

Climate and environmental evolution in the Huola Basin of the Mohe permafrost region, Northeast China, since late MIS 3

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Article

Keywords: Marine Isotope Stage 3, Huola Basin, Late Pleistocene, Pollen, Permafrost–vegetation–climate feedback

Posted Date: October 6th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11104327/v1>

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Additional Declarations: No competing interests reported.

Abstract

To reconstruct the Quaternary climatic and environmental evolution of the high-latitude permafrost region of Northeast China, a 4.15-m-long sediment core retrieved from the Huola Basin, on the western margin of the Mohe Basin, was analyzed using accelerator mass spectrometry (AMS) ^{14}C and optically stimulated luminescence (OSL) dating, together with pollen, grain-size, and magnetic susceptibility measurements, establishing a chronological framework spanning the last 30 ka. The results indicate that the climate and environment of the study area evolved through four successive stages: (i) during 30.0–26.7 ka BP, vegetation was sparse under cool and arid conditions; (ii) during 26.7–13.36 ka BP, the climate was cold and relatively dry, coinciding with the maximum permafrost expansion of the Last Glacial Maximum (LGM); (iii) during 13.36–8.29 ka BP, shrubs and herbs expanded under a cool, gradually warming climate in response to deglacial warming; and (iv) since 8.29 ka BP, flourishing coniferous forests and developing peat bogs have indicated a cold and humid climate. The sediments contain abundant coarse silt (18.45–40.64%), median grain size (M_d) ranges from 5.51 to 14.20 μm , with a mean of 9.78 μm , and magnetic susceptibility values ($5.6\text{--}20.4 \times 10^{-8} \text{m}^3/\text{kg}$) increase up-core, reflecting intensified pedogenesis during the Holocene. Principal component analysis reveals that grain-size, magnetic-susceptibility, and pollen assemblages jointly constitute the dominant controls on palaeoenvironmental variability. The Huola Basin sequence is broadly synchronous with records from the Beiji wetland, Tuofengling Lake, Hulun Lake, the Greenland GISP2 $\delta^{18}\text{O}$ record, and Sea of Japan sea-level fluctuations, indicating regulation by global ice-volume and temperature changes superimposed on modulation by the East Asian summer monsoon and local permafrost–hydrological processes. The increase in basin humidity during the late Holocene, despite concurrent cooling, demonstrates a positive permafrost–vegetation–climate feedback. This study extends the palaeoclimatic record of the Huola Basin back to 30 ka BP for the first time, providing a robust basis for understanding the historical evolution and anticipating the future degradation of the high-latitude permafrost region of Northeast China.

1. Introduction

Permafrost, a product of cold climates, is highly sensitive to fluctuations between warm and cold climatic intervals and therefore serves as an important indicator of global climate change^{1–3}. The high-latitude permafrost of Northeast China is generally regarded as relict permafrost of Quaternary age⁴ and has likely undergone repeated episodes of expansion and contraction. In particular, the frequent alternations between cold and warm, and between humid and arid, conditions since the Late Pleistocene must have driven substantial changes in the permafrost environment^{5–9}.

In permafrost regions, vegetation succession and permafrost dynamics interact closely: vegetation succession alters the thermal and hydrological regimes of the ground and thereby influences permafrost development¹⁰; conversely, climate and permafrost changes constitute the dominant drivers of boreal forest succession, and the degradation and expansion of permafrost in turn modify the succession of

the overlying vegetation⁷. The Mohe area of the Great Hinggan Mountains is a typical high-latitude permafrost region of China and lies at the southern margin of the Eurasian permafrost zone; its history of climatic and environmental evolution therefore provides a valuable reference for understanding permafrost dynamics. Considerable work has been devoted to Quaternary palaeoclimate and palaeoenvironmental reconstruction in the Great Hinggan Mountains, focusing primarily on alpine lakes and river-valley wetlands, including the Beiji wetland^{11–13}, Hulun Lake¹⁴, the Huola Basin^{15–18}, the Beihong wetland¹⁹, the Tuqiang (TQ) peatland²⁰, and the Mangui wetland²¹. These studies demonstrate that, although the historical climate and environment of the Great Hinggan Mountains have been driven by multiple factors—including Northern Hemisphere ice volume, the westerlies, adjacent seas, volcanic activity, and human activities—the pattern of climatic evolution has been most sensitive to fluctuations of the East Asian summer monsoon (EASM); abundant lacustrine and wetland sedimentary records confirm that changes in vegetation, hydrology, and dust deposition in the Great Hinggan Mountains are closely linked to variations in the strength of the winter and summer monsoons^{8,14,22–24}.

In recent years, the northern Great Hinggan Mountains permafrost region, where the Huola Basin is located, has exhibited pronounced degradation under global warming. Based on observations from meteorological stations in Northeast China, Gong et al.²⁵ reported an increase of 0.9–2.2°C in mean annual air temperature in the Great Hinggan Mountains over the past 50 years, at a warming rate exceeding national and global averages, accompanied by rising ground temperatures and decreasing frost depths. Li et al.²⁶ further found that the permafrost region of Northeast China experienced sustained warming during 1961–2019: the permafrost area of the Great Hinggan Mountains decreased by approximately 40.6% relative to the 1960s, and the southern limit of permafrost retreated markedly northward. Borehole monitoring in the Huola Basin likewise indicates that, under the combined impacts of climate warming and coal mining, the ground temperature at the depth of zero annual amplitude in the disturbed zone rose by 0.2–0.5°C within six years, the permafrost changed from a cold to a warm type, and the permafrost table declined by 0.8–7.0 m¹⁸. Permafrost in the northern Great Hinggan Mountains is thus undergoing rapid degradation, and a detailed reconstruction of its historical climatic and environmental evolution is of great significance for understanding the mechanisms of permafrost degradation and for projecting future changes.

In this study, samples for AMS ¹⁴C dating, optically stimulated luminescence (OSL) dating, pollen, grain-size, and magnetic susceptibility analyses were systematically collected from a borehole drilled on the northeastern margin of the Huola Basin to investigate the Quaternary climatic and environmental evolution of the basin. The results were compared with other records from the high-latitude permafrost region of the Great Hinggan Mountains in order to elucidate the patterns of climatic and environmental evolution of the Huola Basin and, more broadly, of the Mohe area since late Marine Isotope Stage (MIS) 3, together with the factors controlling permafrost evolution. This work not only enriches our understanding of the ecological processes and developmental history of the Huola Basin—extending its dated palaeoclimatic record back to 30 ka BP for the first time—but also provides a reliable basis for

research on vegetation–climate–environment interactions in high-latitude permafrost regions since late MIS 3 and contributes to establishing a permafrost–vegetation–climate feedback framework.

2. Materials and methods

2.1. Study area and sampling

The Huola borehole (HL; 53.0432°N, 122.0479°E) is situated 33 km from Mohe City in the northern Great Hinggan Mountains, Northeast China (Fig. 1), within a low-relief, eroded low-mountain terrain.

The Huola Basin is a headwater catchment of the Gulihe River, a tributary of the Emuer River, and represents one of the intermontane basins within the low-to-medium mountain terrain of the northern Great Hinggan Mountains^{27,28}. It lies on the western margin of the Mohe Basin and covers an area of approximately 60 km². Controlled by regional geological structures, the basin trends NE, with higher terrain in the north and lower terrain in the south; its mean elevation is approximately 450 m, and it is surrounded by low mountains and hills²⁹. The basin originated as a Mesozoic fault-depression basin in which the Quaternary strata are relatively well developed; the dominant genetic types are residual and colluvial deposits, comprising silty clay, gravel-bearing silty clay, and gravel beds with a total thickness of 3–8 m^{15,17}. The principal drainage within the basin consists of the Gulihe and Huola rivers. The vegetation belongs to the cold-temperate coniferous forest type: the surrounding mountains display a forested landscape, whereas within the basin shrubs such as *Vaccinium* spp. and *Betula fruticosa* are abundant, and tussocks and mosses are well developed²⁹.

The Mohe Basin, within which the Huola Basin is situated, lies at the southern margin of the Eurasian permafrost zone and belongs to the discontinuous permafrost zone. The climate is cold-temperate and continental monsoonal: winters, under the influence of the Mongolia–Siberia High, are cold and dry, whereas summers, governed by Pacific air masses, are short, mild, and rainy. The mean January temperature is –29.7°C, with an extreme winter minimum of –53.0°C; the mean July temperature is 19.8°C; the mean annual temperature is –4.9°C; and the mean annual precipitation is approximately 468.9 mm, of which more than 80% falls during July–September. The ground surface remains frozen for more than eight months each year, ground temperatures stay below 0°C throughout the year, and the active layer thaws from April to September^{9,27,28,30}. The mean thickness of active layer within the permafrost in summer is approximately 3–5 m; the permafrost attains a mean thickness of 60 m and a maximum of 120 m^{5,31} and underlies an area of approximately 1.84 × 10⁴ km².

