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ASSESSING LOCK-IN DEPTH AND ESTABLISHING A LATE HOLOCENE PALEOMAGNETIC SECULAR VARIATION RECORD FROM THE MONGOLIAN ALTAI

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ABSTRACT. Although paleomagnetic secular variations (PSV) often corroborate radiocarbon (^{14}C)-based lacustrine sediment chronologies, this is not the case at the high-altitude site Khar Nuur in the Mongolian Altai Mountains. Our results show that the inclination pattern resembles those from a regional reference record from Shireet Naiman Nuur and global geomagnetic field models very well, but with a constant offset of 730 ± 90 yr. Possible reservoir effects from terrestrial pre-aging and hardwater effects can be excluded as the cause of the ~730-yr offset because the different dated compounds correspond very well to each other, and modern reservoir effects are negligible. Instead, the constant ~730-yr offset in the PSV pattern is likely the result of a constant lock-in depth of 26 ± 2 cm below the sediment-water interface at Khar Nuur. This assumption is supported by comparison of paleoclimatological proxies from Shireet Naiman Nuur, where similarities are obvious for the ^{14}C-based chronology of Khar Nuur without a ~730-yr adjustment. Therefore, the previously published ^{14}C-based chronology of Khar Nuur provides a reliable age control. Accepting the lock-in depth of 26 ± 2 cm, the good consistency in inclination between Khar Nuur and global geomagnetic field models highlights the reliability of the latter even in a paleomagnetically understudied area.

KEYWORDS: lake sediments, paleoenvironmental changes, paleomagnetic secular variations, radiocarbon dating, semi-arid Mongolia.

INTRODUCTION

Precise age control is an important precondition for robust paleoenvironmental reconstructions from lacustrine sediments. However, in semi-arid regions such as Mongolia, chronological control of the existing paleoenvironmental lacustrine records is often imprecise because most chronologies rely on few ^{14}C-dates, almost exclusively made on bulk organic material (e.g., Sun et al. 2013; Unkelbach et al. 2019; Rudaya et al. 2021). Unfortunately, bulk organic carbon often needs to be dated in semi-arid regions due to the absence of terrestrial macrofossils in lake sediments. Compared to terrestrial macrofossils, which are assumed to be rapidly deposited in lakes (Hajdas et al. 1995), bulk organic carbon can be "pre-aged" because organic material accumulates in the catchment over hundreds to thousands of years. Consequently, bulk organic carbon is possibly too old when finally ending up in the lake, overestimating its "true" deposition age (Haberzettl et al. 2013; Wündsch et al. 2014; Gierga et al. 2016; Douglas et al. 2018; Haas et al. 2019). Moreover, lake sediments comprise organic material from terrestrial and aquatic sources and the radiocarbon (^{14}C)-signal from aquatic contributions can additionally be affected by the so-called "hardwater effect" due to incorporation of carbonate from old calcareous bedrock and/or re-dissolved carbon from in-lake carbonate precipitation (Reinwarth et al. 2013). Therefore, the

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reliability of paleoenvironmental reconstructions can be largely limited due to chronological uncertainties of the potentially reservoir affected ^{14}C-signal.

