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Buried ice-wedge pseudomorphs as indicators of Younger Dryas climate-related lake evolution, Dali Lake, Inner Mongolia

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\textbf{A B S T R A C T}

Ice wedges / pseudomorphs (IWP) are key indicators of cold-climate (periglacial) frozen ground conditions. Their occurrence within the sedimentary sequences of lacustrine landforms can provide important evidence about palaeoenvironmental and palaeoclimatic change. However, research using lake sediments in a geomorphological context to investigate climate change is limited. Here, we use newly discovered IWP's developed within lake sediment sequences to explore climate-related lake-level fluctuations in the Dali Lake region, a key area of the East Asian summer monsoon (EASM) system that drives Quaternary hydroclimate variability across East Asia. The IWP's penetrate down through clay-silt lake sediments and are overlain by coarser-fossiliferous, and finer-diatomaceous lake sediments. This configuration suggests IWP formation occurred within an area transitioning sequentially between subaqueous, subaerially exposed, and resubmerged lake margin setting. We employ the optically stimulated luminescence (OSL) and AMS radiocarbon dating methods to constrain ice-wedge activity timing. Results reveal ice wedge formation between 12.84 and 11.31 ka, corresponding to the globally significant Younger Dryas (YD) cold-climate event. The colder climate since 12.84 ka has led to a marked lake level decline, exposing shoreline areas, which subsequently became frozen, resulting in fissure development and ice infilling. Subsequently, the lake level increased, resulting in a minor highstand, with fossiliferous lake sediment accumulation over the ice wedges during 12.50 ka to 11.94 cal kyr BP. From 11.94 cal kyr BP to 11.31 ka, the lake level declined again, with concomitant ice wedge development. These three lake-level changes and their IWP characteristics reflect regional YD hydroclimatic variability. Wider research using high-resolution multi-proxy analysis of lake sediment cores suggests sustained cold-dry climate conditions during the YD. Our results, using the lake sediment-landform sequence, also suggest a cold climate (−8.2 °C colder than today) but one that fluctuated between dry-humid-dry hydrological patterns during the YD. This study highlights the potential for using IWP affected lake sediment-landform sequences to improve understanding of landscape responses to YD climate variability in the EASM affected region.

1. Introduction

Ice wedges belong to a group of vein- and wedge-shaped structures, characteristic of periglacial environments (Murton, 2007). These structures form by infilling thermal contraction cracks in frozen ground with ice. If ice within the infilled cracks melts, the resultant voids may become filled with sediment, creating IWP's (Ewertowski, 2009; Murton, 2007). Ice wedges and IWP's are direct indicators of permafrost presence and have frequently been used to reconstruct palaeoenvironmental conditions of locations (Cui et al., 2004; Grinter et al., 2019;
Vandenberghe et al., 2019; He et al., 2021; Campbell-Heaton et al., 2021). Many studies have shown that considerable numbers of IWPs can develop in association with lacustrine and marine environments (e.g., Liu et al., 2010; Su et al., 2022; Gagnon et al., 2024). Some of these studies have successfully examined the role of IWPs in reconstructing the historical variations in lake levels within the Qinghai-Tibet Plateau (e.g., Madsen et al., 2008; Liu et al., 2010), whose position relative to major Asian climate systems makes it sensitive to global climate change. Consequently, IWPs emerge as promising candidates that document lake-level fluctuations, particularly those situated within climate-sensitive regions.

Globally and within East Asia, climatic warming following the last glacial maximum, was temporarily interrupted by a marked and abrupt cooling event called the Younger Dryas spanning ~12.9–11.6 ka during the Late Pleistocene-Holocene transition (e.g., Broecker et al., 2010; Renssen et al., 2018). Lake systems are key archives for understanding the spatio-temporal patterns and climate-landscape characteristics of the Younger Dryas event (e.g., Stansell et al., 2010; García et al., 2022). Lakes document the Younger Dryas event in their geomorphological and sedimentary records. They do so via lake-level fluctuations and related shoreline position movements (Goldsmith et al., 2017), alongside changes in physical, chemical, and biological properties of the lake sediments (e.g., Cao et al., 2021; Huang et al., 2018; Hu et al., 2024). These collectively reflect catchment scale variations in weathering, hydrology and vegetation that change in concert with the YD climate variability according to the lake location with respect to the shifting monsoonal systems. Lake-related and wider climate proxy research on the YD event reveals differences in the temperature and humidity levels. Some records show that the climate was characterized by sustained cold and dry conditions (e.g., Cai et al., 2008; Baroni et al., 2021), whilst others suggest cold conditions but fluctuating humidity levels (e.g., Zhou et al., 2001; Ma et al., 2012). Periglacial involutions and IWPs have been proven to yield additional insights into the YD event (e.g., Rémillard et al., 2015; Fraser et al., 2018). Ice wedges form through the thermal-contraction cracking of frozen ground during cold periods (Buylaert et al., 2009). Therefore, if the ages of ice wedges can be constrained to the YD, they have the potential to serve as reliable indicators of climate conditions during this period.

Dali Lake is in eastern Inner Mongolia, at the northern margin of the EASM (Fig. 1a). As a major component of the global climate system, the EASM significantly influences global hydrologic and energy cycles (An, 2000; Liu et al., 2009). Therefore, the region’s lacustrine deposits contain a wealth of paleoclimatic information, including documentation of the YD event (e.g., Xiao et al., 2009; Liu et al., 2016; Wen et al., 2017). Most studies have focused on sediment cores, using physical, chemical, and biological proxies such as grain size, pollen, and organic matter, while fewer studies have concentrated on beach ridges to research climate-controlled lake evolution (e.g., Fan et al., 2019; Zhen et al., 2020; Jiang et al., 2020). Results indicate periods of relatively drier and wetter climate conditions within a fluctuating lake system. However, contradictions exist concerning the level of Dali Lake during the YD event (Liu et al., 2016b; Fan et al., 2017; Goldsmith et al., 2017; Jiang et al., 2020). Although most results suggest dry climatic conditions in the Dali Lake region (Fan et al., 2017; Goldsmith et al., 2017; Jiang et al., 2020), a minor lake highstand within the event has been identified (Liu et al., 2016b) suggesting humidity fluctuations. Moreover, pollen evidence from Daihai Lake (Fig. 1a) also suggests unstable humidity levels during the YD period but with some timing uncertainty (Li et al., 2004). Thus, the specific humidity patterns during the YD event in the Dali Lake region require further consideration.