The Huola borehole was drilled in August 2024 under project code GLZK05. The upper part of the core consists of Quaternary colluvial deposits approximately 4.15 m in thickness, recovered with a core diameter of 110 mm. The interval of 0–160 cm comprises dark-brown loam with a crumb (granular) structure, relatively moist and compact; the interval of 160–415 cm comprises yellowish-brown sandy soil, compact and relatively moist, containing iron–manganese nodules, charcoal particles, and rust-coloured mottles and streaks. The deposits of the 0–415 cm interval were formed in a fluvial

sedimentary environment. Samples for pollen, grain-size, and magnetic susceptibility analyses were collected at 18 cm intervals down-core for palaeoenvironmental proxy analysis, and AMS ^{14}C and OSL samples were taken at additional depths for age determination.

2.2. Chronology

To establish the chronological framework of the strata, two AMS ^{14}C samples and four OSL samples were collected at various core depths. The AMS ^{14}C samples, each comprising 100 g of organic sediment, were packed in sealed, labelled polyethylene bags and analyzed at Beta Analytic Inc. (Miami, USA) using an NEC accelerator mass spectrometer coupled with a Thermo Scientific isotope ratio mass spectrometer (IRMS). Calibrated ages (2σ ranges) were obtained using BetaCal 4.2 with the highest-probability-density (HPD) method and the IntCal20 calibration curve.

OSL sampling was performed using steel tubes (10 cm in diameter) that were driven into the target layers immediately after drilling and prior to core hardening. The ends of the tubes were sealed with wooden plugs and wrapped in opaque material to prevent light exposure. Samples were sent to the Research Center of Palaeontology and Stratigraphy, Jilin University, where OSL dating was performed using a Risø TL/OSL-DA-20 luminescence reader under controlled laboratory conditions (23–25°C and 30–50% relative humidity). Equivalent doses were determined using the single-aliquot regenerative-dose (SAR) protocol: an OSL growth curve was established for each sample, and the natural OSL counts were projected onto the growth curve to obtain the equivalent dose. The annual dose rate was calculated from measurements of the radionuclide contents of the samples, and the burial age was obtained by dividing the equivalent dose by the annual dose rate.

2.3. Pollen analysis

Altogether, 23 fossil sediment samples were analyzed palynologically following conventional methods³⁴. Laboratory preparation involved treatment with hydrochloric acid (HCl), sodium hydroxide (NaOH), and hydrofluoric acid (HF), acetolysis with a 9:1 mixture of acetic anhydride and concentrated sulfuric acid, sieving through a 10- μm mesh screen in an ultrasonic bath, and mounting in glycerine. One Lycopodium tablet (5155 grains per tablet) was added to each sample at the beginning of pretreatment as a tracer to estimate absolute pollen concentrations (grains/g). Pollen identification and counting were carried out under an Olympus BX-51 light microscope at 400 $\times$ magnification, with the aid of the published pollen atlases of Wang et al.³⁵ and Tang et al.³⁶. More than 400 terrestrial pollen grains were identified and counted per sample where pollen preservation permitted. The total sum of terrestrial pollen taxa in each sample was used as the denominator when calculating pollen percentages, whereas the percentage of Sphagnum was calculated on the sum of terrestrial pollen plus Sphagnum. The pollen diagram was drawn using Tilia version 1.7.16, with a 10-fold exaggeration applied to the pollen percentages, and pollen-assemblage zones were delimited on the basis of stratigraphically constrained cluster analysis (CONISS).

2.4. Grain-size and magnetic susceptibility analyses

The granulometric analysis samples were sent to the Institute of Geophysical and Geochemical Exploration, Chinese Academy of Geological Sciences. In the laboratory, organic matter was removed using 10 mL of 30% H₂O₂, followed by the addition of 10 mL of 10% HCl to eliminate carbonates. After rinsing with distilled water and centrifugation, 10 mL of 0.05 mol/L sodium hexametaphosphate ((NaPO₃)₆) was added as a dispersant, and the samples were dispersed by oscillation. Distilled water was added again before measurement. The grain-size distribution was determined using a Malvern Mastersizer 3000 laser diffraction particle-size analyzer (measurement range 0.01–3500 µm; repeatability error < 0.2%).

Magnetic susceptibility (MS) samples were collected in non-magnetic cubic plastic boxes (2 cm × 2 cm × 2 cm). Measurements were performed at the Research Center of Palaeontology and Stratigraphy, Jilin University, using a Bartington MS-2 magnetic susceptibility meter, with the test conditions maintained at 20–22°C and 39–40% relative humidity.

2.5. Numerical analyses

Based on the sample suite analyzed from the Huola borehole, six indicators sensitive to climatic and environmental change were selected: conifer pollen, broad-leaved tree pollen, shrub and herb pollen, coarse silt content (16–63 µm), M_d , and magnetic susceptibility. Their interrelationships were investigated through principal component analysis (PCA). Prior to analysis, all variables were standardized (z-scores) to eliminate the influence of differing units and scales; the PCA was therefore based on the correlation matrix. Principal components with eigenvalues > 1 were extracted, and the first two components (PC1 and PC2), which jointly explain 68.0% of the total variance, were retained for interpretation. Variable loadings and sample scores are jointly displayed in a biplot to visualize the associations between variables and samples. All statistical analyses were performed in OriginPro 2021 using the PCA function.

3. Results

3.1. Dating results

The results of the age determinations are presented in Fig. 2. The two AMS ¹⁴C samples were collected from shallow depths of 0 m and 0.13 m and yielded calibrated ages of 620 ± 30 and 1470 ± 30 cal yr BP, respectively. The four OSL samples were collected between 0.21 m and 4.02 m and yielded ages of 6.16 ± 1.09 to 29.65 ± 5.31 ka BP. Linear regression through all six age determinations yields a strong linear fit ($R^2 = 0.9882$). Extrapolation indicates that the base of the core (4.15 m) corresponds to approximately 30 ka BP, within MIS 3 (Stuiver and Grootes, 2000), which facilitates subsequent comparison with existing regional records.

3.2. Pollen assemblages of the Huola borehole

The total pollen concentration varies among samples, reflecting differences in vegetation abundance through time; such variations are closely related to climatic conditions and the sedimentary environment. Detailed identification and analysis revealed that all 23 samples yielded Quaternary pollen assemblages, with the total counted pollen grains ranging from 61 to 616 per sample. A total of 24 families and 33 genera were identified, representing predominantly cool-temperate plant taxa with minor warm-temperate elements. The pollen types occurring in relatively high abundances include *Pinus* (pine), *Betula* (birch), *Patrinia*, *Artemisia* (mugwort), *Ericaceae* (heath family), and reticulate-type *Asteraceae* (aster family). Based on cluster analysis of the total pollen concentration and relative pollen percentages (Fig. 3), the Huola borehole sequence can be subdivided, from bottom to top, into four distinct pollen-assemblage zones, characterized as follows.

Pollen Zone I (415–350 cm; 30.0–26.7 ka BP) is dominated by coniferous pollen (62.12–94.29%), with relatively minor contributions from shrub and terrestrial herb pollen (2.0–24.32%) and deciduous broad-leaved tree pollen (0–21.97%). Among the conifers, *Pinus* pollen is predominant (62.12–94.29%), whereas *Picea* pollen occurs only sporadically (0–1.0%). The overall pollen concentration in this zone is extremely low, indicating sparse local vegetation during deposition. Although *Pinus* pollen is the most abundant taxon, its absolute abundance remains low because of the overall paucity of palynomorphs, suggesting only a limited local presence of pine trees. Deciduous broad-leaved trees, shrubs, and terrestrial herbs are likewise scarce, collectively pointing to a cool and arid depositional environment.

Pollen Zone II (350–160 cm; 26.7–13.36 ka BP) is dominated by coniferous pollen (77.23–94.23%), followed by substantially lower proportions of shrub and terrestrial herb pollen (3.37–16.19%) and deciduous broad-leaved tree pollen (2.16–9.46%), with fern spores occurring only in trace amounts (0–1.13%). Among the conifers, *Pinus* pollen is the most abundant (77.23–93.75%), whereas *Picea* pollen occurs only sporadically (0–0.95%). Among the deciduous broad-leaved trees, *Betula* (0–6.08%), *Corylus* (0–2.70%), *Carpinus* (0–1.08%), *Tilia* (0–0.95%), *Alnus* (0–0.68%), and *Quercus* (0–0.28%) are all present in minor quantities. The total pollen concentration is relatively high at the base of this zone but remains low in the middle and upper sections, indicating that, during the early phase of deposition, the vegetation cover near the coring site was relatively dense and dominated by well-developed pine forest, with only sparse representation of deciduous broad-leaved trees, shrubs, and terrestrial herbs—suggesting a cold and dry depositional environment.