In this context, paleomagnetic secular variation (PSV) stratigraphy is a valuable chronostratigraphic tool to evaluate and potentially refine ^{14}C-based chronologies (Barletta et al. 2010; Ólafsdóttir et al. 2013; Haberzettl et al. 2015, 2019, 2021; Bliedtner et al. 2022). PSV changes are ideally suited to study shortterm changes especially throughout the Holocene. The principle behind PSV in lacustrine sediments is that magnetic particles align themselves with the surrounding geomagnetic field during deposition and preserve their direction when locked-in during ongoing deposition (Merrill and McFadden 2007; Roberts and Turner 2013). The recorded pattern of inclination and declination can therefore serve as valuable chronostratigraphic indicators. For the semi-arid regions of Mongolia, we recently proposed a dual chronological approach in the high-altitude Shireet Naiman Nuur (Nuur = lake) sediments (46°31'55.04"N, 101°49'16.23"E; Khangai Mountains, central Mongolia), where we (1) established a high-resolution ^{14}C-chronology for the past 7.4 cal. ka BP by dating terrestrial macrofossils and (2) corroborated the ^{14}C-based chronology by a newly obtained PSV record from the lake (Bliedtner et al. 2022). The PSV record from Shireet Naiman Nuur very well confirms our ^{14}C-based chronology and provides a valuable regional master record for using PSV stratigraphy in semi-arid Mongolia to evaluate and potentially refine ^{14}C-chronologies when compared to our record. Therefore, if successful, the combination of ^{14}C-dating and corroboration by PSV data is a valuable chronological approach to establish more reliable chronologies in semi-arid regions, especially regarding the large age uncertainties of bulk organic carbon dating often has in such regions.

Here we present a newly obtained PSV record from the high-altitude Khar Nuur in the Mongolian Altai Mountains. As in this case PSV data do not corroborate the existing good age control published by Bliedtner et al. (2021), we aim to detect causes for age offsets and establish a reliable continuous inclination and declination record for the last 4.2 cal. ka BP from the lake.

MATERIAL AND METHODS

Study Area

Khar Nuur is of para-glacial origin and situated at high-altitude (2486 m a.s.l.) in the Mongolian Altai (48°37'22.9"N, 88°56'42.5"E; Figure 1). The lake was previously described in detail by Strobel et al. (2021, 2022). The endorheic Khar Nuur basin was formed during the Last Glacial Maximum by glacial advances from the Tsengel Khairkhan Massif, leaving prominent moraine lobes in the main valley (Walther et al. 2017). The lake has a small hydrological catchment (44.8 km^2) with quite steep slopes, which are mostly composed of friable black clay shales and granitic moraine deposits. Due to the continental position of Khar Nuur, mean annual temperatures and precipitation are low with −2.4 ± 0.7°C and 145 ± 35 mm, respectively (station Tolbo sum; period 2009–2019; DWD Climate Data Center 2020). Moreover, the lake is ice-covered for 8–9 months per year (2016–2019; Planet Team 2017).

Chronostratigraphy of the Khar Nuur Sediments

The investigated lake sediments of Khar Nuur and its chronostratigraphy were previously described in detail by Bliedtner et al. (2021). The 141-cm-long sediment core from Khar

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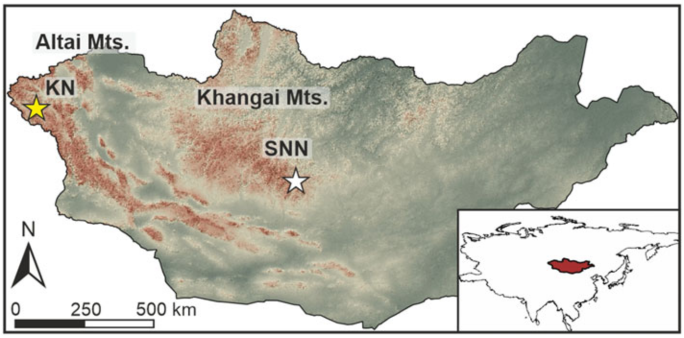

Figure 1 Overview of semi-arid Mongolia located in central Asia. The investigated site at Khar Nuur (KN) in the Mongolian Altai Mountains is indicated by the yellow star and the regional comparison record from Shireet Naiman Nuur (SNN) (Bliedtner et al. 2022) in the Mongolian Khangai Mountains is indicated by the white star. (Please see online version for color figures.)