We achieve this by examining Dali Lake from a geomorphological and sedimentological perspective. We collect new data using previously undescribed naturally exposed sections through Dali Lake lacustrine landforms and sediment sequences. These lacustrine landform sequences present IWP structures, which we describe and date, to provide insights into their genesis and formation timing. We then analyze the relationship between the development of the IWPs and Dali Lake water level fluctuations in relation to humidity and palaeotemperature change during the YD event. Finally, we then compare and discuss our new findings alongside previously published results from: 1) a Dali Lake sediment core (DL04: e.g., Xiao et al., 2009); 2) sediments at Dali Lake palaeolake shorelines (Liu et al., 2016b; Goldsmith et al., 2017; Jiang et al., 2020; Zhang et al., 2023b), and 3) other YD lake data across the northern EASM margin (Chen et al., 2015; Wu et al., 2016; Zhang et al., 2018) to consider EASM climate change responses and patterns during the YD event.

2. Study area

Dali Lake (43°13′-43°23′N, 116°29′-116°45′E) lies 90 km west of

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Fig. 1. Location and climate of the study area. (a) Present-day climatic systems of China (modified from Xiao et al., 2008) showing the Dali Lake study area located at the summer monsoon limit. (b) Details of the Dali Lake area showing locations of the five natural sections at the DLP, DDP sites, and C, D, and H gullies in this study. The location of sediment core DL04 is from Xiao et al., 2009, conducted at a water depth of 10.8 m in the depocenter of Dali Lake and extracted to a total depth of 11.83 m beneath the lake floor.
the modern Dali Lake while the DDP site (43°15′17.30″N, 116°27′04.53″E, 1272 masl) is located about 3 km west of the modern Dali Lake while the DDP site (43°15′17.30″N, 116°27′04.53″E, 1272 masl) is located approximately 500 m northwest of DLP. The other three profiles relate to the C, D, and H gullies, which were exposed by long-term surface water erosion. The DDP section occupies the uppermost landscape position, the DLP is in the middle, while C, D, and H are distributed in the lower spatial positions (Fig. 1b). These five profiles were logged carefully in the field.

Samples for laboratory analysis were taken from the five profiles, based on cryo-stratigraphic observations, targeting the sedimentary layers surrounding the wedge structures, the sedimentary infill of the wedges at the DLP site, and some layers from the other four profiles. The analyses involved characterization of the physical properties of the sediment (grain size, scanning electron microscope [SEM]) and geochronological dating (OSL and AMS radiocarbon techniques).

3.2. Grain size analysis

Grain-size characteristics reflect sediment sources, transporting mechanisms, and sedimentary environments, such as fluvial, lacustrine, and aeolian settings that dominate the Dali Lake region (Xiao et al., 2009, 2015; Lan et al., 2018), making them key proxy indicators for palaeoclimatic and palaeoenvironment reconstruction (Sun et al., 2001). Thirteen grain size samples were collected from the DLP section, with two from infill sediments of the wedge structures and eleven from the surrounding layers (Fig. 2a). The grain size distribution for a given sample was determined using a Malvern Mastersizer 2000 laser grain size analyzer with a measurement range of 0.02–2000 μm at the Quaternary Laboratory, Institute of Geomechanics, Chinese Academy of Geological Sciences.

3.3. SEM analysis

Sediments exposed in the DDP section were tentatively identified as having lacustrine origin from field observation, comprising an off-white color when dry and dark grey when wet, with a different texture and feel from the clay and sand. The DDP sediments are light in density and have a slippery feel when worked between the fingers. Based on these characteristics, the sediments were likely to be diatomaceous sediments (cf. diatomaceous ooze of Zahajská et al., 2020). Diatoms can be found in all aquatic environments, including wetlands, lakes, and the marine environment (Clarke, 2003). If diatom fossils occur in the DDP section, we can speculate that the DDP site was a lacustrine setting. This is further

Fig. 2. Lithology and overview of the DLP section (Fig. 1b) with its two wedge structures. (a) Lithologic log showing the location of samples taken for grain size analysis. (b) Photo of the DLP section showing the location of the two wedge structures. The red dashed line picture depicts the sedimentary hiatus between Layers 2 and 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
likely given its positioning along the shoreline of the modern Dali Lake. In addition, similar characteristics are observed in some layers within the nearby DLP section and other sections at C and H gullies. SEM analysis facilitates the identification of diatom fossils and enables the determination of their specific species by examining their morphological characteristics (Wang et al., 2006). Eight samples were collected for SEM analysis, including five samples obtained from the DDP section (Fig. 3) and one each collected from the DLP section (Fig. 2), C, and H gullies. The analyses were undertaken at Tsinghua University using an FEI Quanta 200F SEM in 2020 and at China University of Geosciences, Beijing, using an MIRA3 XMU SEM in 2023. Diatom classification uses https://diatoms.org/.