Pollen Zone III (160–88 cm; 13.36–8.29 ka BP) is dominated by coniferous pollen (40.49–77.42%), accompanied by relatively abundant shrub and terrestrial herb pollen (11.98–48.29%) and minor occurrences of deciduous broad-leaved tree pollen (6.07–9.68%) and fern spores (0.92–2.44%). The total pollen concentration toward the top of this zone is comparatively high, varying between 96 and 331 grains/g, indicating substantial vegetation cover near the coring site during the late depositional phase and relatively vigorous development of pine forest. The proportion of coniferous pollen declines to 40–77%, while shrub and terrestrial herb pollen increases markedly relative to Pollen Zone II, suggesting a cool and temperate, gradually warming depositional environment.

Pollen Zone IV (88–0 cm; 8.29 ka BP to present) is dominated by coniferous pollen (74.91–95.99%), with relatively minor contributions from deciduous broad-leaved pollen (2.37–18.73%) and sparse occurrences of shrub and terrestrial herb pollen (1.64–6.37%). Among the conifers, *Pinus* pollen is the most abundant (74.91–95.99%), whereas *Picea* pollen occurs only in trace amounts (0–0.16%). Within the deciduous broad-leaved group, *Betula* pollen is the most prevalent (1.82–11.61%), while minor quantities of *Carpinus* (0.18–3.93%), *Alnus* (0–1.87%), *Corylus* (0–1.31%), and *Quercus* (0–0.36%) pollen are also present. The total pollen concentration in this zone is exceptionally high, indicating dense local vegetation cover during deposition—characterized by vigorous pine growth and a relatively abundant presence of cold- and moisture-adapted deciduous broad-leaved trees, particularly birch. The frequent occurrence of *Sphagnum* spores further suggests well-developed peatland environments near the coring site during this period.

3.3. Grain-size and magnetic susceptibility results

Following the widely accepted grain-size classification boundaries of 63, 16, and 4 μm , the sand, coarse silt, fine silt, and clay fractions were distinguished^{37–41}. The grain-size results (Table 1) show that the coarse silt fraction (16–63 μm) comprises 18.45–40.64% of the samples, with an average of 25.99%. Grain-size parameters were calculated using the formulae of Folk and Ward⁴²; the M_d ranges from 5.51 to 14.20 μm , with a mean of 9.78 μm .

The magnetic susceptibility of the Huola borehole ranges from 5.6 to $20.4 \times 10^{-8} \text{m}^3/\text{kg}$, with an average of $12.86 \times 10^{-8} \text{m}^3/\text{kg}$. Magnetic susceptibility generally increases in the upper part of the borehole, indicating enhanced pedogenesis and a climatic trend toward warmer and more humid conditions. In the lower part of the borehole, magnetic susceptibility exhibits low-amplitude oscillations, with the frequency-dependent susceptibility (fd%) repeatedly exceeding 10%, suggesting localized enrichment of fine-grained superparamagnetic particles and relatively intense pedogenic weathering. Magnetic susceptibility correlates well with the grain-size data, collectively reflecting an overall climatic shift from cold–arid to warm–humid conditions with pronounced fluctuations; this interpretation is well supported by the palynological record.

Table 1
Grain-size and magnetic susceptibility data of the Huola borehole samples

Grain-size sample	Coarse silt 16 ~ 63 $\mu\text{m}/\%$	$M_d/\mu\text{m}$	Magnetic susceptibility sample	High-frequency magnetic susceptibility/ $10^{-8} \text{ m}^3/\text{kg}$
L01	31.927199	11.91	CHL01	9.3
L02	31.222527	11.23	CHL02	10.05
L03	31.036742	11.28	CHL03	13.1
L04	31.705276	11.81	CHL04	18.45
L05	35.051489	12.72	CHL05	9.9
L06	40.636737	14.20	CHL06	11.2
L07	35.965482	12.32	CHL07	10.8
L08	30.310542	10.55	CHL08	12.8
L09	25.801332	9.28	CHL09	13.4
L10	22.650494	8.56	CHL10	14.0
L11	20.474219	7.96	CHL11	15.6
L12	20.105984	9.21	CHL12	17.8
L13	20.908427	7.07	CHL13	9.0
L14	21.857643	6.94	CHL14	10.9
L15	22.129641	5.51	CHL15	13.4
L16	24.097665	9.45	CHL16	5.6
L17	22.825605	10.63	CHL17	16.4
L18	20.897665	11.04	CHL18	12.3
L19	19.425476	8.87	CHL19	10.6
L20	18.448553	7.81	CHL20	16.7
L21	19.897665	8.76	CHL21	10.8
L22	24.133811	9.23	CHL22	20.4
L23	26.404914	8.61	CHL23	13.2

3.4. Principal component analysis

The PCA results indicate that PC1 accounts for 38.58% of the total variance and PC2 for 29.41%, jointly explaining approximately 68% of the total variance and thus demonstrating satisfactory

representativeness (Fig. 4). PC1 reflects an environmental gradient characterized by a transition of sediment grain size from coarse to fine coupled with a vegetation shift from broad-leaved/herbaceous to coniferous. PC2 likely represents temperature and moisture conditions: broad-leaved forest co-occurs with enhanced magnetic susceptibility under warm–humid conditions, whereas coniferous forest is associated with coarser sediment under cold–dry conditions. The samples are densely clustered along the negative direction (left side) of PC1, predominantly representing coniferous forest and fine-grained sedimentary environments. In contrast, samples along the positive direction (right side) of PC1 are sparsely distributed but exhibit substantial vertical spread, indicating greater variability among samples from broad-leaved/shrub–herb vegetation environments. The distribution of samples along PC2 is relatively uniform, with no distinct clustering, suggesting that variation along PC2 is gradual rather than discrete.

The PCA plot reveals a coupling between depositional environments and vegetation types: (1) coarse-grained deposits (high coarse-silt content) are primarily associated with deciduous broad-leaved forest and shrub–herb communities; (2) fine-grained deposits characterized by high magnetic susceptibility are predominantly linked to coniferous forest; (3) coniferous and broad-leaved vegetation exhibit a pronounced negative correlation across the study area, indicating marked habitat differentiation; and (4) the first two principal components jointly account for nearly 68% of the total variance, suggesting that grain size, magnetic susceptibility, and vegetation composition are the primary controlling factors of palaeoenvironmental change in this region.

4. Discussion

4.1. Vegetation and climate change in the Huola Basin

Based on stratigraphically constrained cluster analysis (CONISS) of the pollen data (Fig. 4), the Huola borehole sequence is subdivided into four pollen-assemblage zones with boundaries at 26.7, 13.36, and 8.29 ka BP. Notably, these boundaries correspond closely to major events in the global climatic sequence: the Zone I/II boundary at ca. 26.7 ka BP coincides with the onset of the Last Glacial Maximum⁴³ (LGM, ca. 26.5–19 ka BP); the Zone II/III boundary at ca. 13.36 ka BP broadly coincides, within the dating uncertainties of the OSL-based age model, with the end of Heinrich Stadial 1 and the onset of Bølling-type deglacial warming (ca. 14.7 ka BP); and the Zone III/IV boundary at ca. 8.29 ka BP coincides, within dating uncertainty, with the 8.2 ka cold event. This close correspondence indicates that the vegetation and hydrological history of the Huola Basin was paced by hemispheric-scale climatic variations, the drivers and feedbacks of which are discussed below.

4.1.1. Pollen Zone I (30.0–26.7 ka BP): Open, sparsely wooded landscape under a cool and arid climate

Pollen Zone I (30.0–26.7 ka BP) is overwhelmingly dominated by coniferous pollen (62.1–94.3%, almost entirely *Pinus*), with only sporadic *Picea* (0–1.0%) and minor proportions of deciduous broad-leaved taxa (0–22.0%) and shrub and terrestrial herb pollen (2.0–24.3%). Crucially, the total pollen concentration of

this zone is extremely low, indicating very sparse vegetation cover around the coring site during deposition. Given the well-documented over-representation of *Pinus* pollen—owing to its high productivity, buoyancy, and capacity for long-distance dispersal—the high relative percentage but low absolute abundance of *Pinus* most likely reflects a combination of long-distance transport and minimal local input, rather than dense local pine forest. We therefore infer that, during late MIS 3, the Huola Basin supported an open, sparsely wooded landscape characterized by scattered pines on well-drained sites and a poorly developed shrub–herb understory, under a cool and arid climate.

This interpretation indicates that climatic deterioration toward full-glacial conditions had already commenced before the LGM. It is consistent with the inference that permafrost re-expanded across northeastern China during late MIS 3^{9,44,45}; harsh permafrost conditions, with shallow active layers, restricted rooting space, and low soil nutrient availability, would have suppressed woody vegetation and may directly account for the extremely low pollen concentration of this zone. The interval thus records a long-term climatic transition into the LGM rather than an abrupt deterioration at ca. 26.5 ka BP. The relatively fine grain size of the corresponding sediments (coarse silt 18.45–26.40%, M_d 7.81–9.23 μm) indicates weak hydrodynamic energy within a sparsely vegetated catchment, consistent with this reconstruction.