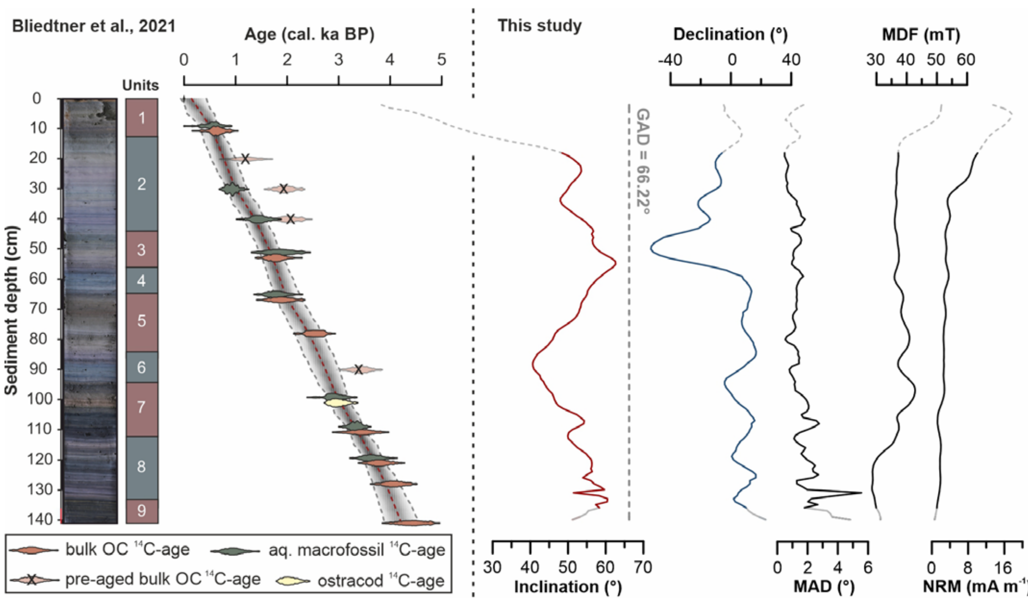

Figure 2 Chronostratigraphy of the Khar Nuur sediments previously published by Bliedtner et al. (2021). Inclination, declination, maximum angular deviation (MAD), median destructive field (MDF) and natural remanent magnetization (NRM) of the Khar Nuur sediments.

Nuur consists of well laminated silty sediments, which are characterized by alternating phases of increased lake primary productivity in the brown and blackish dark sediments and reduced productivity in the bluish-gray sediments (Figure 2). The chronology is based on ^{14}C-datings of 12 bulk organic carbon samples, 8 aquatic macrofossil samples and 1 ostracod sample. Additionally, we accounted for possible terrestrial reservoir and hardwater effects by ^{14}C-dating a surface sediment bulk organic carbon sample and one modern water plant at the coring location. ^{14}C-analyses were carried out at the Laboratory for the Analysis of

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Radiocarbon with AMS (LARA AMS) of the University of Bern, Switzerland (Szidat 2014) using a MIni CArbon DAting System (MICADAS) AMS coupled online to an Elementar Analyzer (Ruff et al. 2010; Wacker et al. 2010). Results were reported as fraction modern ($F^{14}C$) and corrected for cross and constant contamination after the contamination drift model of Salazar et al. (2015). Resulting ^{14}C-ages were calibrated with the IntCal20 calibration curve (Reimer et al. 2020) using OxCal (Bronk Ramsey 2009), except the surface sediment bulk organic carbon and modern water plant ^{14}C-age, which were calibrated with the bomb 13 NH1 calibration curve (Hua et al. 2013) likewise using OxCal.