3.4. OSL dating

OSL dating was used to constrain the wedge structures’ ages and build a chronological framework for the host sediments. Six samples were taken from the DLP section, including four from the host sediments: three above the wedges, one below, and two from the lowermost sediments within the wedge structures. Additionally, one sample was taken from the DDP section, and two were taken from C gully, and one articulated bivalved shell sample from the H gully. Measurements were undertaken using an Accelerator Mass Spectrometer (AMS) system (NEC Pelletron) from the Beta Analytic Testing Laboratory in Miami, USA. The 14C ages were determined using the Libby half-life of 5568 years. The 14C/12C and 13C/12C ratios of each sample were measured with an oxalic acid standard (NIST SRM—4990C). In order to correct conventional radiocarbon ages, the δ13C value of each sample was analyzed with Thermo Isotope Ratio Mass Spectrometers (IRMSs).

The resulting 14C and OSL ages allow for a comparative analysis between the materials obtained from our sections and the findings of previous work conducted at the DLW site (Liu et al., 2016a), the DL04 sediment core (e.g., Xiao et al., 2009), and several other relevant research endeavors. This comparative approach was employed to elucidate the evolutionary processes of Dali Lake.

4. Results

4.1. Sedimentary characteristics of the DLP section

The exposed DLP section is approximately 3 m high and 14 m long and can be delineated into seven distinct layers (Layer 1 = lowest and oldest). The field-based characteristics of the DLP section are described in Table 1.

Grain-size frequency distribution curves for the wedge infill and the host material in the DLP section are illustrated in Fig. 4. For the host sediments, Layers 1 and 2 are dense clayey silt layers with high proportions of fine-grained components with a peak value of ~100 μm in
the unimodal curve. Layer 3 comprises sand and gravel, displaying a bimodal distribution with peak values at 100 μm and 650 μm, indicating a markedly coarser texture compared to Layers 1 and 2. Subsequently, a reduction in peak grain size to 40 μm occurred within Layer 4. Notably, there is a progressive increase in peak grain size from 40 to 350 μm, spanning across Layers 4 to 6. The sediments comprise clayey silt, which partly overlays Layer 6, signifying finer sedimentation after Layer 6, possibly consistent with the deposition of the DDP section. The grain size differences between layers likely reflect changing hydrodynamic conditions in the lacustrine environment (Xiao et al., 2009; Lan et al., 2018). It is concluded that the DLP section records two lake regression instances from Layer 2 to Layer 3 and Layer 4 to Layer 5, and two lake transgression occurrences from Layer 3 to Layer 4 and after Layer 6 based on the grain size analysis of each layer (Fig. 4a).

4.2. Morphological and sedimentary characteristics of wedge structures

Two wedge structures are developed in the DLP section, extending from Layers 2 to 1, spaced at about 5 m apart (Fig. 2). Wedge structure I is 1.4 m deep and 0.05–0.15 m wide, having a clear boundary with the overlying Layer 3. Wedge structure II has a wider, ‘pot’-shaped upper part, which is 0.3 m deep and 0.25 m at its widest point, below which it tapers down to a point with a depth of 1.3 m. Outside the wedge structures, extrusion deformation can be observed, characterized by the side walls inside the wedges exhibiting unevenness (Fig. 5a). The deposits in the upper part of Layer 2 show the disturbance features (Fig. 5a, b). Within this disturbance layer are some small wedge deformations (Fig. 5c). Also, gastropod shells from Layers 5 and 6 are present in the wedge infill (Fig. 5a). The grain size distributions for the wedge infill samples reveal peak sizes of ~450 μm and ~ 550 μm, significantly coarser than the host sediments (Fig. 4b).

4.3. Confirmation of diatomaceous sediments from SEM analysis

The hypothesis that the DDP section corresponds to lacustrine sedimentation according to our field observations is supported by laboratory identification of diatoms. The SEM analysis reveals a diverse range of diatom species in the samples obtained from the DDP section (Fig. 6a). Hence, we can confirm that the DDP site comprises sediments derived from lacustrine deposition due to the notable presence of diatoms. The most common diatom species in the DDP section are *Cymbella*, *Navicula*, and *Staurosira*, typical of benthic algae in freshwater lakes. Moreover, diatoms can also be observed in the nearby DLP section (Fig. 6b) and other sections from the C and H gullies (Fig. 6c, d). According to the similarities in the sedimentary sequence, the layer of diatomaceous sediments can serve as a stratigraphic and environmental marker across the palaeolake area encompassed by the five sections studied here.

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Table 1

Description of the sedimentary characteristics for each layer of the DLP section.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth (m)</th>
<th>Lithology</th>
<th>Color</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>①</td>
<td>0–0.1</td>
<td>paleosol</td>
<td>grey-brown</td>
<td>Contains plant roots.</td>
</tr>
<tr>
<td>②</td>
<td>0.1–0.35</td>
<td>sand and gravel</td>
<td>grey-brown</td>
<td>Comprises basalt gravel clasts of &lt;5 mm, with decreasing concentrations of gravel from bottom to top. Gastropod shells occur, mainly in the lower portion. Off-white clayey silt deposits appear locally in this layer, similar to those in the DDP section.</td>
</tr>
<tr>
<td>③</td>
<td>0.35–0.65</td>
<td>sand and gravel</td>
<td>light grey-brown</td>
<td>Comprises coarse sand, gastropod shells, and poorly sorted, well-rounded gravel up to 2 cm diameter consisting mainly of vesicular basalt. Exhibits a sharp boundary with Layer 3 (Fig. 2), indicating a sedimentary hiatus.</td>
</tr>
<tr>
<td>④</td>
<td>0.65–0.7</td>
<td>clay</td>
<td>grey-white</td>
<td>Comprises coarse sand and well-sorted, well-rounded gravel varying from 1 to 5 cm. Exhibits a gradational boundary with Layer 1. Wedge structures developed within this layer and Layer 1.</td>
</tr>
<tr>
<td>⑤</td>
<td>0.75–2</td>
<td>clayey silt</td>
<td>light grey-yellow</td>
<td>Exhibits a gradational boundary with Layer 1. Wedge structures developed within this layer and Layer 1.</td>
</tr>
<tr>
<td>⑥</td>
<td>2–3</td>
<td>clayey silt</td>
<td>grey-yellow</td>
<td>Sediments are uniform.</td>
</tr>
</tbody>
</table>

---

Fig. 4. Grain size results for the DLP section. (a) Grain size distribution curves for selected layers. (b) All grain size distribution curves from sample points in Fig. 2. Peak grain size of host sediments is 100 μm while the infill of wedge structures is ~450 μm and ~ 550 μm, respectively.
(a) Sample III from the DDP section. (b) Sample from the DLP section. (c) Sample from the section at the C gully. (d) Sample from the section at the H gully.