4.1.2. Pollen Zone II (26.7–13.36 ka BP): Open pine woodland–steppe under the LGM permafrost maximum – cold and dry

Pollen Zone II (26.7–13.36 ka BP) spans the Last Glacial Maximum (LGM, ca. 26.5–19 ka BP) and Heinrich Stadial 1. Coniferous pollen remains dominant throughout (77.2–94.2%, almost entirely *Pinus*), whereas shrub and terrestrial herb pollen (3.4–16.2%) and deciduous broad-leaved taxa (2.2–9.5%) are consistently minor, and fern spores occur only in trace amounts. The total pollen concentration is relatively high at the base of the zone but declines markedly in its middle and upper parts, suggesting that relatively dense pine stands persisted locally during the initial phase of the LGM but that vegetation cover thinned progressively as full-glacial conditions intensified. The landscape is interpreted as open pine woodland–steppe under a cold and dry climate, representing the coldest and driest interval of the last 30 ka recorded at this site.

This reconstruction is consistent with the "Last Permafrost Maximum" documented for northeastern China^{4,9,44}, when the southern limit of permafrost shifted 4–5° of latitude southward to 41–42°N and the total permafrost area of China reached $5.3\text{--}5.4 \times 10^6 \text{ km}^2$, roughly three times its present extent. The Huola Basin would then have been located within the core of this permafrost zone. Permafrost expansion restricts rooting depth, reduces soil nutrient cycling, and lowers soil moisture availability, thereby suppressing woody vegetation—providing a mechanistic explanation for the low pollen concentrations of the middle and upper parts of Zone II.

Grain-size data provide an independent line of evidence for full-glacial environmental severity⁴⁶. The LGM sample (L15, 21–23 ka BP) yields the finest median grain size of the entire core (M_d = 5.51 μm) together

with a low coarse-silt content (22.13%), indicating the accumulation of fine-grained sediments under weak hydrodynamic energy within a sparsely vegetated, frozen catchment; a supplementary input of periglacial aeolian dust under cold, dry, and windy conditions cannot be excluded, by analogy with the loessic deposits that accumulated during the same interval on the adjacent Songnen Plain^{38,41,47–49}. Magnetic susceptibility in this interval maintains low values with low-amplitude oscillations, consistent with weak pedogenesis and limited organic matter input under the cold, arid full-glacial climate.

4.1.3. Pollen Zone III (13.36–8.29 ka BP): Shrub–herb expansion during deglacial warming – cool and temperate

Pollen Zone III (13.36–8.29 ka BP) records the most pronounced vegetation turnover of the entire sequence: shrub and terrestrial herb pollen increases markedly to 11.98–48.29%, coniferous pollen declines to 40.49–77.42%, and deciduous broad-leaved taxa are continuously represented (6.07–9.68%), with fern spores slightly more abundant than before (0.92–2.44%). The total pollen concentration rises toward the top of the zone (96–331 grains/g), indicating substantial recovery of vegetation cover. The timing of this turnover broadly coincides, within dating uncertainty, with the end of Heinrich Stadial 1 and the onset of Northern Hemisphere deglacial warming (ca. 14.7 ka BP), implying that the shrub–herb expansion was a direct ecological response to deglaciation⁵⁰. The sequence—pioneering shrub and herb communities expanding first, followed by the re-establishment of dense coniferous forest—is characteristic of deglacial vegetation succession in periglacial landscapes.

Sedimentological evidence corroborates the deglacial intensification of hydrological processes: the coarse-silt content and M_d increase progressively through the zone and culminate in the maxima of the entire core (40.64% and 14.20 μm , sample L06, ca. 8–9 ka BP), indicating enhanced fluvial competence and sediment supply attributable to intensified meltwater discharge and catchment reworking accompanying permafrost thaw and snow–ice depletion in the surrounding mountains. The PCA results support this interpretation: samples of this interval shift toward the positive direction of PC1, reflecting the coupled expansion of broad-leaved, shrub, and herbaceous vegetation together with coarser sediments—that is, the coincidence of deglacial hydrodynamic enhancement with pioneer-community expansion. Warmth- and moisture-dependent magnetic susceptibility begins to increase in this interval, marking the onset of intensified pedogenesis after the LGM.

The deglacial warming trend in the Huola Basin is broadly consistent with the abrupt warming recorded in the Greenland GISP2 $\delta^{18}\text{O}$ record at the Bølling transition⁵¹ and with post-LGM sea-level rise⁵², whereas the pronounced local humidification indicates that meltwater release from degrading permafrost and residual snow and ice provided an additional, regionally amplified moisture source superimposed on the hemispheric temperature signal⁵³.

4.1.4. Pollen Zone IV (8.29 ka BP to present): Coniferous forest–peatland development under a cold and humid climate

Pollen Zone IV (8.29 ka BP to present) is characterized by exceptionally high pollen concentrations, overwhelming dominance of *Pinus* pollen (74.9–96.0%) with substantial *Betula* (1.8–11.6%), and the frequent occurrence of *Sphagnum* spores. These data indicate the establishment of dense conifer–birch forest together with well-developed peatland environments near the coring site, under a cold and humid climate. The initiation of peat accumulation at ca. 8.3 ka BP coincides, within dating uncertainty, with the global 8.2 ka cold event and with the regional onset of rapid wetland expansion across northeastern China at ca. 8 ka BP, suggesting that enhanced moisture retention associated with deglaciated but still continuously frozen ground provided the hydrological threshold for peatland initiation. The accompanying decline in M_d (to 11.2–12.7 μm) and coarse-silt content (31.0–35.1%) reflects the stabilization of the catchment under denser vegetation cover and an expanding wetland, and the generally rising magnetic susceptibility with high $fd\%$ (> 10%) records intensified pedogenesis and organic matter input during the Holocene.

Notably, the expression of the Holocene Climatic Optimum (HCO) in this high-latitude permafrost basin differs fundamentally from that in the monsoon core regions of China, where the optimum is marked by a pronounced expansion of thermophilous broad-leaved trees. In the Huola borehole record, coniferous forest persists throughout the Holocene: even during the mid-Holocene optimum (8.3–5.8 ka BP), *Pinus* remains overwhelmingly dominant and the broad-leaved component never exceeds 18.7%. This indicates that temperatures in the Huola Basin remained comparatively low relative to other monsoonal regions of China, in agreement with regional pollen syntheses for the northern sector of Northeast China¹⁹. In this permafrost setting, the climatic optimum is therefore expressed primarily in hydrological rather than thermal terms—maximum vegetation density, exceptional pollen concentrations, and vigorous peat accumulation—reflecting the joint effect of peak EASM moisture delivery and permafrost-controlled water retention (see Sections 4.3.2 and 4.3.3).

Toward the late Holocene, the continued dominance of cold- and moisture-adapted *Pinus*, the persistent occurrence of *Sphagnum*, and sustained high pollen concentrations indicate progressive cooling accompanied by maintained, and possibly increased, surface wetness. As the climate cooled, permafrost re-expansion impeded subsurface drainage, promoting surface-water accumulation and peatland maintenance, which in turn favoured moisture-adapted coniferous forest. This dynamic is consistent with the Neoglaciation documented for northeastern China, when the climate cooled again from 4 ka BP, reached its coldest phase at 2800–2700 cal yr BP, and permafrost re-expanded to an extent 20–30% larger than at present^{9,54}. A mosaic landscape of coniferous forest–peatland ecotones was thereby established, indicative of the cool and humid climate that characterized the late Holocene in the Huola Basin.

4.2. Regional climate change at the EASM margin

4.2.1. Comparison with records from the northern Great Hinggan Mountains: Beiji wetland and Tuqiang peatland

The Beiji wetland record (BJC-3 core), located 51.3 km from the Huola Basin within the Mohe permafrost region, provides the most direct regional comparison, as both records span the last 30 ka BP^{11–13}. From the LGM through the Holocene the two records show broadly consistent patterns: cold and dry full-glacial conditions, deglacial vegetation recovery, and maximum Holocene vegetation density with late Holocene coniferous forest–wetland development. However, they diverge markedly during MIS 3: the Beiji wetland record indicates cold and humid conditions with well-developed meadow wetland and abundant aquatic vegetation, whereas the Huola borehole record yields extremely low pollen concentrations and an open, sparsely wooded landscape under cool and arid conditions. At least three factors may account for this divergence. First, the chronological windows differ: the Huola borehole covers only late MIS 3 (30.0–26.7 ka BP), when summer insolation had already declined and the climate was deteriorating toward the LGM, whereas the Beiji record encompasses the relatively mild pleniglacial portion of MIS 3. Second, the depositional settings differ: the fluvial clastic sediments of the Huola borehole may dilute pollen concentrations relative to the organic-rich wetland deposits at Beiji, so concentration-based inferences of vegetation density must be made with caution⁵⁵. Third, the hydrological contrasts between an enclosed intermontane basin and a floodplain wetland imply different moisture sources and taphonomic conditions⁵³. These differences highlight the importance of sedimentary context in palynological comparison and suggest that the onset of full-glacial aridity was diachronous across the Mohe permafrost region.