All ^{14}C results can be found in the Supplementary Table S1. ^{14}C-dating of the surface sediment gave a slight terrestrial pre-aging with a mean ^{14}C-age of 129 ± 85 cal. BP (age range: −7 to 279 cal. BP [95.4%]). However, no hardwater effect was presently indicated by modern ^{14}C-ages of the modern water plant (Strobel et al. 2021; Bliedtner et al. 2022). Based on the ^{14}C-ages, a chronology was established for the Khar Nuur sediments by Bayesian age-depth modeling using the Bacon 2.3.4 package in R (Blaauw and Christen 2011). During Bayesian age-depth modeling, the slight terrestrial pre-aging indicated by the surface sediment bulk organic carbon sample was subtracted from all conventional bulk organic carbon ^{14}C-ages. Bayesian age-depth modeling gave a modeled basal median age of 4.2 $^{+0.4}/_{-0.3}$ cal. ka BP with all aquatic macrofossil ^{14}C-ages being in stratigraphic position, likely indicating the timing of sediment deposition (Figure 2). Terrestrial pre-aging corrected bulk organic carbon ^{14}C-ages very well correspond to the aquatic macrofossil ^{14}C-ages, except for four ages at 90, 40, 30, and 20 cm sediment depth, which were pre-aged and overestimated their timing of deposition. Those samples contain an erosive signal from aged terrestrial organic carbon in the catchment soils and we therefore excluded them from Bayesian age-depth modeling (Figure 2).

Paleomagnetic Measurements

Natural remanent magnetization (NRM) was continuously measured at 1-cm intervals on a u-channel from the Khar Nuur sediment core with a 2G Enterprise DC-4K liquid helium-free magnetometer at the GFZ Potsdam. NRM was measured using stepwise (11 steps) alternating field (AF) demagnetization with peak AFs of 0, 5, 10, 15, 20, 30, 40, 50, 65, 80, and 100 mT. Inclination and declination of the characteristic remanent magnetization and maximum angular deviation (MAD) were derived from principal component analyses (Kirschvink 1980). The median destructive field (MDF) was also calculated. We have to note that declination data are relative and centered to 0 because the azimuth could not be controlled during coring. Because of the width of the response function of the SQUID sensors (~7.8 cm), some smoothing occurs in the data. In order to eliminate edge effects, the upper and lowermost 5 cm are plotted in gray.

RESULTS

NRM intensities range from 0.6 to 17.6 mA m^{-1} in the Khar Nuur sediments and MDF values from 28.5 to only 51.7 mT at the very top of the sediment core (Figure 2), indicating a low coercivity mineral such as magnetite as carrier of the natural remanent magnetization. Well preservation and stable single-component magnetization of the sediments is indicated by low MAD values (Stoner and St-Onge 2007) below 5.6°. Orthogonal vector plots confirm stable single-component magnetizations, which trend to the origin during AF treatments (see Supplementary Figure SI 1). Distinct changes are shown by the declination and

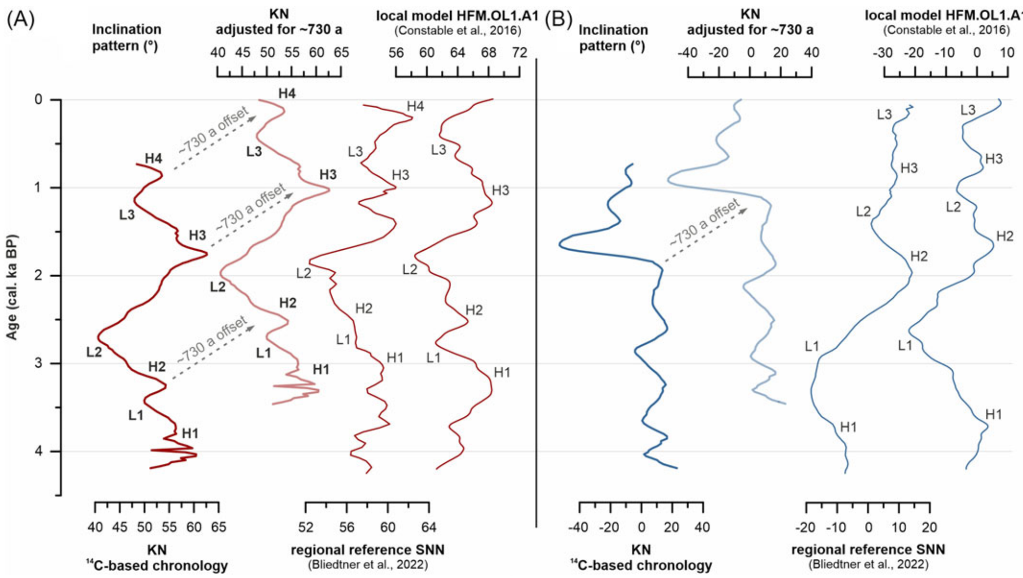

Figure 3 Comparison of (A) inclination and (B) declination pattern of the Khar Nuur sediments with the regional reference sediments from Shireet Naiman Nuur (Bliedtner et al. 2022) and the spherical harmonic geomagnetic field model HFM.OL1.A1 (Constable et al. 2016).