(Names of the diatom species: a. Staurosira construens; b & c. cannot be identified to the specific species due to their incompleteness; d. Cyclotella distinguenda)

4.4. OSL and radiocarbon ages

Details of the OSL results from the DLP section, DDP section, and C gully are shown in Table 2. The isodose distributions of the samples are clustered, suggesting sediments were well exposed before deposition and burial, meaning the determined ages are reliable. At the DLP section, host sediments underlying the wedges give an age of 12.84 ± 0.79 ka, whilst those overlying the wedges date to around 9 ka (Fig. 8). The samples taken from the bottom of the wedge infills give ages of 11.31 ± 0.78 ka (wedge I) and 11.07 ± 0.58 ka (wedge II). At the lower segment of the DDP section, the dating result yields an age of 11.79 ± 0.6 ka. At the C gully, the OSL ages are 9.21 ± 0.44 ka and 10.17 ± 0.47 ka, respectively.

In paleo-limnologic studies, calibrated 14C dates are often older than the actual sediment ages due to the hard water and other reservoir effects on the lake sediments (Oldfield et al., 1997; Chu et al., 2014). To address this issue, we first subtracted the reservoir age of 472 yr, referring to Fan et al., 2016, from the original 14C ages and then converted the resulting ages to calibrated ages using the OxCal v4.4.4 age calibration program (Bronk, 2021) with the INTCAL20 calibration curve (Reimer et al., 2020). The calibrated age is reported, with the 2-sigma range provided in Table 3. The reservoir effect of Dali Lake may have changed in different periods linked to changes in the hydrological setting and the variations in atmospheric 14C levels (Zhou et al., 2015; Fan et al., 2018), but this aspect is currently too difficult to confirm based on present studies. Furthermore, the macrofossils of terrestrial plants for more optimal biostratigraphic dating (Zhou et al., 2015) have not yet been found. Additionally, the reservoir effect may differ between bulk sediments and fossil shells. There is insufficient evidence to support the specific reservoir effect of fossil shells in Dali Lake. Thus, we assumed the reservoir effect was the same for sediments and shells and was constant. OSL dating and previous age results were used to validate this assumption.

14C dating of bivalved fossil shells from the bottom of the diatomaceous sediments in the H Gully (Fig. S1a) gives an age of 10.21 cal kyr BP, representing the onset of diatomaceous deposition in Dali Lake (Fig. 8). The sample of organic matter from the top of the diatomaceous sediments in the DDP section (Fig. 3) is dated to 4.63 cal kyr BP, corresponding to the end of diatomaceous deposition. The dating of gastropod fossil shells from the DLP section (Fig. 7, S1b) implies sediments were deposited over the IWPs at 11.94 cal kyr BP. The gastropod shells in the C and D gullies (Fig. S1c) yield ages 11.03 cal kyr BP and 13.45 cal kyr BP, respectively.

5. Discussion

5.1. Interpretation of wedge structures

We compared the resulting sedimentary and morphological characteristics of the wedges and host sediments observed in the DLP section with similar material described in the literature (e.g., Cui et al., 2002; Whiteman, 2002; Ewertowski, 2009) and can conclude that the two wedge structures can be interpreted as ice-wedge pseudomorphs.

Six lines of evidence support this IWP interpretation. Firstly, the wedge structures are developed into lacustrine sediments at the lake-shore. Lake shorelines mark the local water table position, and such a setting would have sediments with high water content. This water would be prone to freezing under cooling temperatures during the onset of cold climatic conditions, favoring thermal-contraction cracking (Remillard et al., 2015). Ice-wedge growth is highly probable when the lake level recedes and the temperature is cold enough (Su et al., 2022). Secondly, the host sediments show evidence of extrusion deformation adjacent to the wedges (Fig. 5a), indicating frost cracking during wedge development. Thirdly, ice wedges form within the permafrost layer, and the active layer above the permafrost layers undergoes stratigraphic disruption due to freezing and thawing, resulting in the development of a disturbance layer (Murton, 2007). The morphological characteristics...
of the wedges align with this feature (Fig. 5a,b). Modern IWP examples have been reported from a thermokarst lake setting in Canada (Gagnon et al., 2024), with similarities to the IWPs reported here from Dali Lake.

