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Microbial Membrane Tetraether lipid-inferred paleohydrology and paleotemperature of Lake Chenghai during the Pleistocene-Holocene transition

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ABSTRACT

Over the past few decades, paleoenvironmental studies in the Indian Summer Monsoon (ISM) region have mainly focused on precipitation change, with few published terrestrial temperature records from the region. We analyzed the distribution of isoprenoid glycerol dialkyl glycerol tetraethers (isoGDGTs) in the sediments of Lake Chenghai in southwest China across the Pleistocene–Holocene transition, to extract both regional hydrological and temperature signals for this important transition period. Lake-level was reconstructed from the relative abundance of crenarchaeol in isoGDGTs (%cren) and the crenarchaeol'/crenarchaeol ratio. The %cren-inferred lake-level identified a single lowstand (15.4-14.4 cal ka BP), while the crenarchaeol'/crenarchaeol ratio suggests relatively lower lake-level between 15.4-14.4 cal ka BP and 12.5-11.7 cal ka BP, corresponding to periods of weakened ISM during the Heinrich 1 (H1) and Younger Dryas (YD) cold event. A filtered TetraEther indeX consisting of 86 carbon atoms (TEX_{86} index) revealed that lake surface temperature reached present-day values during the YD cold event, and suggests a substantial warming of ~4 ℃ from the early Holocene to the mid-Holocene. Our paleotemperature record is generally consistent with other records in southwest China, suggesting that the distribution of isoGDGTs in Lake Chenghai sediments has potential for quantitative paleotemperature reconstruction.

Keywords: Quantitative temperature reconstruction; Lake-level; TEX_{86}; Isoprenoid GDGTs; Lacustrine sediment

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1. troduction

Precipitation in the Indian summer monsoon (ISM) region has decreased substantially with recent global warming, greatly threatening ecosystem function, water availability and economic security across the region (Sinha et al., 2011; Sinha et al., 2015; Ljungqvist et al., 2016). For example, in 2009-2010 severe droughts occurred in southwest China that reduced food production dramatically (Lü et al., 2012). This has stimulated growing scientific interest in understanding the underlying forcing mechanisms behind climate variability in the ISM region on different time-scale, in order to better predict future monsoonal variations.

Over the past two decades, climate evolution in the ISM region since the Last Glacial Maximum has been reconstructed from various paleoclimatic archives, including stalagmites, marine and lacustrine sediments (Dykoski et al., 2005; Rashid et al., 2007; Govil and Divakar Naidu, 2011; Saraswat et al., 2013; Contreras-Rosales et al., 2014; Wang et al., 2014b; Dutt et al., 2015; Wu et al., 2015; Kathayat et al., 2016; Zhang et al., 2017a, 2017b; Li et al., 2018; Zhang et al., 2018; Sun et al., 2019; Zhang et al., 2019). These studies provide evidence that changes in ISM precipitation and temperature were generally synchronous on the orbital- and millennial-scale, with a weakened ISM during cold events, and strengthened ISM during warm intervals. However, there remains a paucity of quantitative reconstructions of both hydrological and thermal parameters from the ISM region (Zhang et al., 2017a; Wu et al., 2018; Ning et al., 2019; Zhang et al., 2019), which hinders our detailed understanding of the dynamics of the ISM and therefore the development of climate models with improved prognostic potential.

Pollen, chironomids, alkenone and glycerol dialkyl glycerol tetraethers (GDGTs) have been widely used for the quantitative reconstruction of terrestrial paleotemperature during the Quaternary (Nakagawa et al., 2003, 2006; Blaga et al., 2013; Stebich et al., 2015; Wang et al., 2017b; Zhang et al., 2017a; Sun et al., 2018; Wu et al., 2018; Ning et al., 2019; Tian et al., 2019; Zhang et al., 2019). Isoprenoi GDGTs (isoGDGTs) are a suit of membrane lipids produced by some speci

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archaea, that are ubiquitous in soils, lacustrine and marine sediments (Schouten et al., 2013). The distribution of isoGDGTs ~~compounds~~ correlates well with surface water temperature, and therefore ~~has~~ great potential ~~for use~~ as a paleotemperature proxy (Schouten et al., 2002; Blaga et al., 2009; Kim et al., 2010; Powers et al., 2010).