inclination pattern throughout the sediment core. Declination has a wide relative range from −53 to 23° and stretches over 76°. Inclination ranges from −3.3 to 62.6°, however, especially inclination seem to be offset in the uppermost part of the sediment core due to disturbed sediment and we therefore plotted the PSV pattern as a dotted gray line there. By excluding the potentially reworked uppermost part of the sediment core, inclination narrows and ranges from 40.6 to 62.6° (Figure 2). Compared to the expected inclination derived from the geocentric axial dipole model (GAD = 66.22°), inclination in the Khar Nuur sediments is flattened and did not intersect with the expected one for the latitude of this site. This has repeatedly been noticed in lake sediments and attributed to postdepositional compaction processes or compaction during coring (Tauxe et al. 2008; Henkel et al. 2016).

DISCUSSION

Distinct changes in inclination during the past 4.2 cal. ka BP in the Khar Nuur sediments are similar to the regional reference record from Shireet Naiman Nuur (Bliedtner et al. 2022) and various outputs of spherical harmonic geomagnetic field models (see Supplementary Figure SI 2 for comparison with different models, exemplarily shown here is the HFM.OL1.A1 model by Constable et al. [2016]; Figure 3A). Despite the similarities in inclination, the Khar Nuur inclination pattern appears to have a temporal offset of 730 ± 90 yr. An adjusted Khar Nuur chronology of ~730 yr, i.e., where we subtracted ~730 yr from the original ^{14}C-chronology, corresponds very well to the Shireet Naiman Nuur reference record and geomagnetic field model, now also temporally resembling their pattern (Figure 3A). Declination also shows no similarities to the regional reference and model pattern without an adjustment of the Khar Nuur ^{14}C-chronology for ~730 yr (Figure 3B). However, also with an adjustment, similarities are not obvious. Less similarities between declination records have also been reported from lakes from

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the Tibetan Plateau (Haberzettl et al. 2015). Moreover, it has often been reported that unwanted and unknown core rotation could largely affect the declination pattern (Nilsson et al. 2018), which might explain the observed differences in the Khar Nuur sediment core. However, if the large shift in declination at 50 cm sediment depth stretching over ∼50° is attributed to core rotation and hence neglected, some similarities in small scale variations can be observed between Khar Nuur and the HFM.OL1.A1 model. Unfortunately, these small-scale declination changes are missing in the Shireet Naiman Nuur sediments which might be explained by the lower sedimentation rates of the Shireet Naiman Nuur sediments (Ohlendorf et al. 2014).