Fourthly, gastropod shells from the layer overlying the wedge are present in the wedge infill (Fig. 5a), indicating that wedges were infilled partly from above. Moreover, the grain size distribution plots of the wedge infills and host sediments clearly demonstrate that the wedge infills are significantly coarser than the host sediments (Fig. 4b), providing additional evidence for secondary infilling. Fifthly, concomitant with the manifestation of IWPs, other phenomena indicative of a periglacial environment occurring in groups have been observed within the studied DLP section. These include small wedge deformations

Table 2

<table>
<thead>
<tr>
<th>Lab number</th>
<th>Location of sample</th>
<th>Depth (m)</th>
<th>U (μg/g)</th>
<th>Th (μg/g)</th>
<th>K (%)</th>
<th>AD (Gy/ka)</th>
<th>De (Gy)</th>
<th>Age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DLP section</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>322</td>
<td>Host material</td>
<td>0.5</td>
<td>1.12 ± 0.03</td>
<td>3.54 ± 0.08</td>
<td>2.15 ± 0.01</td>
<td>2.78 ± 0.12</td>
<td>25.37 ± 1.18</td>
<td>9.13 ± 0.57</td>
</tr>
<tr>
<td>323</td>
<td>Host material</td>
<td>0.7</td>
<td>1.94 ± 0.04</td>
<td>6.97 ± 0.05</td>
<td>2.37 ± 0.01</td>
<td>3.39 ± 0.14</td>
<td>30.49 ± 1.06</td>
<td>9.00 ± 0.49</td>
</tr>
<tr>
<td>321</td>
<td>Host material</td>
<td>0.9</td>
<td>1.26 ± 0.04</td>
<td>4.56 ± 0.05</td>
<td>2.6 ± 0.02</td>
<td>3.29 ± 0.14</td>
<td>30.69 ± 0.96</td>
<td>9.33 ± 0.49</td>
</tr>
<tr>
<td>324</td>
<td>infill</td>
<td>1.9</td>
<td>1.03 ± 0.02</td>
<td>1.83 ± 0.02</td>
<td>1.39 ± 0.01</td>
<td>1.87 ± 0.08</td>
<td>21.19 ± 1.16</td>
<td>11.31 ± 0.78</td>
</tr>
<tr>
<td>325</td>
<td>infill</td>
<td>2</td>
<td>1.33 ± 0.03</td>
<td>3.93 ± 0.11</td>
<td>2.66 ± 0.05</td>
<td>3.26 ± 0.14</td>
<td>36.07 ± 1.04</td>
<td>11.07 ± 0.58</td>
</tr>
<tr>
<td>326</td>
<td>Host material</td>
<td>2.8</td>
<td>0.49 ± 0.01</td>
<td>1.22 ± 0.02</td>
<td>1.5 ± 0.01</td>
<td>1.82 ± 0.08</td>
<td>23.39 ± 1.05</td>
<td>12.84 ± 0.79</td>
</tr>
<tr>
<td>DDP section</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>438</td>
<td></td>
<td>3.1</td>
<td>1.47 ± 0.03</td>
<td>4.07 ± 0.07</td>
<td>2.27 ± 0.02</td>
<td>2.94 ± 0.13</td>
<td>34.67 ± 0.89</td>
<td>11.79 ± 0.6</td>
</tr>
<tr>
<td>C gully</td>
<td></td>
<td>436</td>
<td>1</td>
<td>0.60 ± 0.01</td>
<td>2.32 ± 0.06</td>
<td>2.71 ± 0.01</td>
<td>3.17 ± 0.14</td>
<td>29.13 ± 0.48</td>
</tr>
<tr>
<td></td>
<td></td>
<td>437</td>
<td>2</td>
<td>0.71 ± 0.01</td>
<td>2.38 ± 0.05</td>
<td>2.71 ± 0.01</td>
<td>2.94 ± 0.12</td>
<td>29.89 ± 0.63</td>
</tr>
</tbody>
</table>

Fig. 6. SEM imagery of diatom samples from different sections.
(Fig. 5c) and vein-shaped structures (Fig. 9b,c), presumed to be ice-vein pseudomorphs (cf. Murton et al., 2000). Sixthly, including the DLP section, two other locations exhibit periglacial evidence. A vein-shaped pseudomorph is developed near Duolun Lake, approximately 800 m west of the DLP section (Fig. 9a,d). At the H Gully, periglacial involutions are observed beneath diatomaceous sediments (Fig. S2), constituting a similar sedimentary sequence to that observed in the DLP section. The coexistence of these features within the three sections across a large area substantiates a periglacial origin during the corresponding period.

5.2. Timing of ice-wedge formation and implications for lake evolution

The luminescence and radiocarbon ages provide chronological control for the IWPs and their origin as ice wedges. Ice wedges cannot be dated directly (Liverman et al., 2000), but their age can be constrained by dating the infill and host sediments of ice-wedge pseudomorphs (Cui et al., 2002). The age of the infill indicates the cessation of ice-wedge formation, the onset of ice-melting, and the influx of surrounding material into the void, i.e., when periglacial conditions were ending (Porter et al., 2001; Liu and Lai, 2013). Ice wedges and IWPs only develop in terrestrial settings (van Vliet-Lanoë et al., 2004). Consequently, their formation occurs after lake regression when the land becomes exposed, allowing them to penetrate through lacustrine depositions. At the studied DLP site, IWPs have developed within lacustrine sediments and were then buried by lacustrine sedimentation. This characteristic highlights the potential of IWPs to serve as indicators of the lake-land-lake transition when used with their associated sedimentary deposits.

Using the diatomaceous sediments as a stratigraphic marker across the Dali Lake area, we compare the sedimentary sequences of the five sections in this study and one previous study (Liu et al., 2016a) to constrain the IWPs’ formation time with respect to lake evolution (Fig. 10).

