrost table increased by 25–60 cm while seasonal frost thinned by 5–20 cm. This evident and rapid degradation of frozen ground has close relationships with climate warming and increasing human activities [23,30,146,147]. It is projected that, if assuming warming rates of MAAT of 0.04–0.05 °C/a and those of mean annual soil temperature at the permafrost table of 0.03 °C/a in permafrost regions in China, as measured during the last 20–30 years, the current zone of warm ( $\geq$ -1 °C) permafrost may disappear by 2100 [148].

#### 4. Inadequacies and Challenges

In general, since the LPMax, permafrost in China has been degrading under an intermittently warming climate (Table 1). Permafrost extent was reduced from  $5.30 \times 10^6 \sim 5.40 \times 10^6$  km<sup>2</sup> at the LPMax to  $0.80 \times 10^6 \sim 0.85 \times 10^6$  km<sup>2</sup> at the LPMin [11], and later recovered to the present  $1.59 \times 10^6$  km<sup>2</sup> [58]. During the MWP and the last century, the most intensive, rapid, and extensive degradation of permafrost in China occurred since the LPMin. However, many inadequacies are waiting for further studies on Quaternary permafrost in China.

Epoch	Climate Period	Age (BP)	Permafrost Features	Climate Features & Temperature Decline (°C)	Change in SLLP (°N)	Change in LLAP (m)	Permafrost Extent (10 <sup>6</sup> km <sup>2</sup> )	Ratio to Present pf Extent (%)	Major Direct Evidence	Major Indirect Evidence	Major References
Early Pleistocene (2.68–0.80 Ma BP)	Early cold period	2.68~1.17 Ma	Pf expansion	Glacial	at 47°~50°	Lowered	Increased	Increased	Epigenetic lacustrine permafrost, involutions and periglacial deposits	Cold climate fauna, flora & microorganisms	[60,149]
	Xixiabangma Glacial	MIS 36~20; 1.17~0.78 Ma	Intensive pf expansion	Great glacial	Southward advance	Lowered	Increased	Increased	Involutions & ice-wedge casts	Glacial morainic platforms, Stegodon orientalis, Lufengpithecus keiyuanensis	[63,65,150,151]
Middle Pleistocene (800–130 ka BP)	Wangkun-Kunlun Glacial	MIS 16~18/20: 780~620 ka	Permafrost expansion	Glacial	S advance	Lowered	Increased	Increased	Ice-wedge casts, gravel & sand wedges	Glacial till & boulders, & ice cores	[152–156]
	Antepenultimate glacial	~720–500 ka	Intensive pf expansion	Glacial	S advance	Lowered	Increased	Increased	Sand wedges	Ice-cores, glacial till, glaciofluvial sediments	[8,80,83,152]
	Great Interglacial	620~480 ka: MIS 13~15		Warm/wet period	N shrinkage to 56–58	Risen	Declined	Declined	Involutions, ice-wedge casts	(Red) Plaeosols, pollen records,	[14,74,157,158]
	Zhonglianggan Gl	MIS 12, ~480–420 ka			S advance	Lowered	Increased	Increased		Glacial till	[83,85,87,88]
	Penultimate- Guxiang Glacial	300–130 ka; MIS 6; Gonghe Movement	Intensive pf expansion	Cold/wet, gl scale > LGM	S advance	Lowered	Increased	Increased	Ice wedge casts & sand wedges	Glacial, lacustrine & glaciofluvial sediments	[8,49,80,118,159]
	Last Interglacial	MIS 5, 130–120 ka		MIS 5e, +5 °C	N shrinkage	Risen	Declined	Declined		Ice-core & pollens	[131,160]
Late Pleistocene (130–11.7 ka BP)	LG Early Stadial	MIS 4 ~80/ 75~50 ka	2ndpf expansion	Cold period	S Advance	Lowered	Increased	Increased	Ice-wedge casts, pingo scars, polygons	Glacial till, peat deposits & lacustrine sediments	[5,8,94,161–163]
	LG interstadial	~50–26 ka	Pf degradation	Warm period	S Advance	Lowered	Increased	Increased	Ice wegde casts, sand wedges& involutions	Peat deposits & lacustrine sediments	[5,20,50,93,112]
	Last Glaciation Maximum (LGM/LPMax)	~26 to 19 ka	Intensive pf expansion	Cold/Dry; 4–5 (NE China), 3–11 (N China), 7–9 (QTP).	S Advance 4–5 (NE China)	Lowered by 1200–1400	5.3–5.4	>300	Cryogenic wedges or casts	Glacial landforms, ice-cores, past timberline, pollens, sandland, cold climate fauna and flora, numerical models	[9,19,30,35,49–51, 114,116,128]
	Last Deglacial, or Late Glacial	19–12.2 ka	Relative pf degradation		Relative N shrinkage	Risen	4.0-4.5	Relative pf degradation	Involutions, cryogenic cracks and wedges/casts	Terminal moraines, loess & humic soils	[15,20,21,30,49,50, 127,164]
	YD Glacial Advance	12.2–10.8 ka	Relative pf degradation	–3 (S China Sea)	Relative N shrinkage	Risen	3.5-4.0	Relative pf degradation	Ice wedge & casts, sand wedges, involutions	Ice-cores, aeolian sands, pollens, glacial boulders and terminal moraines	[30,51,83,128,131– 134,165]