Comparison with the Tuqiang (TQ) peatland record²⁰, which covers the last 3300 cal yr BP at high resolution, is relevant to the upper part of Zone IV. The cool and humid phases of the TQ record, characterized by pine forest expansion, are consistent with the sustained coniferous forest–peatland conditions recorded in the Huola borehole. However, the cold–dry interval of the TQ record (600–300 cal yr BP, corresponding to the Little Ice Age) and the subsequent warm–dry trend are not clearly expressed at Huola. This discrepancy is most readily attributed to differences in topographic and hydrological setting: the enclosed Huola Basin, underlain by continuous permafrost acting as an aquiclude, retains surface water effectively and buffers local hydrology against centennial-scale precipitation variability, whereas the TQ site is more sensitive to direct precipitation changes. The TQ record overlaps only with the uppermost part of the Huola record, covering one-tenth of its duration (ca. 3 ka); consequently, the 18-cm sampling interval of the Huola borehole cannot resolve centennial-scale events such as those captured at TQ.

The Tuofengling Lake biomarkers record³³, from a crater lake in the central Great Khinggan Mountains, provides an additional regional benchmark: it documents cold and dry conditions during the LGM followed by stepwise hydroclimatic amelioration through the Holocene, a sequence consistent with that recorded in the Huola Basin and supporting the regional coherence of the climatic evolution in the Great Hinggan Mountains.

4.2.2. Comparison with records from the marginal zone of the East Asian monsoon: Hulun Lake and the Huola Basin

Hulun Lake is located at the present-day northern margin of the EASM, approximately 6° of latitude south of the Huola Basin. The Hulun Lake record spans the entire Holocene and provides a critical comparison for understanding monsoon-margin dynamics. It shows that during the early Holocene (11–8 ka BP) temperatures reached their Holocene maximum while precipitation remained relatively low (~ 300 mm); precipitation increased significantly at ca. 8 ka BP (reaching ~ 340 mm) and then declined gradually, with an extreme dry interval at 4400–3350 cal yr BP (~ 260 mm).

The Huola borehole record displays a markedly different moisture trajectory. During the early Holocene portion of Zone III (13.36–8.29 ka BP), conditions were gradually ameliorating but the basin remained relatively dry, as evidenced by modest pollen concentrations and the absence of peatland indicators—consistent with limited monsoon penetration into the northern Great Hinggan Mountains at that time, as also recorded at Hulun Lake. In striking contrast, the abrupt humidification at ca. 8.3 ka BP at Huola—recorded by the initiation of peat accumulation, exceptional pollen concentrations, and the expansion of *Sphagnum*—coincides closely with the precipitation increase at Hulun Lake at ca. 8 ka BP. This synchronicity suggests that the northward migration of the EASM front at ca. 8 ka BP enhanced moisture delivery to the northern Great Hinggan Mountains, superimposed on local permafrost-controlled hydrological feedbacks that amplified the effective humidity of the basin.

For the late Holocene, the two records diverge in opposite directions: Hulun Lake records progressively decreasing precipitation under a weakening EASM, including the extreme dry interval at 4400–3350 cal yr BP, whereas the Huola Basin maintained, and likely increased, its humidity, as shown by sustained high pollen concentrations and persistent peatland conditions. This contrast demonstrates a pronounced north–south gradient in moisture response across the EASM margin: in the south, late Holocene humidity is governed primarily by monsoon precipitation; in the northern permafrost region, cooling-driven permafrost aggradation impedes infiltration and promotes surface-water accumulation, locally compensating for—and potentially exceeding—the reduced monsoonal precipitation. In this respect, the Hulun Lake dry interval at 4400–3350 cal yr BP has no counterpart at Huola, underscoring the buffering role of the permafrost aquiclude.

The comparison with the earlier Huola Basin record from Yueya Lake¹⁹ (9100 cal yr BP to present) shows good consistency for the overlapping period, with both records documenting coniferous forest dominance, a mid-Holocene optimum expressed primarily as maximum forest development, and late Holocene cold-temperate vegetation. The Huola borehole record extends the palaeoclimatic archive of the Huola Basin back to 30 ka BP, revealing for the first time the full-glacial and late MIS 3 history of the basin, which was not covered by previous investigations^{8,17}.

4.2.3. Comparison with global records: Greenland GISP2 $\delta^{18}\text{O}$ and sea level in the Sea of Japan

The Greenland GISP2 $\delta^{18}\text{O}$ record provides a benchmark for hemispheric temperature variability⁵¹. The Huola borehole record is broadly consistent with this sequence: the cold and arid conditions of Zone I

(30.0–26.7 ka BP) correspond to the declining late MIS 3 interstadial in Greenland, marking the transition toward full-glacial conditions; Zone II (26.7–13.36 ka BP) corresponds to the coldest phase of the last 30 kyr, encompassing the LGM and Heinrich Stadial 1; the pronounced vegetation turnover of Zone III coincides with the abrupt deglacial warming at the Bølling transition; and Zone IV corresponds to the Holocene, within which the progressive establishment of the conifer–peatland system mirrors the gradual late Holocene cooling. Deviations between the records arise mainly from local moisture variability—driven by monsoon dynamics and permafrost hydrology—that is not expressed in the Greenland temperature signal, underscoring the role of regional processes in shaping the climate of the EASM margin.

The Sea of Japan sea-level record reflects global ice-volume changes⁵². The LGM sea-level lowstand of – 120 m corresponds to the maximum permafrost expansion and the coldest, driest conditions of Zone II in the Huola Basin; the rapid deglacial sea-level rise corresponds to the warming, hydrodynamic intensification, and shrub–herb expansion of Zone III; and the Holocene highstand corresponds to the establishment of the conifer–peatland system of Zone IV⁴⁶. The close coupling between sea level, global ice volume, and the Huola Basin palaeoenvironmental sequence indicates that long-term climatic evolution in this high-latitude permafrost region was ultimately regulated by hemispheric-scale ice-volume and temperature changes, upon which monsoon and permafrost-related feedbacks were superimposed.

4.3. Possible forcing mechanisms of climate change at the EASM margin

The Quaternary climatic and environmental evolution of the Mohe permafrost region was remotely regulated by global ice-volume–temperature variations while being simultaneously modulated by EASM precipitation changes and local geomorphic processes, producing an evolutionary record that exhibits both global coherence and regional distinctiveness.

4.3.1. Orbital-scale forcing: Northern Hemisphere summer insolation

Long-term climatic evolution in the Huola Basin was primarily paced by variations in Northern Hemisphere summer insolation⁵⁷. During late MIS 3 (30.0–26.7 ka BP), declining summer insolation is consistent with the sparse vegetation and cool, arid conditions of Zone I, indicating that the climate had already entered a deteriorating orbital-scale trend well before the LGM; the subsequent insolation minimum during the LGM corresponds to the coldest and driest conditions of Zone II. The post-14.7 ka increase in summer insolation drove the deglacial warming recorded by the shrub–herb expansion and hydrodynamic intensification of Zone III. The early Holocene insolation maximum laid the orbital foundation for the vegetation recovery and hydrological amelioration of the basin⁵⁶, whose culmination—maximum vegetation density and peatland development—occurred after ca. 8.3 ka BP under the joint influence of peak monsoon moisture delivery and permafrost-controlled water retention. The gradual

decline in summer insolation after 8 ka BP matches the progressive cooling recorded within Zone IV, expressed as the persistent dominance of cold-adapted coniferous forest and the sustained development of peatlands. The overall correspondence between the Huola borehole record and the insolation curve confirms orbital forcing as the primary driver of long-term climate trends at the EASM margin, whereas the amplitude and precise timing of local responses were modulated by monsoon dynamics, permafrost feedbacks, and ocean–atmosphere interactions, as discussed below.

4.3.2. Variations of the East Asian monsoon system

The EASM constitutes the primary moisture source for its northern marginal zone, and the Huola Basin, lying at the northern edge of the modern EASM influence zone, is particularly sensitive to variations in monsoon intensity. Three stages can be recognized in the Huola borehole record.

Early stage (13.36–8.29 ka BP, Zone III): the EASM was strengthening but had not yet reached its maximum northern extent, as indicated by the relatively low early Holocene precipitation (~ 300 mm) reconstructed at Hulun Lake¹⁴. Consistently, the Huola Basin at this time shows gradual climatic amelioration but no peatland development and only moderate pollen concentrations, suggesting that effective moisture was still limited and largely sustained by meltwater from thawing permafrost and residual snow cover rather than by monsoonal precipitation.

Middle stage (8.3 ka BP onward, lower Zone IV): the EASM reached its maximum intensity and northernmost penetration, as reflected in the precipitation peak at Hulun Lake at ca. 8 ka BP. The nearly synchronous initiation of peat accumulation, exceptional pollen concentrations, and Sphagnum expansion at Huola at ca. 8.3 ka BP indicate that the intensification of monsoonal moisture delivery, superimposed on permafrost-controlled water retention, crossed the hydrological threshold required for peatland establishment.