The TetraEther indeX consisting of 86 carbon atoms (TEX_{86} index), which represents the relative number of cyclopentane moieties in isoGDGT molecules derived from aquatic Thaumarchaeota, has ~~also~~ been successfully applied as a paleothermometer in large lakes (Tierney et al., 2008; Berke et al., 2012; Blaga et al., 2013; Wang et al., 2015). However, the index may not be a reliable proxy for past temperature in small lakes~~-~~(Blaga et al., 2009; Powers et al., 2010; Sinninghe Damsté et al., 2012a). In addition, ~~the proportion of crenarchaeol in isoGDGTs~~ has been suggested to be a lake-level proxy due to a preference of the producer of this compound for a niche above the oxycline in the upper part of the water column in lacustrine systems (Wang et al., 2014a; Wang et al., 2017a; Wang et al., 2019). In this study, we present an isoGDGT record from Lake Chenghai in the southwest China. We use the results to test the reliability of isoGDGT-based proxies as lake-level and temperature indicators, by comparing our results with other paleoenvironmental records from adjacent areas.

2. Materials and methods

2.1. Regional setting

Lake Chenghai (26°27′-26°38′N, 100°38′-100°41′E, Fig. 1A) is a tectonic lake located in Yongsheng County in Yunnan Province (Wang and Dou, 1998). The present elevation of the lake-level is ~1500 m above sea level (a.s.l.), and the maximum depth is ~35 m with a mean depth of ~20 m. The lake has a surface area of ~77 km^2 with a catchment of ~318 km^2 (Wu et al., 2004). The annual mean lake surface temperature (LST) is ~16 ℃ (Wan et al., 2005). The lake water is slightly brackish (average= ~1‰) and alkaline (average pH= ~8). There are no perennial inlets or outflow streams

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at present, and the lake is mainly maintained by direct precipitation and groundwater (Wan et al., 2005). Lake Chenghai was linked to the Jinsha River via the Haikou River ~~during the Ming Dynasty (1368-1644 CE)~~, but became a closed lake in the 1690s CE when a dam (~1540 m a.s.l.) was constructed on its southern side (Wang and Dou, 1998).

The lake basin is surrounded by mountains ranging ~~from~~ 2300-4000 m a.s.l. Topsoil types include lateritic red earths and mountain red brown soils (Wang and Dou, 1998). The region is mainly affected by a warm-humid monsoonal airflow from the tropical Indian Ocean from June to September, and by the southern branch of the Northern Hemisphere westerly jet between October and May (Wang and Dou, 1998). Observed climatic data spanning the past 30 years from the Yongsheng meteorological station (26.68 °N, 100.75 °E; elevation of 2130 m a.s.l.) indicate a mean annual temperature of 14 °C, an annual precipitation of 660 mm, ~80% of which falls ~~from~~ June ~~to~~ September.

2.2. Sampling and dating

An 874-cm-long sediment core was retrieved at 26°33′29.4″N, 100°39′6.7″E using a UWITEC coring platform system with a percussion corer in July 2016 ~~CE~~. The water depth was 30 m. ~~The sediment cores were~~ split ~~longitudinally,~~ photographed and then sectioned at a 1-cm interval in the laboratory~~, and~~ the samples stored at 4 °C until analysis.

The chronology was established using accelerator mass spectrometry (AMS) ^{14}C dating of terrestrial plant macrofossils and charcoal (Sun et al., 2019). Macrofossils of leaves, woody stems and charcoal were hand-picked under the microscope. Eight dates covering the period from the last deglaciation to early Holocene were obtained. The analyses were performed at the Beta Analytic Radiocarbon Dating Laboratory in Miami, USA. The age model was developed utilizing Bacon, implemented in R 3.1.0 at 5-cm intervals (Blaauw and Andres Christen, 2011; R Development Core Team, 2013). All AMS ^{14}C dates were calibrated to calendar years before present (0 BP

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=1950 CE) using the program Calib 7.1 and the IntCal13 calibration data set (Reimer et al., 2013). The basal mean weighted age is ~15.6 cal ka BP (Fig. 2, Sun et al., 2019).