The ∼730-yr offset in inclination at Khar Nuur could be explained by remaining reservoir effects in the bulk organic carbon and aquatic macrofossil ^{14}C-ages, potentially biasing the ^{14}C-based chronology. However, we have good indications that reservoir effects, i.e., from terrestrial pre-aging and hardwater effects, are negligible in the Khar Nuur sediments. While we corrected the bulk organic carbon ^{14}C-ages for a slight terrestrial pre-aging using a surface sediment sample from the coring location with a ^{14}C-age of 129 ± 85 cal. BP (age range: −7 to 279 cal. BP [95.4%]), no hardwater effects were found by modern ^{14}C-ages of a modern water plant at the coring location (Bliedtner et al. 2021; Strobel et al. 2021). Although reservoir effects are not recently present in the surface sediments of Khar Nuur, they can still variably occur through time. However, the very good agreement of the bulk organic carbon and aquatic macrofossil ^{14}C-ages questions variable reservoir effects, especially since the bulk organic carbon ^{14}C-ages, corrected for terrestrial pre-aging, should include hardwater effects to a lesser degree than the aquatic macrofossils and would therefore be younger. Moreover, the bulk organic carbon and aquatic macrofossil ^{14}C-age at 10 cm sediment depth gave younger modeled ^{14}C-ages (0.6 ± 0.3 and 0.6 $^{+0.3}/_{-0.2}$ cal. ka BP) than the observed offset of ∼730 yr in inclination (Bliedtner et al. 2021), further providing evidence for non-existing reservoir effects. Ultimately, a constant reservoir effect of ∼730 yr over time, especially a constant hardwater effect, is rather unlikely for the Khar Nuur sediments. In the carbonate-free Khar Nuur catchment only the incorporation of bicarbonate (HCO_3^-) could provide old carbonate for potential hardwater effects (Strobel et al. 2021). However, distinct lake primary productivity changes occur in the Khar Nuur sediments, which are related to changes in growing season temperature and the duration of ice cover (Bliedtner et al. 2021). Especially changes in the duration of ice coverage would result in a variable hardwater effect due to increased/reduced exchange with atmospheric $^{14}CO_2$ and the reduced/increased incorporation of $H^{14}CO_3^-$ (i.e., old carbon), respectively. Since the ∼730-yr offset in inclination is constant throughout the Khar Nuur sediments, a bias from remaining variable reservoir effects, and especially from hard water effects, is therefore very unlikely as this would have caused unpredictable offsets between the individual inclination highs and lows in the compared records after the adjustment of ∼730 yr. Therefore, the ^{14}C-based chronology provides a robust age control.

A more likely explanation for the observed age offset of ∼730 yr at Khar Nuur might be that magnetic particles become finally locked-in several centimeters below the sediment-water interface, which is the so-called "lock-in depth" (Roberts and Winklhofer 2004; Mellström et al. 2015). It has been proposed that magnetic particles can re-align to the geomagnetic field after deposition during dewatering and compaction, incorporating a post-depositional remanent magnetization (pDRM) signal which can lead to a delay and smoothing of the recorded geomagnetic signal (Roberts and Winklhofer 2004; Nilsson et al. 2018). Although the underlying physical processes are poorly understood, pDRM is thought to mostly

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depend on water content, grain size, magnetic concentration, sedimentation rate and/or bioturbation (Tauxe et al. 2006; Roberts et al. 2013; Zhao et al. 2016; Valet et al. 2017). Evidence for lock-in depths in lacustrine environments is mostly from varved sediments so far, but lock-in depths up to several decimeters below the sediment-water-interface were repeatedly reported, leading to centennial to millennial delays of the geomagnetic signal (e.g., Stockhausen 1998; Snowball et al. 2013; Mellström et al. 2015; Scheidt et al. 2022). Considering the relatively constant sedimentation rate at Khar Nuur (Figure 2), a lock-in depth of 26 ± 2 cm would very likely explain the constant 730 ± 90 year offset in PSV.