Late stage (late Holocene, upper Zone IV): the EASM gradually weakened, as documented by the Dongge Cave stalagmite $\delta^{18}\text{O}$ record⁵⁸. A weakened monsoon should have reduced precipitation across the EASM margin, yet the Huola Basin records maintained or increased humidity, as reflected in sustained high pollen concentrations and persistent peatland conditions. This apparent paradox is resolved by the permafrost–wetland feedback: cooling-driven permafrost aggradation impeded infiltration and promoted surface-water accumulation, and the local hydrological effect of permafrost compensated for the reduced monsoonal precipitation. A comparable mechanism has been proposed for the Beiji wetland¹¹, where the permafrost environment buffers local moisture conditions against weakening monsoon circulation.

4.3.3. Permafrost–vegetation–climate feedback mechanisms

The Huola borehole record provides direct sedimentary evidence for a permafrost–vegetation–climate feedback that operated throughout the last 30 ka, with contrasting configurations during glacial,

deglacial, and interglacial states^{45,59}.

Glacial state (Zones I–II, 30.0–13.36 ka BP): climatic cooling promoted permafrost expansion and thickening; shallow active layers restricted rooting depth, reduced soil nutrient availability, and limited soil moisture, suppressing woody vegetation and resulting in the extremely low to low pollen concentrations of Zones I–II. The reduction in vegetation cover weakened evapotranspiration and exposed the land surface, promoting local aridification and periglacial aeolian activity—the finest sediments of the entire core occur within the LGM interval, consistent with weak fluvial energy and possible dust accession under a sparsely vegetated, frozen catchment. This positive feedback amplified cold and arid glacial conditions and maintained the open pine woodland–steppe landscape¹³.

Deglacial state (Zone III, 13.36–8.29 ka BP): climatic warming activated permafrost thaw and released large volumes of meltwater, humidifying the basin and enhancing hydrodynamic energy (the grain-size maximum at ca. 8–9 ka BP). Pioneer shrub–herb communities expanded first, vegetation cover recovered (rising pollen concentrations), and catchment stabilization followed.

Interglacial state (Zone IV, 8.29 ka BP to present): the combination of peatland development and the impermeable permafrost table sustained surface-water accumulation, favouring cold- and moisture-adapted coniferous forest (*Pinus* at its maximum). The coupled peatland–conifer system maintained high local humidity through enhanced water storage and evapotranspiration recycling. Critically, during the late Holocene cooling, permafrost re-expansion further strengthened the aquiclude effect, so that basin humidity increased despite the weakening EASM—a positive feedback between cooling, permafrost aggradation, and wetland expansion that produced a cold yet humid environment, in sharp contrast to the drying trend recorded at southern monsoon-margin sites such as Hulun Lake^{60–62}.

This mechanism is supported by the regional comparison: wetland development during warm or humid intervals is systematically more pronounced at permafrost-underlain sites (e.g., the Huola Basin, the Beiji wetland, and the Nenjiang River source wetland) than in non-permafrost regions (e.g., Dali Lake and Sihailongwan Maar Lake), where the absence of a frozen aquiclude allows deeper infiltration and drier surface conditions^{63–66}. The permafrost–wetland feedback therefore constitutes a first-order control on the spatial heterogeneity of hydroclimatic responses across the EASM margin⁶⁷.

4.3.4. Ocean–atmosphere interactions and human activities

Ocean–atmosphere interactions in the tropical Pacific play a critical role in modulating EASM variability. Western tropical Pacific sea surface temperature (SST) and the Kuroshio Current influence the strength and position of the EASM front.

The Hulun Lake record¹⁴ shows that the extreme dry interval at 4400–3350 cal yr BP coincided with a significant drop in western tropical Pacific SST and a weakening of the Kuroshio Current, suggesting that tropical Pacific ocean–atmosphere interactions are important drivers of millennial-scale precipitation

variability in the EASM margin region. The Huola Basin record, with its long time span covering both glacial and interglacial periods, provides an opportunity to investigate how these ocean–atmosphere interactions varied under different background climate states.

During the LGM (Zone II, 26.7–13.36 ka BP), reduced SST and a weaker Kuroshio would have contributed to the reduced EASM intensity and the cold, dry conditions in the Huola Basin. During the early to middle Holocene (Zone IV, after 8.3 ka BP), warmer SST and a stronger Kuroshio would have enhanced the EASM, bringing more moisture to the EASM margin region. The late Holocene cooling and Kuroshio weakening would have reduced the EASM intensity, but the local permafrost–wetland feedback may have compensated for this effect in the permafrost region. Notably, the extreme dry interval at Hulun Lake at 4400–3350 cal yr BP, attributed to reduced western tropical Pacific SST and a weakened Kuroshio Current, finds no counterpart in the Huola record, where pollen concentrations and peatland indicators remained high; the permafrost aquiclude evidently insulated basin hydrology from this millennial-scale monsoon failure.

Human activities, particularly since the mid-to-late Holocene, may have influenced local vegetation. The study of Han et al.²⁰ at the TQ peatland suggests that selective logging and land-use changes since ca. 600 cal yr BP have contributed to the expansion of birch forest and the decline of pine forest. The Huola Basin, being a relatively remote and sparsely populated area, may have been less affected by human activities; however, the modest *Betula* expansion (up to 11.6%) within Zone IV may partially reflect human influence.

5. Conclusions

(1) By integrating AMS ¹⁴C and OSL age determinations, a reliably dated Quaternary chronological framework has been established for the Huola Basin, extending its palaeoclimatic record to 30 ka BP for the first time; linear regression of the six age determinations yields an R² of 0.9882.

(2) The climate and environment of the Huola Basin evolved through four stages: (i) from 30.0 to 26.7 ka BP, vegetation was sparse under cool and arid conditions; (ii) from 26.7 to 13.36 ka BP, the climate was cold and relatively dry, corresponding to the maximum permafrost expansion of the LGM; (iii) from 13.36 to 8.29 ka BP, shrub–herbaceous vegetation expanded under cool, gradually warming conditions, reflecting the deglacial climatic amelioration; and (iv) since 8.29 ka BP, coniferous forest has flourished and peatlands have developed, indicative of a cold and humid climate.

(3) The sediments are characterized by abundant coarse silt (18.45–40.64%), M_d ranges from 5.51 to 14.20 μm , with a mean of 9.78 μm , and the magnetic susceptibility ($5.6\text{--}20.4 \times 10^{-8} \text{m}^3/\text{kg}$) increases up-core, reflecting enhanced Holocene pedogenesis. Principal component analysis indicates that the grain-size–magnetic susceptibility–vegetation assemblage constitutes the primary controlling factor of palaeoenvironmental change.

(4) The evolutionary sequence of the Huola Basin is broadly synchronous with records from the Beiji wetland, Tuofengling Lake, Hulun Lake, the Greenland GISP2 $\delta^{18}\text{O}$ record, and sea-level changes in the Sea of Japan, indicating that basin evolution was remotely regulated by global ice-volume and temperature variations, superimposed on modulation by the East Asian summer monsoon and local permafrost–hydrological processes. Furthermore, this study reveals a positive permafrost–vegetation–climate feedback mechanism.

Declarations

Author contributions (CRediT)

Haonan Song and Zhongkai Liang: writing – review & editing; Yuxue Sun and Yihui Wu: writing – original draft; Shoude Han, Longlong Fu, Youtao Xin and Guoqiang Zhao: data acquisition and processing. All authors reviewed the manuscript.

Declaration of competing interest

This work has not been submitted elsewhere for publication, in whole or in part, and all of the authors listed have approved the manuscript. The authors declare no conflict of interest.

Funding

Geological Survey Project of the China Geological Survey, DD20240100902.

Author Contribution

Haonan Song and Zhongkai Liang: writing – review & editing; Yuxue Sun and Yihui Wu: writing – original draft; Shoude Han, Longlong Fu, Youtao Xin and Guoqiang Zhao: data acquisition and processing. All authors reviewed the manuscript.