## **Table 1.** Summary of evolutionary stages and basic features of permafrost in China during the Quaternary.

#### Table 1. Cont.

Epoch	Climate Period	Age (BP)	Permafrost Features	Climate Features & Temperature Decline (°C)	Change in SLLP (°N)	Change in LLAP (m)	Permafrost Extent (10 <sup>6</sup> km <sup>2</sup> )	Ratio to Present pf Extent (%)	Major Direct Evidence	Major Indirect Evidence	Major References
	Dramatic change	10.8 to 8.5~7 ka	Stable & degrading	Cold/dry, turning warm/wet	Pf degradation	Lowered by 600–700	2.2–2.4	140-150	Pingo scars & sand wedges	Ice cores, diatoms, pollens, peat & sand dunes	[18,96,166,167]
	Holocene Megathermal (HMP/LPMin)	8.5~7 to 4~3 ka	Intensive degradation	Warm/wet, 2~3 (most), 4~5 (QTP), 1.0~3.5 (N China),	N shrinkage 3–4 (NE China)	Risien 300–500 (QTP & W China)	0.8–0.85	50	Ice wedges, buried pf, thaw lakes, paleopf tables, gelifluction	Mineralogy, peat, ice cores (δ 18O), aeolian sands, charcoals, timberline & pollens	[6,9,21,30,97,111,115, 128,139,167,168]
Holocene (11.7–0 ka BP)	Neoglacial	4~3 to 1 ka	Re-expansion	Cooling -2~-1 (NE China & QTP)	S Advance 2 (NE China)	Lowered ~300 (QTP)	1.9–2.1	120–130	Pingo scars, involutions, polygons, gelifluction obes, ice wedges	Gacial till, peat, detached/buried pf	[9,35,115,140–142]
	Medieval Warming (MWP)	1~0.5 ka	Relative degradation	Warm/wet, 1.5	N retreat 1~2	Risen~150-250	1.4–1.5	80	Pingo scars, buried pf, paleopf tables, ground ice	Historical archives, humus	[9,21,139]
	Little Ice Age (LIA)	500~100 a	Relative expansion	Cooling -1.5~-1	S Advance 1~1.5	Lowered ~150-200	2.1–2.2	115-120	Paleopf, relict blockfields and rock glaciers	Ice core, glacial tills, humus, salt lake silt, sandlands	[21]
	Recent warming	100~0 a	Persistent degradation	Warming/drying 0.3~0.8	N retreat 0.5–1.5	Risen 50~100	1.59	100	MAGT, LLAP, pf extent	Measured & thermokarsting	[11,21,23,30,59]