![Fig. 7. Lithology of the DLP section showing the OSL ages of the wedge structures and their host sediments and the $^{14}$C age of gastropod shells.](image)

Table 3

<table>
<thead>
<tr>
<th>Lab number</th>
<th>Sample location</th>
<th>Dating material</th>
<th>$\delta^{13}$C (‰)</th>
<th>AMS $^{14}$C age (yr BP)</th>
<th>Corrected $^{14}$C age (yr BP)$^a$</th>
<th>Calibrated $^{14}$C age (2σ BP) (cal yr BP)</th>
<th>Median $^{14}$C age (cal yr BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>676056</td>
<td>DDP</td>
<td>Organic matter</td>
<td>-23</td>
<td>4560 ± 30</td>
<td>4108 ± 37</td>
<td>4729–4520</td>
<td>4633</td>
</tr>
<tr>
<td>675256</td>
<td>DLP shell</td>
<td>shell</td>
<td>-2.4</td>
<td>10,720 ± 40</td>
<td>10,105–11,808</td>
<td>10,394</td>
<td>11,941</td>
</tr>
<tr>
<td>675258</td>
<td>C gully shell</td>
<td>shell</td>
<td>-3.4</td>
<td>10,120 ± 30</td>
<td>9648 ± 37</td>
<td>11,189–11,066</td>
<td>11,034</td>
</tr>
<tr>
<td>678061</td>
<td>D gully shell</td>
<td>shell</td>
<td>-4.3</td>
<td>12,060 ± 30</td>
<td>11,588 ± 37</td>
<td>13,510–13,346</td>
<td>13,454</td>
</tr>
<tr>
<td>678060</td>
<td>H gully shell</td>
<td>shell</td>
<td>-0.7</td>
<td>9490 ± 30</td>
<td>9018 ± 37</td>
<td>10,245–10,150</td>
<td>10,205</td>
</tr>
</tbody>
</table>

$^a$ The weighted uncertainty is the root of the sum of squares of the errors of the AMS $^{14}$C ages and reservoir $^{14}$C ages (Zhang et al., 2018).
Fig. 8. H gully stratigraphy and lithology showing $^{14}$C age of bivalved shells at the bottom of the diatomaceous sediments overlying the periglacial involution.

Fig. 9. Ice-vein pseudomorphs at the DLP section (b-c) and a nearby section close to the Duolun Lake (d). (a- Google Earth image based on Maxar Technologies and CNES/Airbus sources). See Fig. 1 for the regional setting.
Fig. 10. (a) Map showing the location of different lacustrine profiles in Dali Lake. (b) Histogram of lacustrine profiles (DLW profile modified from Liu et al., 2016a, $^{14}$C ages are recalibrated using the same calibration curve as this study; other profiles are from this study. Big gravels mean those exceeding 5 cm in size, while small gravels refer to those measuring <5 cm).
sedimentation of the host sediments. The host sediment grain-size data from the bottom part of the DLP section suggests a deep-water sedimentary environment. Accordingly, a lake highstand exceeding 1269 masl must have been present at 12.84 ka. After 12.84 ka, Dali Lake have receded to below 1269 masl at this locality until 11.94 cal kyr BP, as evidenced by the radiocarbon age of the gastropod shells overlying the ice wedges. The OSL ages are younger than the radiocarbon age obtained for the corresponding layers (Fig. 10b). This discrepancy strongly suggests the likelihood of post-depositional disturbances induced by the freeze-melt process and bioturbation, resulting in the secondary exposure of the sediments (Zhang et al., 2023a). Consequently, luminescence ages may appear younger than the actual age of the sediments. Furthermore, the OSL age of 1.79 ka derived from the DDP section, in conjunction with the radiocarbon ages obtained from the nearby DLW section (Liu et al., 2016a), helps validate the age of 11.94 cal kyr BP. DDP and DLP sections present a well-defined sedimentary sequence (Fig. 10). Additionally, involutions beneath the diatomaceous sediments in the H gully (Fig. S2) provide additional evidence supporting periglacial activity before 10.21 cal kyr BP. Thus, the radiocarbon age of 11.94 cal kyr BP is deemed credible for constraining the formation process of ice wedges, and the reservoir effect of 472 yr is effective for correcting the ages of the shells dated in this study.

Ice wedge formation encompasses fissure cracking and ice filling (Murton, 2007; Rémillard et al., 2015). These processes are incompatible within a subaqueous environment (van Vliet-Lanoë et al., 2004; Su et al., 2022), so it can be inferred that the extended timeframe for the initial fissure cracking and ice filling occurred between 12.84 ka and 11.94 cal kyr BP. However, the effective cracking and ice-filling duration was shorter than this. The material that fell into the cavities was left by the melting wedges, whose chronological results are not contemporaneous with the periglacial activity that formed the wedges but provide a maximum age for the start of the cooling degradation phase (Rémillard et al., 2015). Thus, the OSL dating results for the lowermost part of the infill sediments, determined as 11.31 ± 0.78 ka and 11.07 ± 0.58 ka, document the time of ice-melting, representing the warmer climate. Between 11.94 cal kyr BP and 11.31 ± 0.78 ka, a plausible temporal window exists during the second ice-filling occurrence. Consequently, the formation time of ice wedges in the DLP site can be constrained to 12.84–11.31 ka, encompassing three main development phases. Following this, the wedge structures became filled with overlying sediments.
sediments and surrounding materials, ultimately forming ice-wedge pseudomorphs (IWPs).

Previous studies have reconstructed the history of lake-level fluctuations from the Late Pleistocene to the Holocene at Dali Lake. Several highstands were identified during the Holocene (Fig. 11b-e) (Liu et al., 2016b; Goldsmith et al., 2017; Jiang et al., 2020; Zhang et al., 2023b). However, the lake-level fluctuations during the last deglaciation, marked by dramatic climate changes, have not been studied enough, limited by the research material. To illustrate the history of Dali Lake’s evolution during the last deglaciation and to put the YD lake response studied here in detail into context, we present a comparative analysis and synthesis of our newly acquired data derived from periglacial landform IWPs and lacustrine sediments (Fig. 11). The stages of lake level evolution with respect to lacustrine sedimentation, IWP formation, and climate change are as follows:

Stage 1: ~12.84-12.50 ka. The lake level exceeded 1269 masl at approximately 12.84 ka, supported by the wider Dali Lake literature, which documents a highstand of 1275 masl at that time (Fig. 11b) (Goldsmith et al., 2017). From 12.84 to 12.50 ka, there was an evident declining lake level trend, resulting in a lake level of 1253 masl at 12.50 ka (Fig. 11d) (Liu et al., 2016b). At the beginning of this period, the DLP section was not suddenly exposed but continued to accumulate sediments (Fig. 11d) (Liu et al., 2016b). At the beginning of this period, the DLP section was not suddenly exposed but continued to accumulate sediments. The transition from finer sediments in Layers 1 and 2 to coarser sediments in Layer 3 within the DLP section clearly documents this lake level evolution event. Due to the lake regression, the DLP section underwent exposure, leading to a sedimentary hiatus that facilitated ground cracking, frost fissures developing, and subsequent ice filling.