Acknowledgement

This research was funded by the Geological Survey Project of the China Geological Survey (Grant No. DD20240100902). The authors express their sincere gratitude to Professor Xie Yuanyun and Dr. Wang Yehui of Harbin Normal University for their guidance and assistance.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

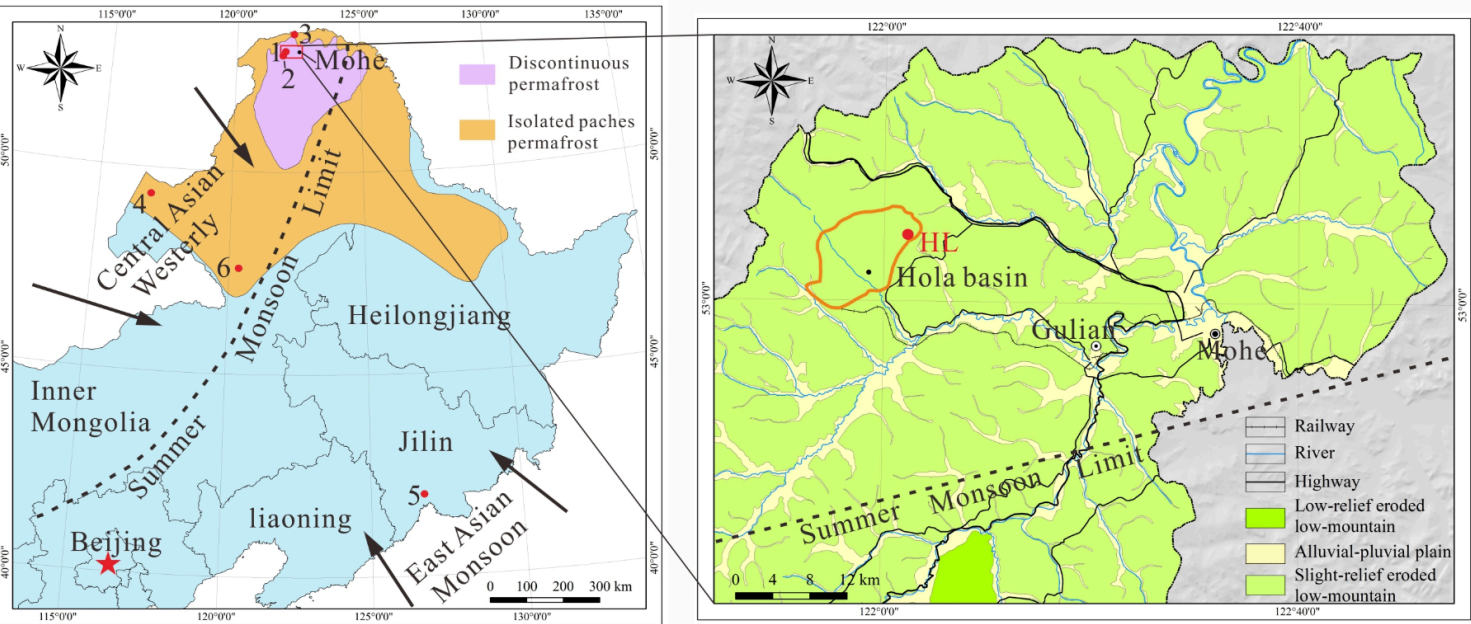


Figure 1

Locations of the Huola Basin in the Great Hinggan Mountains and of the other sites discussed in this study. 1, Huola borehole (HL); 2, Huola Basin^{8,17,19}; 3, Beiji wetland^{11,24}; 4, Hulun Lake¹⁴; 5, Hani and Jinchuan peatlands and Sihailongwan Maar Lake^{22,23,32}; 6, Tuofengling Lake³³.