To finally confirm that the observed age offset of 730 ± 90 yr in PSV at Khar Nuur is indeed attributed to a lock-in depth of 26 ± 2 cm and not to potential reservoir effects, we compare paleoclimatological proxies from the Khar Nuur sediments with those from the well-dated Shireet Naiman Nuur sediments (Bliedtner et al. 2022; see Figure 1 for location). Log ratio of calcium and titanium (log Ca/Ti) and center log ratios of Ti (Ti_{clr}) are therefore plotted on both the ^{14}C-based chronology and a ~730-yr adjusted chronology of Khar Nuur (Figure 4). Although the sample resolution slightly differs between Khar Nuur and Shireet Naiman Nuur, both lakes are ideal for direct comparison since they are located at high-altitudes (~2400 m a.s.l.) and have comparable environmental settings and therefore very likely respond to identical forcing mechanisms. Changes in log (Ca/Ti) are interpreted as changes in lake primary productivity controlled by growing season temperatures in both lakes, whereas Ti_{clr} indicates terrigenous minerogenic input (Bliedtner et al. 2021; Bliedtner et al. 2022). Although similarities can be found between the paleoclimatological proxies of Shireet Naiman Nuur and paleoclimatological proxies from Khar Nuur plotted on both, the ^{14}C-based and ~730 year adjusted chronology of Khar Nuur, a better fit is obvious between Shireet Naiman Nuur and the ^{14}C-based chronology of Khar Nuur (Figure 4). Despite some differences in the magnitude, distinct changes in lake primary productivity and terrigenous input occur at ~4.1, ~3, and ~1.8 cal. ka BP. Between those distinct changes, productivity and terrigenous input follow similar characteristic trends (Figure 4). It is notable that slight temporal offsets in the order of 10–100 yr exist between Shireet Naiman Nuur and the ^{14}C-based chronology of Khar Nuur, but those offsets are well within the 2σ uncertainty of the chronologies of both records (Figure 4). Moreover, differences in the sedimentological proxies during the last ~1.5 cal. ka BP could exist due to increased sediment erosion and relocation in the Khar Nuur catchment, potentially climatically and/or anthropogenically induced. This is also supported by the pre-aged bulk organic carbon ^{14}C-ages in the sediments from ~45 to 20 cm of the core, overestimating their true burial age due to longer residence times in the catchment soils which were hence removed from age-depth-modeling as extensively discussed by Bliedtner et al. (2021) (Figure 2).

Because of the very consistent trend of log (Ca/Ti) in the Khar Nuur and Shireet Naiman Nuur sediments, some paleoclimate interpretations can finally be made. Changes in log (Ca/Ti) have previously been interpreted in terms of changes in lake primary productivity primarily determined by growing season temperatures in those high-altitude lakes (Bliedtner et al. 2021, 2022). This is because air temperature strongly controls the duration of ice-cover and the growing season of aquatic producers at high altitudes (Willemse and Törnqvist 1999; Mischke et al. 2010). Higher growing season temperatures are indicated in both lakes from ~4.2–4.0, 3.2–2.8 and 2.2–1.9 cal. ka BP (highlighted by reddish bars in Figure 4). In contrast, lower growing season temperatures occur from ~4.0–3.2, 2.8–2.2, and 1.9–1.6 cal. ka BP (highlighted by bluish bars in Figure 4). Based on our well dated records from Khar Nuur and Shireet Naiman Nuur, a similar regional temperature evolution is suggested by

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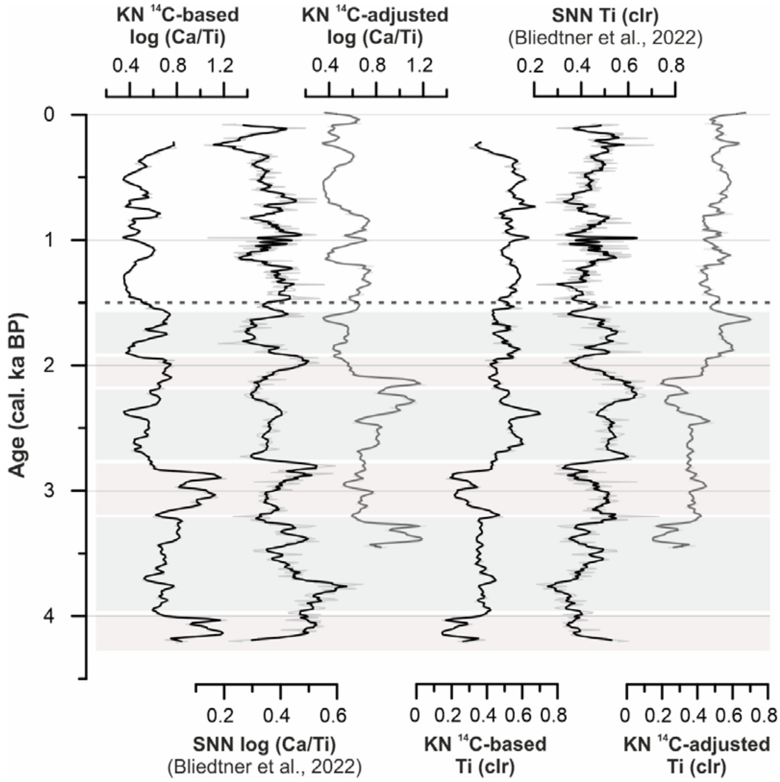