Until now, no residual permafrost prior to the LPMax has been directly discovered in China. Compared to the Arctic, permafrost in China is generally warm, thin, and thus sensitive and vulnerable to climate warming. This might be due to the southern location of permafrost in China on the edge of the latitudinal permafrost body in Eurasia. Strong insolation on the QTP mandates colder MAAT for permafrost, but climate-driven permafrost is more sensitive to climate warming. Thus, permafrost in China is thermally unstable. In addition, earlier permafrost might have thawed under warm interglacial climates prior to the LPMax. However, more sophisticated techniques for dating and identifying the early permafrost and for distinguishing the permafrost and periglacial climate and environment, probably at larger depths or higher elevations, should be better developed and applied for in-depth and sophisticated investigations on much older permafrost in China. Furthermore, permafrost development in relation to the uplift of the QTP is still a challenge, although there are some encouraging results on the relationships of climate and glaciations with the Quaternary plateau uplifts, the Late Quaternary in particular. Quaternary glaciations in China were influenced mostly by the Kunlun-Huang'he (1.1~0.7 Ma BP) and Gong'he (c. 150 ka BP) movements [90,91]. Because of varied tectonic rising rates of mountains, their timing for reaching the elevations of the alpine cryosphere (generally  $\geq$  3000–3500 m amsl) also differed substantially. The Gong'he Movement mainly affected the eastern QTP. As a result of contemporaneous LGM cold climate and rapid plateau uplifts, extensive glaciations, and permafrost expansion concurred, but the buildup of alpine or high-plateau permafrost may lag somewhat behind that of mountain glaciers. However, the timing of the LPMax and LGM varied significantly, and the LPMax in China still needs further studies and more systematic integration. Finally, the evidence for occurrences of early permafrost, such as that during the Early and Middle Pleistocene, has seldom been discovered, probably due to the low elevations of sites with currently known permafrost evidence. Most of those older glacial tills and landforms are generously found at very high elevations, such as those at upper parts of the Himalayas or Karakorums on the western QTP (e.g., [8,12,27,63,150]). In one word, the plateau uplift and concurrent climate changes have jointly controlled or impacted the development and evolution of permafrost in China.

On the QTP and in North and Northeast China, ice-wedges and their casts have seldom been discovered, or the sizes are relatively smaller for the inactive ice-wedges in comparison with those in arctic regions. This might be attributed to a very cold but dry climate in China, even more so during the LGM/LPMax. Most identified wedges in China are sand wedges, except few inactive ice wedges in northern Da Xing'anling Mountains in Northeast China, where the ecosystem protection has been crucial for those ice wedges. Based on their latitudes and elevations, during the LGM/LPMax, Tarim, and Zhungger deserts in the Xinjiang Uygur Autonomous Region in Northwest China, as well as some sandlands and deserts in North and Northeast China should have been subjected to the harsh periglacial climate. However, so far, no reliable evidence has been found for the presence or absence of past permafrost and periglacial remains in these regions. As Vandenberghe et al. (2014) pointed out, a possible reason could be the extremely dry and evaporative climate and high permeability of sandy soils, where some periglacial phenomena, such as ice-wedges and cryoturbations, can hardly develop under such a desert environment [29]. Too many wedges were formerly interpreted as ice-wedge casts, where an interpretation for sand wedges is more convincing, and; similarly, many fissures should not be considered as cryogenic wedges (e.g., [110]). More in-depth and systematic studies and further discussions on these topics may help clarify the criteria and techniques for distinguishing the evidence for permafrost and seasonal frost and possibly for dating the sediments of permafrost and periglacial climate and environment.

The debates for the extensive ice caps and glaciers or a unified ice sheet seem already or temporarily settled for the scales and duration of glaciations on the QTP during the three major Pleistocene glaciations, but less is known about those of interglacials. Furthermore, much less is known on the relationships between permafrost and glaciers [169,170]. Are there spatiotemporal asymmetries in the buildup and decay of permafrost and glaciers in China? In most cases, in our studies, we include the glaciated areas in estimating permafrost extents because of difficulties in distinguishing them and

arguments about the extents of Quaternary glaciations in China. Thus, a more reliable permafrost extent should exclude that of concurrent glaciers. For example, the areal extent of glaciated zones of at least 350,000 km<sup>2</sup> should be extracted from the permafrost extent for the Penultimate Glaciations on the QTP. Thus, it is reasonable to assume that the glacial and permafrost maxima/minima generally did not concur because of asymmetrical development or lag of surface and subsurface aggradation/degradation of permafrost and advance/retreat rates of glaciers. During the LGM, the extent of plateau permafrost of the LPMax could still be largely correct because the latest studies indicate limited glaciations on the QTP (e.g., [171–173]).