2.3. Lipid extraction and analysis

~~After freeze-drying, a total of 102 samples at 4-cm interval over the Pleistocene-Holocene transition were collected for GDGT analysis, and this was increased to 1-cm resolution across 792-806 cm span due to the low sedimentation rate over this interval,~~ A ~4 g aliquot ~~of~~ each sample was extracted ultrasonically (4 times) with a mixture of dichloromethane and methanol (9:1, v/v). The supernatants were condensed and base hydrolyzed in a 1 M KOH/methanol solution. The neutral fractions were then separated into apolar and polar fractions on a silica gel column, using *n*-hexane and methanol, respectively. The polar fraction containing the GDGTs was concentrated and filtered through 0.45 μm polytetrafluoroethylene syringe filters using *n*-hexane/ isopropanol (99:1 v/v). These fractions were then dried in N_2 and stored at -20 ℃ until further analysis.

GDGTs were analyzed using an Agilent 1200 series high performance liquid chromatography-atmospheric pressure chemical ionization-mass spectrometer (HPLC- APCI- MS), following the procedure of Yang et al. (2015) at the Institute of Tibetan Plateau Research, Chinese Academy of Sciences. Briefly, the GDGTs were separated using three silica columns in tandem (150 mm× 2.1 mm, 1.9 μm; Thermo Finnigan, U.S.A.), maintained at 40 ℃. The elution gradients were 84% *n*-hexane (A): 16% ethyl acetate for 5 min, 84/16 to 82/18 A/B for another 60 min, then to 100% B for 21 min and kept for 4 min, followed by a return to 84/16 A/B for 30 min. The total flow rate of pump A and pump B was maintained at 0.1 ml/min. The APCI-MS conditions were: vaporizer pressure 60 psi, vaporizer temperature 400 ℃, drying gas flow 6 L/min and temperature 200 ℃, capillary voltage 3500 V and corona current 5 μA (~3200 V). Selected ion monitoring (SIM) mode was performed to target specific *m/z* values for each GDGT compound, including 1302 (GDGT-0), 1300 (GDGT-1), 1298 (GDGT-2), 1296 (GDGT-3), 1294 (crenarchaeol), 1292 (crenarchaeol'), 1050

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(IIIa, IIIa'), 1048 (IIIb, IIIb'), 1046 (IIIc, IIIc'), 1036 (IIa, IIa'), 1034 (IIb, IIb'), 1032 (IIc, IIc'), 1022 (Ia), 1020 (Ib) and 1018 (Ic). The chemical structures of these compounds are presented in Supplementary Fig. S1. The results are presented as the fractional of the sum of the isoGDGTs or the sum of the branched GDGTs (brGDGTs), based on the integration of the peak areas of the $[M+H]^+$ ions.

2.4. Index calculation and temperature reconstruction

The percentage of each isoGDGT (X) was calculated according to the following equation:

$$\%X = X / (\text{GDGT-0} + \text{GDGT-1} + \text{GDGT-2} + \text{GDGT-3} + \text{crenarchaeol} + \text{crenarchaeol'}) \quad (1)$$

The TEX_{86} index was defined by Schouten et al. (2002) as follows:

$$TEX_{86} = (\text{GDGT-2} + \text{GDGT-3} + \text{crenarchaeol'}) / (\text{GDGT-1} + \text{GDGT-2} + \text{GDGT-3} + \text{crenarchaeol'}) \quad (2)$$

TEX_{86}-inferred LST was calculated using the global lake calibration of Castañeda and Schouten (2015):

$$LST = 49.03 \times TEX_{86} - 10.99 \quad (r^2 = 0.88, n=16, RMSE = 3.1\ ^\circ C) \quad (3)$$

The ratio of branched to isoprenoid tetraethers (BIT index), used as an indicator of soil organic matter input and as a test of the utility of the TEX_{86} paleotemperature proxy, was calculated following Hopmans et al. (2004):

$$BIT = (Ia + IIa + IIa' + IIIa + IIIa') / (Ia + IIa + IIa' + IIIa + IIIa' + \text{crenarchaeol}) \quad (4)$$

3. Results

A wide variety of isoGDGT compositions is present in the sediments of Lake Chenghai. As illustrated in Fig. 3, the relative abundances of crenarchaeol (%cren) ranged ~~from~~ 2.4-61.3% with a mean of 52.4%. The %cren values were relatively low