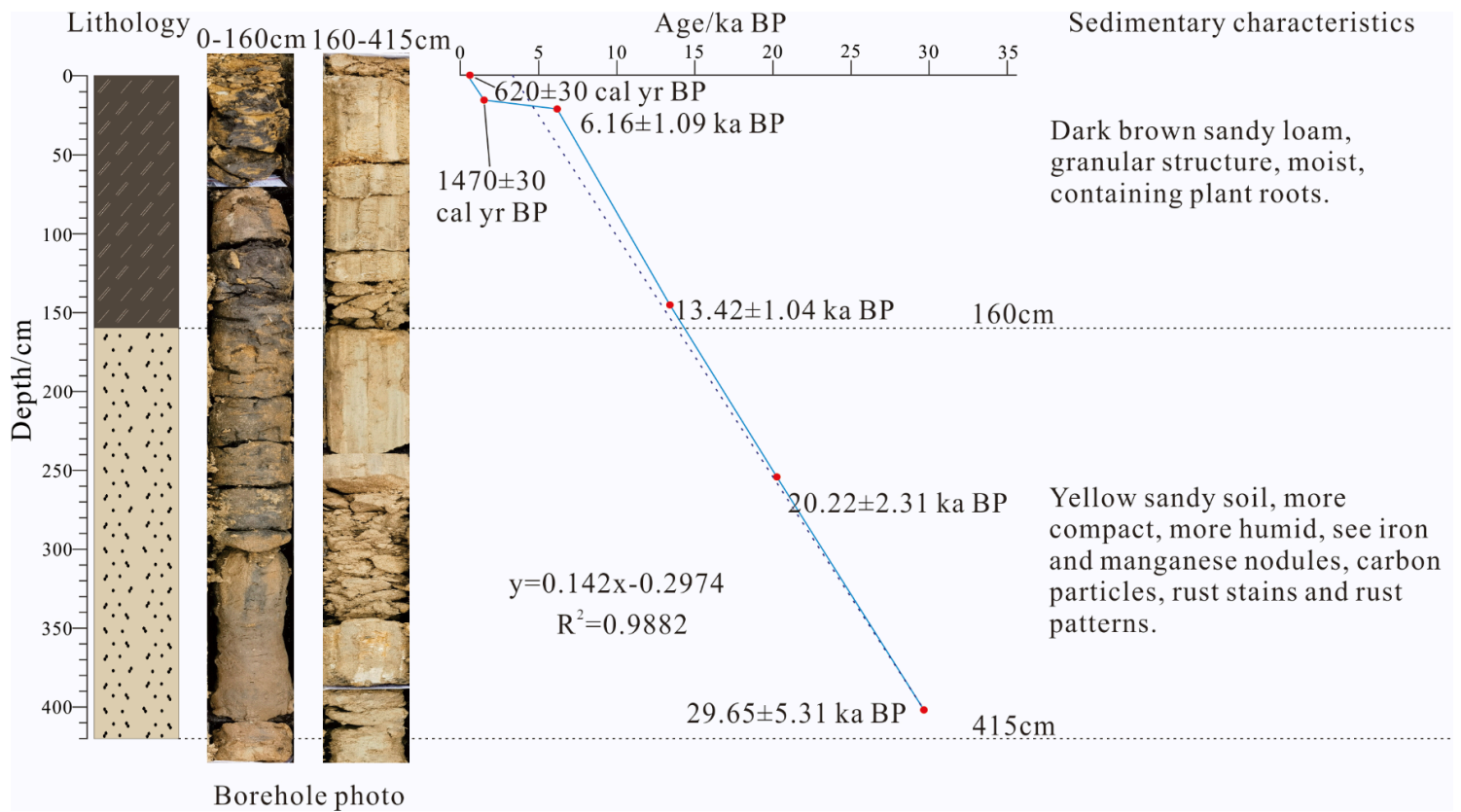


Figure 2

Lithology and age–depth model of the Huola borehole

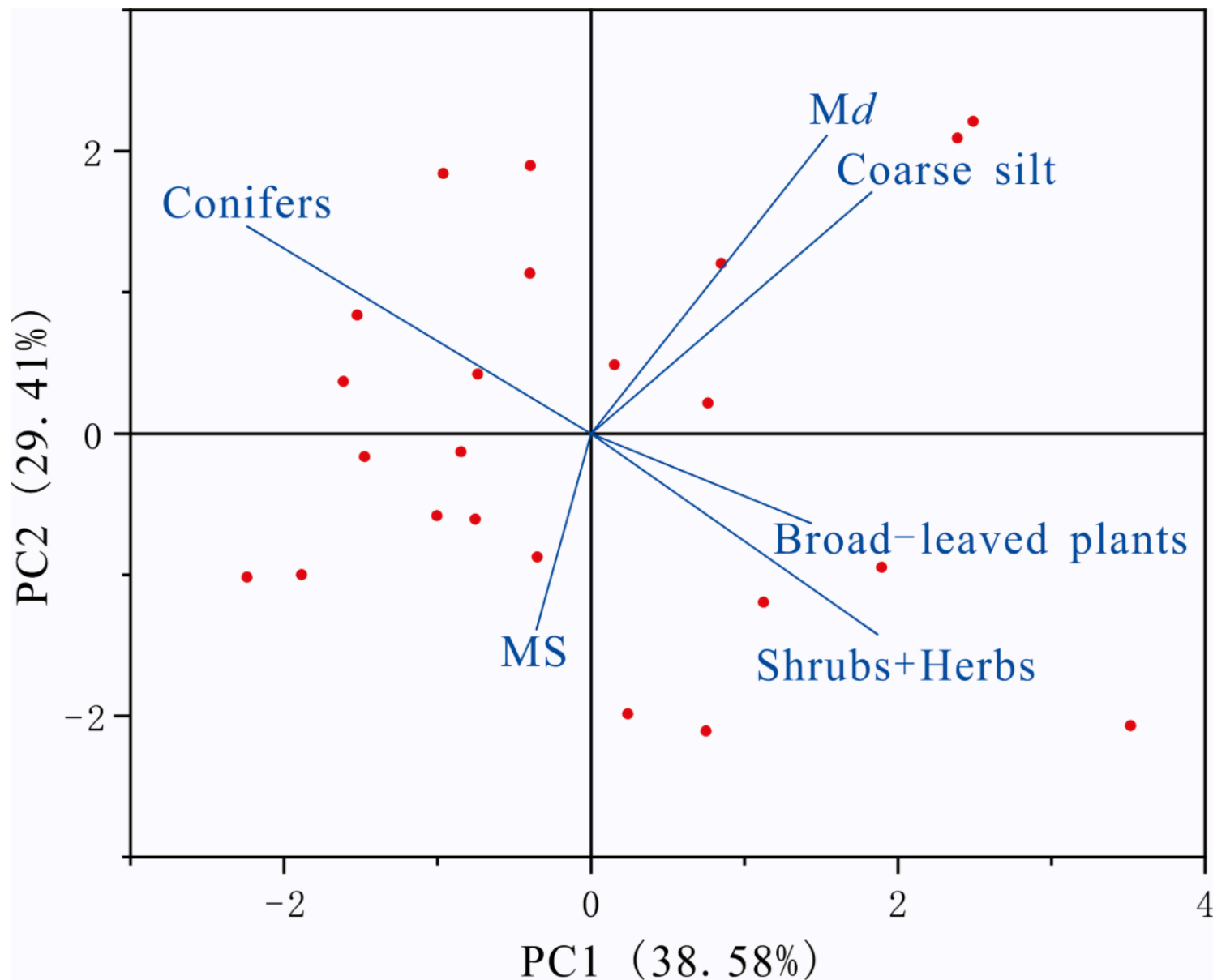


Figure 3

Pollen percentage diagram of the Huola borehole

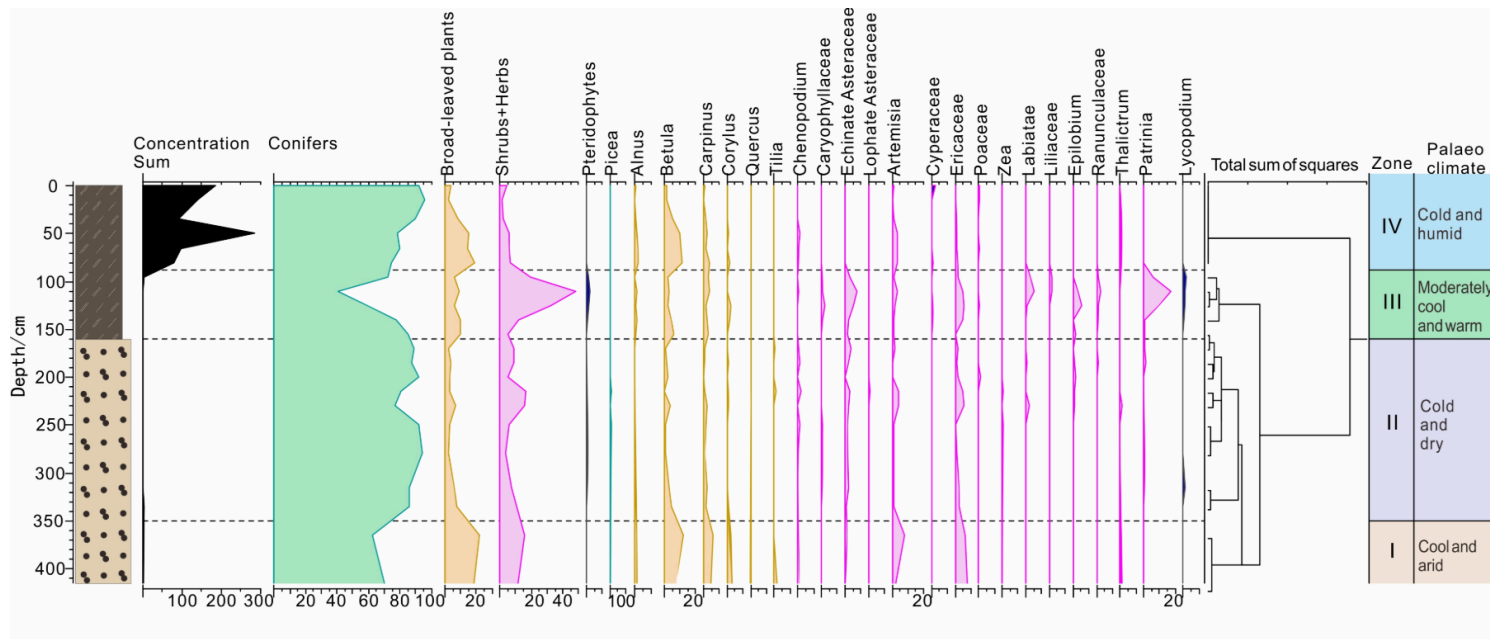


Figure 4

Biplots of the PCA for the six environmental variables of the Huola borehole

The PCA plot reveals a coupling between depositional environments and vegetation

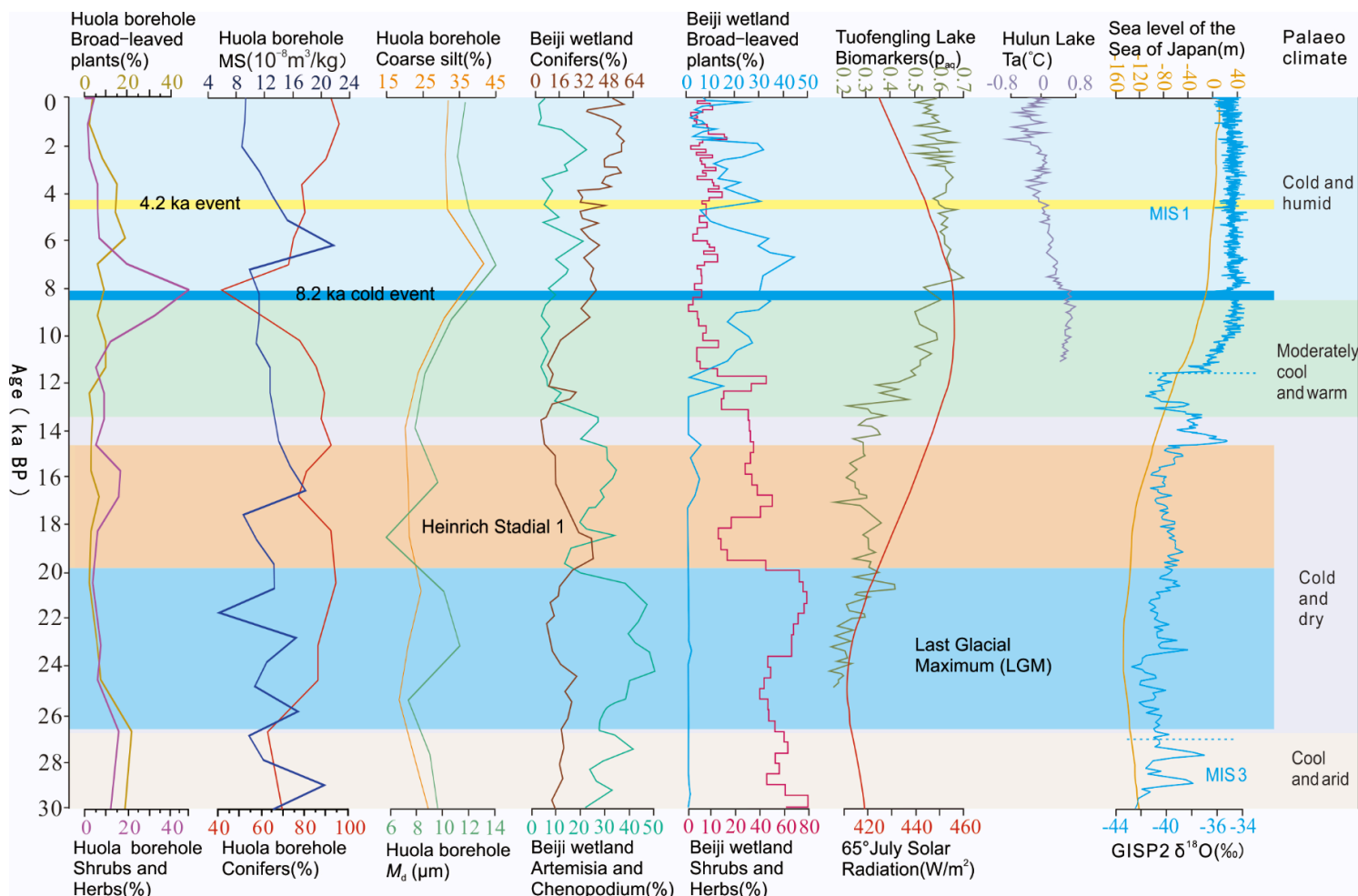


Figure 5

Comparison of pollen, grain-size, and magnetic susceptibility records from the Huola Basin with regional and global records. 1, Beiji wetland^{11,24}; 2, Hulun Lake¹⁴; 3, Tuofengling Lake³³; 4, July insolation at 65°N⁵⁶; 5, sea level of the Sea of Japan⁵²; 6, GISP2 $\delta^{18}\text{O}$ ⁵¹.