In addition, more studies should be carried out on the relationships between the Quaternary permafrost and other aspects of Quaternary studies, such as those on cold-climate paleo-fauna and -flora, as well as the -microbe fossils, or paleo-anthropology and ancient civilizations. At present, we have an inadequate understanding regarding the relationships between Quaternary permafrost distribution and vegetation patterns, such as those of permafrost evolution with deserts or sandlands. Additionally, what are the relationships between lakes and permafrost, as during the Quaternary? There were many large and persistent lakes in China during glacial and interglacial periods. In particular, the paleo-lakes in the source area of the Yellow river and their outbursts or interconnections during the Gong'he Movement coinciding with the ending of the Penultimate Glaciations or connections of smaller basins on northeastern QTP at the end of the LGM might have created the upper Yellow River basin and shifted the headwaters of the Yellow River toward the east. In addition, the formation and disintegration of the Tianshuihai-Akseqin Lakes on the western QTP during the last 70 ka have great impacts on plateau permafrost and periglacial environments, but were seldom studied. Substantial changes in sea level may also have greatly affected Quaternary permafrost in China, because during the cold periods of lower sea levels, many continental shelves of eastern and southern China seas were extensively exposed to the chilly climate and the arctic fronts at much southerly positions, or even closed into inland basins (e.g., [170]). Could some exposed continental shelves have been frozen for a long-term, as some cold climate paleo-fauna and -flora fossils have been unearthed by drilling or excavations in Eastern China seas? Many thermokarst lakes and pingos (or pingo scars), as well as (buried) palsas, lithalsas, and peat blankets or plateaus, have been reported on the QTP, in alpine regions in West China and in the northern part of Northeast China. However, their formation and evolutionary processes and their relationships with past permafrost remain poorly investigated and largely unknown. How about the buried and multi-layered permafrost being formed now and during the different warm periods of the Quaternary, especially during the numerous interglacials? How to classify and map their distribution under a warming and cooling climate? How would they impact the alpine ecosystems and hydrology-hydrogeology, as well as engineering geology, and the ecosystems and socio-economic situation downstream? Additionally, there are large knowledge gaps regarding spatial and temporal relationships of permafrost and periglacial development and distribution during the Quaternary and each stage at the borders of China and neighboring countries or regions. Can the results be seamlessly or unanimously matched or merged regionally and globally? These inter-comparisons and cross-examinations may greatly advance studies on Quaternary geocryology and geology and international cooperation in Eurasia and the northern hemisphere.

In summary, there are numerous unanswered questions for Quaternary geocryology in China. With rapidly progressing computing, communicating, dating, mapping, and surveying techniques, these questions can be approached from different, interdisciplinary, or integrated perspectives and techniques. For example, there should be a systematic study and integration on the evolution of SLLP and LLAP in China and adjacent regions, in Eurasia and the northern hemisphere, and on their spatiotemporal relationships and evolutionary processes. Although it is complicated and difficult to implement these studies in Central Asia, these studies may reveal many key geocryological insights.

#### 5. Conclusions

The fluctuating climate of glacial and interglacial cycles controlled the formation, aggradation, and degradation of permafrost in China during the Quaternary. Based on the above discussions, the following conclusions can be drawn:

Only limited evidence for paleo-permafrost and periglacial environments during the Early Pleistocene has been preserved and identified in China. However, such evidence awaits further clarification and confirmation. During the earlier part of the Early Pleistocene (2.68–1.17 Ma BP), Eurasian permafrost advanced southwards to at least 47–50° N in China, and alpine permafrost may have developed in major mountains in West China. Afterwards, during and after the Himalaya-Shixiabangma Glaciations in the later part of the Early Pleistocene (ca. 1.17-0.80 Ma BP), permafrost may have developed in China, but its extent cannot yet be delineated because of the paucity of relevant data. The evidence for the occurrence of early permafrost is rare and less reliable. Further efforts should be made for clarifying such evidence or discovering more reliable evidence at higher elevations on the western QTP, such as on the upper parts of the Karakorums and Himalayas. Four glaciations occurred in the Middle Pleistocene (800-130 ka BP; MIS 20 to MIS 6): Permafrost expansion during Wangkun-Kunlun Glaciations (ca. 800/780-620 ka BP; MIS 20 to MIS 16) or Antepenultimate Glaciations (ca. 720–500 ka BP) permafrost expansion during the Zhonglianggan Glaciations (480–420 ka BP; MIS 12), and the Penultimate Glaciations (300–130 ka BP; MIS 6), with its late-stage at 150–130 ka BP, the largest Quaternary glaciations on the QTP, forming the largest extent of permafrost in China. Sharp climate changes and transitions occurred during the Late Pleistocene, which can be divided into six periods of cold and warm climates, resulting in different states of permafrost development and degradation: Last Interglacial Period (MIS 5; 130-72 ka BP) with permafrost thaw; Early Last Glacial Stadial (ca. 72-50 ka BP) with permafrost expansion; Interstadial of Last Glaciation (ca. 50-26 ka BP) with permafrost thaw; LGM/LPMax (ca. 26–19 ka BP) with intensive permafrost development and expansion (in its later half, the extent of permafrost in China reached  $5.3 \times 10^6 \sim 5.4 \times 10^6$  km<sup>2</sup>, shaping the major body of existing permafrost in China); Last Deglacial (19-12.9 ka BP) with relative permafrost degradation, and the Younger Dryas (12.9–11.7 ka BP) with relative permafrost aggradation.

Holocene changes in the permafrost environment in China were frequent, but not as substantial as those during the Pleistocene. Six stages of evolution of permafrost can be distinguished: Relative stable and generally degrading permafrost under an unstable climate during the Early Holocene (11.7~8.5/7 ka BP), intensive and extensive permafrost under warming of 4–5 °C during the HMP/LPMin (8.5/7 to 4/3 ka BP) (with permafrost extent in China reduced to  $8.0 \times 10^5 - 8.5 \times 10^5$  km<sup>2</sup>, or about half that of the present), substantial permafrost expansion during the Neoglaciation (4/3~1 ka BP), relative permafrost degradation during the MWP (1000~500 ka BP), relative permafrost expansion during the LIA (500~100 ka BP), and permafrost degradation during the past 100 years, with the areal extent of permafrost in China reduced to  $1.59 \times 10^6$  km<sup>2</sup>. During the past 30 years, particularly since the 21st century, permafrost degradation has been accelerated in China. By 2100, warm (<–1 °C) permafrost is projected to thaw completely in China. Thus, in the near future, degrading permafrost will result in extensive and profound changes in ecology, hydrology, hydrogeology, environmental and engineering geology, and subsequent ecological and hydrological impacts, as well as sustainable socio-economic development in permafrost regions and in downstream river catchments relying on water supplies from the mountain cryosphere.

For the existing permafrost in China, only about 200–300 ka of its evolutionary history has been preliminarily studied, and only that of the last 30 ka are supported by relatively richer data. However, the formation, development, and evolutionary processes of Quaternary permafrost in China are complicated because of overlapping impacts of various spatiotemporal climate changes and human activities on the depths, extents, and features of permafrost in China. They have resulted in possible simultaneous degradation and aggradation of permafrost in different regions and at different depths at a given time. In particular, permafrost at shallow depths and on the margins of permafrost zones may have experienced the repeated ground freezing–thawing as results of cyclic climatic fluctuations

of varying amplitudes and intensity, forming the mosaicked distributive features of permafrost and taliks. Thus, the ages of permafrost can hardly be accurately determined. In addition, large-scale economic development has led to substantial damage to the existing permafrost or periglacial remains; it is necessary to timely rescue and systematically study these precious archives.

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