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and highly variable during 15.4-14.4 cal ka BP, ranging from 1.8-32.0%, with a mean of 11.6%. By contrast, the values were relatively stable during 14.4-7.0 cal ka BP, ranging from 41.8-61.3% with a mean of 58.3%. The relative abundances of its regioisomer, crenarchaeol', had a mean of 1.7%. The ratios of crenarchaeol'/crenarchaeol were highly variable during 15.4-14.4 cal ka BP with a mean of 0.07. After this time, the values gradually decrease during 14.4-11.7 cal ka BP with a minor reversal during 12.5-11.7 cal ka BP, where the ratio averaged 0.05. The crenarchaeol'/crenarchaeol ratios were generally stable and fluctuated around 0.03 during the period 11.8-7.0 cal ka BP.

The relative abundances of GDGT-0 (%GDGT-0) showed a significant negative correlation with the reciprocal of %cren (r^2= 0.98, p< 0.001). The %GDGT-0 values had a mean of 74.0% during 15.4-14.4 cal ka BP and a mean of 19.6% during the 14.4-7.0 cal ka BP interval. The ratios of GDGT-0/crenarchaeol were generally >2 during the period 15.4-14.4 cal ka BP, ranging from 1.4-49.9 with a mean of 16.7, and all <2 from 14.4-7.0 cal ka BP. The relative abundance of GDGT-1, GDGD-2 and GDGT-3 were generally low in the sediments, with a mean of 8.9, 9.2, and 1.3, respectively.

The TEX_{86} values were also highly variable during 15.4-14.4 cal ka BP period, ranging from 0.36-0.68 with a mean of 0.54. Thereafter the values generally followed an increasing trend, ranging from 0.49-0.63 with a mean of 0.58. The BIT values exhibited a significant negative correlation with cren% values (r^2= 0.94, p< 0.001), ranging from 0.39-0.99 with a mean of 0.54. An abrupt decrease from 0.96 to 0.52 occurred at 14.4 cal ka BP. After this time, the BIT values gradually decreased to a minimum value at 9.3 cal ka BP, and fluctuated thereafter around 0.48 during 9.3-7.0 cal ka BP.

4. Discussion

4.1. Environmental significances of the isoGDGT-based proxies

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Crenarchaeol and its regioisomer are considered to be produced specifically by mesophilic Thaumarchaeota in aquatic environments (Schouten et al., 2002; Schouten et al., 2013). In marine conditions, Thaumarchaeota have a physiological mechanism to increase the weighted average number of cyclopentane rings in their membrane lipids with growth temperature, thus a significant linear correlation is found between TEX_{86} values and mean annual sea surface temperature (Schouten et al., 2002). In the studies of lacustrine systems, the temperature calibration of TEX_{86} has been found to be nearly identical to the marine calibration, suggesting that the paleothermometer can also be applied in lacustrine sediments (Powers et al., 2004; Blaga et al., 2009; Powers et al., 2010; Castañeda and Schouten, 2011). In addition, aquatic Thaumarchaeota are nitrifers, that prefer to live above the oxycline of relatively deep lakes, as has been observed by a range of lipid biomarker and DNA based investigations of vertical changes in archaea communities in lake water columns (Sinninghe Damsté et al., 2009; Blaga et al., 2011; Schouten et al., 2012; Buckles et al., 2013; Meegan Kumar et al., 2019).

Some Thaumarchaeota are considered to be suppressed by a high light level, which consequently might also prohibit them from thriving right near the surface layer of lake water (Schouten et al., 2013). In addition, Thaumarchaeota are chemoautotrophic and thrive predominantly near the oxycline in stratified lakes, mainly due to the release of ammonia derived from descending particulate organic matter that is recycled primarily by photoautotrophs or heterotrophs in the photic zone (Tierney et al., 2010). Furthermore, mixing of the water column will be much more frequent at lowstand conditions (Filippi and Talbot, 2005), and therefore periodically or permanently oxic, high nutrient availability water and enhanced nitrogen cycling would be likely result in a relatively lower production of crenarchaeol. Therefore, the cren% value measure in lacustrine sediments has been proposed to be a potential proxy for lake level change, with high values indicating highstand and deep lake status, while low values reflecting lowstand and shallow lake status (Wang et al., 2014a; Wang et al., 2017a; Wang et al., 2019).