Stage 2: ~12.50 ka-11.94 cal kyr BP. During this temporal interval, a minor lake-level highstand occurred, marked by the clay deposition of Layer 4 overlying the ice wedges. The thin sedimentation of Layer 4 and abrupt grain size change compared with Layer 3 imply a rapid and short lake transgression. Then, the lake level slightly decreases according to the coarser deposition of Layers 5 and 6 with gastropod shells at 11.94 cal kyr BP, suggesting a nearshore sedimentary environment. Consequently, the inferred lake level at 11.94 cal kyr BP is estimated to be approximately 1269 masl at 12.30 ka (Fig. 11d) (Liu et al., 2016b). During this interval, there was an overall lake level fluctuation, comprising a rising trend followed by a lowering and receding event derived from grain size analysis. In addition, there is a possibility that the ice within the wedges experienced partial melting according to the described small fluctuation pattern.

Stage 3: ~11.94 cal kyr BP-11.31 ka. After 11.94 cal kyr BP, a pronounced reduction in the lake level ensued, leading to the re-exposure of the DLP section. It is plausible that the wedge structures underwent expansion during this period.

Since 11.31 ka, ice began to melt under a warming climate, and ice wedges would have been filled with overlying sediments and surrounding materials. The upper deposits collapsed into the open wedge structure, substantiated by sediments containing gastropod shells from the overlying sedimentary layers within its interior (Fig. 5). In addition, the diatomaceous sediments overlying the IWPs indicate that the IWPs were buried for a long period during the Holocene.

5.3. Response of IWPs to the Younger Dryas cold climate

The dating results reveal that ice-wedge activity in the Dali Lake area is temporally constrained to the interval spanning 12.84 to 11.31 ka, coinciding with the YD event (e.g., Fiedel, 2011; Renssen et al., 2018). The climate structure of the YD event is similar in global regions at the millennial scale (Fig. 12), which is relatively cold and dry. However, there are many differences concerning the centennial scale, with some secondary fluctuation (Liu et al., 2013; Liu et al., 2022). Previous studies identified a sustained cold and dry climate pattern at the millennial scale during the 12.7-11.5 ka in the Dali Lake region (Fan et al., 2018; Goldsmith et al., 2017; Zhang et al., 2023b) (Fig. 12f-h). However, our study presents an alternative interpretation. The development process of the IWPs provides essential insights into the climate’s timing, magnitude, and style during the YD episode.

Between 12.84 and 12.50 ka, the marked reduction in lake water levels correlates with the abrupt onset of the colder climate associated with the YD event. A cold and dry climatic pattern characterized this temporal phase. The exposed lake shoreline transformed into terrestrial land, and ice wedges commenced their development on the exposed frozen surface. Subsequently, from 12.50 ka to 11.94 cal kyr BP, an increase in lake level suggests a shift toward a more humid climatic pattern. During this period, temperatures remained relatively low, yet

Fig. 12. Comparison of the climate pattern during the YD period at Dali Lake with other regional and global environmental signals. The three green bars indicate three possible humid events in the (a) Kulishu record (A1’-A3’) (Ma et al., 2012) and in the (b) NGRIP record (Rasmussen et al., 2006) (A1-A3). (c) Pollen record from Moon Lake (Wu et al., 2016). (d) Pollen record from Hulun Lake (Zhang et al., 2020). (e) Pollen-based PANN record from Gonghai Lake (Chen et al., 2015). (f-h) δ18O values and TOC, TN concentrations from Dali Lake sediment core DL04 (Fan et al., 2018). (i) δ18O record from GISP2 (Stuiver and Grootes, 2000). (j) Synthesized Northern Hemisphere (30°-90°N) temperature record during the last deglaciation (Shakun et al., 2012). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
there is a possibility of increased moisture (precipitation minus evaporation) and a rise in lake level, contributing to the deposition of thin lacustrine sediment overlaying the ice wedges. Then, from 11.94 cal kyr BP to 11.31 ka, a decline in lake level indicates a return to a drier climate pattern. Consequently, it is concluded that the YD event at this site is expressed as three fluctuating temperature-humidity phases, specifically characterized as cold dry-humid-dry, in the records of IWPs and related sedimentary sequences. These fluctuating temperature-humidity timing patterns provide a new, more detailed perspective on the YD event in the Dali Lake region compared to previous studies. Our new fluctuating climate pattern of cold-dry, cold-humid to cold-dry conditions for the YD event on the centennial scale at Dali Lake based on dated IWP structures appears to be in keeping with other more regional and global studies using a range of different climate archives. There are also some geologic records and numerical experiments that have shown that climate conditions in the mid-YD (12.5–11.6 ka) were not stable globally (e.g., Wang et al., 2001; Nakagawa et al., 2006). Several aridity/moisture fluctuations recorded by stalagmites and loess-paleosol sequence have been identified during this period (e.g., Zhou et al., 1999; Ma et al., 2012). For example, the record from Kuling Cave, approximately 80 km southwest of Beijing city, also located at the northwestern fringe of EASM at present, reflects three possible humid events (A1–A3) during the mid-YD (Fig. 12a) (Ma et al., 2012), correlating to the NGRIP record (A1-A3) (Fig. 12b) (Rasmussen et al., 2006). Our record from IWPs (12.5 ka – 11.94 cal yr BP) aligns with two humid events shown in Fig. 12a-A2’, A3’ (Ma et al., 2012) and Fig. 12b-A2, A3 (Rasmussen et al., 2006) during mid-YD. Moreover, all three records (Fig. 12a, b, and our data) consistently indicate a dry climate during the early and late YD (12.8–12.5 ka and c. 11.9–11.3 ka), coinciding with periods of ice-wedge development (Fig. 12).