Figure 4 Comparison of the sedimentological proxies log (Ca/Ti) and center log-ratio Ti (Ticlr) from Khar Nuur and Shireet Naiman Nuur (Bliedtner et al. 2022). Sedimentological proxies from Khar Nuur are shown both on the ^{14}C-based chronology and the adjusted chronology for ~730 yr (transparent curve). Please note that the black lines of the inorganic elements at Khar Nuur refers to a 2-point running and the black lines for the inorganic elements at Shireet Naiman Nuur refers to a 5-point running mean to create a comparable data resolution of 1 cm. Reddish (bluish) bars indicate periods of higher (lower) growing season temperature at Khar Nuur and Shireet Naiman Nuur. The timespan from 1.5 cal. ka BP until present is separated by the dashed black line since climatically and/or anthropogenically induced sediment erosion and relocation took place in the Khar Nuur catchment during this time.

the very good agreement of log (Ca/Ti) for the Altai Mountains (i.e., western Mongolia) and the Khangai Mountains (i.e., central Mongolia). Our results are further supported by previous regional studies, e.g., Bayan Nuur (Yang et al. 2020) and Telmen Nuur (Struck et al. 2022), who suggested total solar irradiance (TSI) as a main driver for temperature dynamics during the Late Holocene in the region, i.e., colder conditions during minima in TSI and warmer conditions during maxima in TSI.

CONCLUSIONS

Inclination pattern from Khar Nuur closely resembles those from the regional reference record from Shireet Naiman Nuur and the geomagnetic field models, however, with a constant offset of 730 ± 90 yr. We can exclude that the constant ~730-yr offset is caused by reservoir effects from terrestrial pre-aging and hardwater effects because bulk organic carbon and aquatic macrofossil ^{14}C-ages very well agree with each other, almost no modern reservoir effect was indicated by surficial sediment dating and dating a modern water plant, and the uppermost ^{14}C-datings at 10-cm sediment depth gave younger ages than the offset of ~730 yr in inclination. Instead, an almost constant lock-in depth of 26 ± 2 cm below the sediment-water-interface very well explains the observed constant 730 ± 90 yr offset in the PSV pattern at Khar Nuur. This is further supported by comparison of paleoclimatological proxies from Khar Nuur with Shireet Naiman Nuur, both high-altitude lakes with comparable environmental settings, where obvious similarities in log (Ca/Ti) and Ti_{clr} exist between Shireet Naiman Nuur and the ^{14}C-based chronology of Khar Nuur.

We emphasize the importance of the potential lock-in of magnetic particles several centimeters below the sediment-water-interface for future studies since the lock-in depth can complicate the estimation of potential reservoir effects and finally challenge the refinement of ^{14}C-based chronologies. Nevertheless, PSV will give an additional chronological indicator, and our combined approach will largely help to improve and potentially refine chronologies in semi-arid regions.

SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit https://doi.org/10.1017/RDC.2023.38

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AUTHOR CONTRIBUTIONS

Marcel Bliedtner: conceptualization, formal analysis, investigation, writing—original draft, writing—review and editing; Torsten Haberzettl: conceptualization, investigation, writing—review and editing; Norbert Nowaczyk: investigation, writing—review and editing; Enkhtuya Bazarradnaa: writing—review and editing; Roland Zech: writing—review and editing; Paul Strobel: conceptualization, investigation, writing—review and editing.

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