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Although TEX_{86} and cren% show great potential as paleotemperature and paleo-lake-level proxies, they may be significantly biased when a substantial amount of soil and/or methanogenic archaea isoGDGTs are identified in the same lacustrine sediment (Weijers et al., 2006; Blaga et al., 2009; Powers et al., 2010; Wang et al., 2019). BIT index values are generally >0.90 in soils, whereas values are close to zero for large lake sediments (Hopmans et al., 2004; Weijers et al., 2006). ~~In this study, Lake Chenghai sediment the BIT index values range from~~ 0.39-0.99, indicating that a considerable proportion of isoGDGTs could derive from soils. However, recent studies ~~of modern processes~~ in a wide variety of lakes have suggested that at ~~least partly~~ branched GDGTs ~~are generated by *in-situ* production~~ (Blaga et al., 2010; Tierney et al., 2010; Pearson et al., 2011; Hu et al., 2016; Dang et al., 2018; Russell et al., 2018). Therefore, *in-situ* production of branched GDGTs in Lake Chenghai cannot be fully excluded.

It has also been shown that crenarchaeol' is only present in low abundance in most Thaumarchaeota except for the group I.1b Thaumarchaeota, where it is one of the major GDGTs (Kim et al., 2012; Sinninghe Damsté et al., 2012b). The crenarchaeol'/crenarchaeol ratios for enrichment cultures of group I.1a aquatic Thaumarchaeota are typically 0.01-0.04, however, for group I.1b Thaumarchaeota enriched from soils the crenarchaeol'/crenarchaeol ratios are around 0.21 and substantially higher (Pitcher et al., 2011; Sinninghe Damsté et al., 2012a). This suggests that the observed down-core changes in crenarchaeol'/crenarchaeol ratios may be due to relatively high contributions of group I.1b Thaumarchaeota from soils during 15.4-11.8 cal ka BP, and that these dominate the contributions of isoGDGTs derived from aquatic group I.1a Thaumarchaeota during the period from 11.8-7.0 cal ka BP.

The TEX_{86} and cren% measures might also be affected by methanogenic and methanotrophic archaea because methanogenesis is the dominant anaerobic metabolic pathway in freshwater ecosystems (Blaga et al., 2009; Dang et al., 2016; Yao et al., 2019). Crenarchaeol and GDGT-0 can be derived from Group I Thaumarchaeota,

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whereas methanogens synthesize GDGT-0, but no crenarchaeol. On this basis, the ratio of GDGT-0/crenarchaeol has been proposed to evaluate the influence of methanogenesis on the distribution of isoGDGTs in lacustrine sediments (Blaga et al., 2009). The ratio typically varies between 0.2 and 2 in group I Thaumarchaeota, thus a value >2 is generally thought to reflect a substantial contribution from methanogens to the total isoGDGT (Schouten et al., 2002; Blaga et al., 2009). Therefore, higher GDGT-0/crenarchaeol values suggest that methanogenic and methanotrophic archaeal were also likely to be an important source of GDGTs in some of Lake Chenghai sediments during 15.4-14.4 cal ka BP.

4.2. Assessment of isoGDGT-based lake-level proxy

Environmental changes at Lake Chenghai as inferred from %cren, crenarchaeol'/crenarchaeol ratio, the BIT index and GDGT-0/crenarchaeol ratio during the period from the last deglaciation to the early Holocene are illustrated in Fig. 4. The relatively low %cren and high GDGT-0/crenarchaeol values during 15.4-14.4 cal ka BP suggest that the Thaumarchaeota were mainly suppressed by methanogenic and methanotrophic archaeal. Deep lake conditions and thermal stratification have also been suggested as important in influencing the Thaumarchaeota's growth, while any increase in water column turbulence would have negatively affected them (Tierney et al., 2010). Thus the abrupt increase in %cren values at 14.4 cal ka BP suggest a lowland of Lake Chenghai during 15.4-14.4 cal ka BP, and a highstand period thereafter.