In the EASM-dominated region, many lakes experienced significant fluctuations in level, reflecting oscillating and unstable precipitation during the YD period. We compared our record from Dali Lake with other lakes across the northern margin of EASM (Fig. 1a). Pollen evidence derived from Daihai Lake suggests a three-phased monsoonal oscillation interval (cold-dry, cold-humid, and cool-dry) corresponding with the YD event (11.2–10 ka, Li et al., 2004), with a considerable time uncertainty, however. Pollen records from Moon Lake (Fig.12c, Wu et al., 2016), Hulun Lake (Fig.12d, Zhang et al., 2018), and Gonghai Lake (Fig.12e, Chen et al., 2015) suggest decreased precipitation from ca. 12.8–11.7 ka, indicating a weakened EASM. Whilst these studies have not explicitly addressed secondary aridity phases, the data nonetheless reveal evident oscillations during the mid-YD (Fig. 12c). These oscillations during the YD cold reversal occurring over northern high latitudes may be attributed to atmospheric coupling mechanisms involving the North Atlantic region, East Asian monsoon areas, and El Niño and Southern Oscillation (ENSO) in the tropical Pacific (McPhaden et al., 2006; Wang et al., 2017; Fan et al., 2018).

5.4. Paleotemperature in the Dali Lake region during the YD episode

Ice-wedge pseudomorphs constitute reliable evidence for the past presence of permafrost and periglacial conditions and can be used to reconstruct paleoenvironment and paleotemperature (e.g., Vandenberghe and Pissart, 1993; Murton, 2007). Temperature thresholds for ice-wedge development can be obtained from modern periglacial environments (Rémillard et al., 2015), and it has been shown that cold conditions with a subzero MAAT are required (Gao, 2005). Ice wedges are frequently used to indicate maximum values of MAAT and mean air temperature of the coldest month (MATCM) (Murton and Kolstrup, 2003).

The reported temperature conditions for ice-wedge development vary regionally. Péwé (1966) suggested ice-wedge growth occurs with a MAAT of –5 to –8 °C, while Washburn (1980) suggested –5 °C as the highest threshold temperature for ice-wedge development. Vandenberghe and Pissart (1993) proposed that the MAAT for ice-wedge occurrence varied with lithology: below –4.5 °C in clay beds, –5 °C in fine sand beds, and –8 °C in sand/gravel beds. The coarser the host sediment, the more difficult it is for ice wedges to develop and the lower temperature required (Cheng et al., 2005). The extensive range in reported temperatures, ranging from slightly below 0 °C to –8 °C, indicates that the relationship between ice-wedge growth and temperature is complex and changeable under different natural conditions. Thus, although ice wedges and pseudomorphs cannot provide reliable quantitative MAAT data, a range can be estimated based on host sediment characteristics. We use this relationship to estimate the temperature range for developing ice-wedge pseudomorphs in the Dali Lake region as an indicator of paleotemperature for the YD. Dali Lake wedge structures are developed in silty host sediments, which suggests an upper MAAT limit of ~5 °C. The current MAAT in the Dali Lake area is around 3.2 °C (Jiang et al., 2020). Thus, ice-wedge formation would require a cooling of 8.2 °C. Accordingly, the prevailing temperature during the YD in Inner Mongolia is estimated to be 8.2 °C lower than present.

Some quantitative analyses of temperature decline during the YD have been reported. A previous study using clumped carbonate isotope reveals a lake-water temperature decrease of about 6 °C during the BA-YD transition in the Dali Lake region (Yue et al., 2021). Evidence based on pollen analysis has played an essential role for reconstructing the temperature drop during the YD. For example, a 3–5 °C decrease in annual temperature in Tianchi Crater Lake (Liu et al., 2023) in NE China and a mean annual temperature of ~1.5–2.4 °C colder than today in Xingyun Lake (Chen et al., 2020) in SW China have been reported. Globally, the temperature over the summit of Greenland was 15 ± 3 °C colder than today (Severinghaus et al., 1998). While the magnitude of temperature decline varies across different regions, these findings collectively indicate a consistent occurrence of distinct temperature changes during the YD period.

6. Conclusions

The wedge structures developed within the lacustrine sediments and subsequently buried by deposits of Dali Lake are interpreted as ice-wedge pseudomorphs (IWPs). The chronological analysis yields compelling evidence suggesting that these IWPs originated as ice wedges between 12.84 and 11.31 ka, coinciding with the YD event. The evolution of IWPs, in conjunction with the analysis of their host sedimentary records, indicates three distinct phases of lake level fluctuations: a pronounced decline spanning the interval from 12.84 to 12.50 ka, a rapid increase occurring between 12.50 ka and 11.94 cal yr BP, and a notable reduction from 11.94 cal yr BP to 11.31 ka, respectively. These delineated phases correspond to three centennial-scale precipitation oscillations during the YD event, offering valuable insights into the region’s climatic patterns, specifically cold dry-humid-dry. Additionally, distinctive characteristics of the IWPs and their host sediments allow paleotemperature to be estimated, suggesting MAAT in the Dali Lake region during the YD was 8.2 °C lower than present. Overall, our study contributes geomorphic perspectives, enriching the understanding of the intricacies of the climatic patterns during the YD event in the EASM region and the role played by IWPs for informing on climate change.

CRediT authorship contribution statement

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.palaeo.2024.112422.

References