The lowstand period is consistent in timing with the stable oxygen isotope ($\delta^{18}O$) record of authigenic carbonates derived from the same core (Fig. 4e, Sun et al., 2019), speleothem $\delta^{18}O$ records from Mawmluh Cave and Bittoo Cave in north India (Fig. 4f, Dutt et al., 2015; Kathayat et al., 2016), and Donnge Cave in southwest China (Dykoski et al., 2005), which all record a substantial positive shift in $\delta^{18}O$ values at that time. Speleothem $\delta^{18}O$ records in the ISM region are used as a rainfall amount proxy, tracking changes in monsoon intensity (Dykoski et al., 2005; Cheng et al., 2012; Dutt et al., 2015). Therefore, the lowstand of Lake Chenghai during 15.4-14.4

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cal ka BP implies a weakened ISM during the Heinrich 1 (H1) cold event, consistent with ~~other evidence,~~

Low lake-levels during the H1 cold event are also ~~indicated by~~ several previous paleolimnolgical studies from the Yunnan Plateau, within the uncertainties of the age model. Diatom and grain-size records from Lake Tengchongqinghai show a significant decrease in acidophilous diatom species and an increase in the grain-size of mineral particles from 18.5 to 15.0 cal ka BP, suggesting that the climate was ~~driest~~ and the ISM was at its weakest since the last deglaciation (Fig. 4g, Zhang et al., 2017b; Li et al., 2018). Similarly, an increase in >30 μm grain-size particles in the late glacial sediments from Lake Xingyun reflects a period of abrupt weak ISM during the H1 cold event (Wu et al., 2015). In Lake Lugu, the loss of the planktonic diatoms and a switch to small *Fragilaria* spp. suggest a weaker stratification during 24.5-14.5 cal ka BP, which might also correspond to low lake-level at that time (Wang et al., 2014b).

Lake Chenghai lake-level does not seem to reduce during the Younger Dryas (YD) cold event, which is also recognized as a millennial-scale period of weak ISM (Dutt et al., 2015; Dykoski et al., 2005; Kathayat et al., 2016; Sun et al., 2019). In contrast, a low lake-level signal is observed in the $\delta^{18}O$ record of authigenic carbonates from Lake Chenghai (Sun et al., 2019). In addition, increased lake water alkalinity and decreased lake-level are also recorded in the diatom and grain-size proxy records during 12.8-11.1 cal ka BP of Lake Tengchongqinghai (Fig. 4g, Zhang et al., 2017b; Li et al., 2018). The differences in lake hydrological conditions to the YD weak ISM inferred from different lake sediment records is possibly due to differences in the sensitivity of the proxy to lake-level variation in the case of Lake Chenghai.

The $\delta^{18}O$ record of authigenic carbonates from Lake Chenghai and speleothem $\delta^{18}O$ records in the ISM region suggest that the weakening of the ISM during the YD was less marked than that occurring during the H1 event, in turn suggesting that lake-levels in southwest China may have been higher during the YD than the H1 event (Dykoski et al., 2005; Dutt et al., 2015; Kathayat et al., 2016; Sun et al., 2019;

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Zhang et al., 2019). For the %cren proxy, we note that the values are significantly correlated to the logarithm of depth in Asian lakes (%cren= 19.59 × log(depth)+ 9.23), suggesting that %cren may be less sensitive to water depth variation when the lake-level is relatively high (Wang et al., 2019). It is also worth noting that the crenarchaeol'/crenarchaeol ratios were not only relatively higher during the H1 cold event, but also showed a minor reversal during the YD cold event. These results are consistent with group I.1b Thaumarchaeota being an important source of isoGDGTs in some small lakes and to the nearshore area of large lakes (Wang et al., 2019).

4.3. Warming in the early Holocene

Robust application of the TEX_{86}-based paleotemperature calibration critically depends on the assumption that the isoGDGTs used for calculation of TEX_{86} values are mainly been derived from group I.1a in the water column (Blaga et al., 2009; Castañeda and Schouten, 2011; Powers et al., 2010; Sinninghe Damsté et al., 2012a). Since the influence of methanogenic archaea in the water column or archaea in the catchment soils have been recognized, Lake Chenghai sediments with BIT values >0.5 and/or GDGT-0/crenarchaeol ratio >2 are excluded from the discussion below (Powers et al., 2010; Castañeda and Schouten, 2015). 57 samples remain that have isoGDGT distributions consistent with their dominant source being the aquatic Thaumarchaeota, most of these being from the time interval between 11.7-8.2 cal ka BP, and only a few from the early YD period (n=2) and 8.2-7.0 cal ka BP (n= 6). Using Equation 4 developed by Castañeda and Schouten (2015) to calculate mean LST, yielded LST values from 15.7-20.1 °C, with a mean of 17.9 °C (Fig. 5a).

LST was ~15.8 °C during the early YD period, a temperature approaching the 16 °C observed in the present Lake Chenghai. Following the YD cold event, LST rapidly increased from 16.2 °C at 11.2 cal ka BP to 18.2 °C at 11.0 cal ka BP, and LST ranged from 16.8 °C to 20.1 °C with a an increasing trend observed during the 11.0-7.0 cal ka BP interval. This result is consistent with other recent reconstructed mean annual temperatures in southwest China, which show the temperatures during the YD cold event were generally similar to the present-day value, and the middle

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Holocene was generally warmer than the early Holocene (Ning et al., 2019; Tian et al., 2019). For example, mean annual temperatures were 1.3 ℃ higher between 7.6 and 5.5 cal ka BP than during 9.4-7.6 cal ka BP as inferred from the branched GDGT record from Lake Ximenglongtan in southwest China (Fig. 5d, Ning et al., 2019). Furthermore, the July temperature derived from the chironomid record from Lake Tiancai and the pollen record from Lake Xingyun also show similar values during the YD cold event with that of the present-day (Fig. 5b and c, Wu et al., 2018; Zhang et al., 2019). The pollen record from Lake Xingyun in southwest China suggested that the July temperatures remained high values at ~25.5 ℃ during 8.0-5.5 cal ka BP, and ~1.6 ℃ higher than those during the early Holocene (Wu et al., 2018). However, July temperatures reconstructed from Lake Tiancai in southwest China display much lower amplitude of change, being only 0.3 ℃ higher during the mid-Holocene than the early Holocene (Zhang et al., 2017a).

Temperature in areas affected by the East Asian summer monsoon was more sensitive to high latitude climate change than in the ISM region. The mean annual temperature was ~8.5 ℃ cooler than present day during 12.3-11.3 cal ka BP in southwest Japan as inferred from the pollen record from Lake Suigetsu, with the variation larger in winter than summer (Fig. 5f, Nakagawa et al., 2003, 2006). The mean annual temperature estimated from the branched GDGTs record from the Shuizhuyang peat bog in southeast China dropped to 10.3 ℃ during the YD cold period, ~5.5 ℃ cooler than present-day (Wang et al., 2017b). In addition, a pollen record from Lake Sihailongwan in northeast China suggests a cool mixed forest biome was the dominant vegetation type during the late YD period, leading to the calculation of a mean July temperature of ~15-16 ℃, 5-6 ℃ cooler than modern July temperature (Fig. 5e, Stebich et al., 2015). The summer LST of Lake Sihailongwan reconstructed from long-chain alkenones shows the average temperature was ~14.2 ℃ during the YD event, ~4.3 ℃ cooler than the modern instrumental water temperature (Sun et al., 2018). Following the YD cold event, the pollen record from Lake Sihailongwan in northeast China suggests that the July temperatures gradually

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increased from 18.0 ℃ at 11.4 cal ka BP to 26.5 ℃ at 8.1 cal ka BP, and remained at generally high values (>25.0 ℃) during the mid-Holocene (Stebich et al., 2015). The branched GDGTs record from Gushantu peat bog in northeast China also shows the highest mean annual temperatures occurred between 8.0 and 6.8 cal ka BP (Zheng et al., 2018). The regionally warmer mid-Holocene is considered to be related to the persistence of remnants of the Northern Hemisphere ice-sheets during the early Holocene, which slowed down the Atlantic Meridional overturning circulation and enhanced the westerlies, resulting in lower temperatures across the downstream Eurasian continent (Zhang et al., 2017a; Wu et al., 2018; Ning et al., 2019).

5. Conclusions

The record of isoGDGTs in the sediments of Lake Chenghai in southwest China presented in this study allows us to test the ability of isoGDGT-based proxies in the ISM region to reconstruct lake-level and temperature during the Pleistocene-Holocene transition. The lake-level history inferred from %cren shows a relative lowstand of Lake Chenghai during 15.4-14.4 cal ka BP, corresponding to a period of weakened ISM during the H1 cold event. The indistinct signal of lake-level variation during the YD cold event may be due to the %cren proxy not being sensitive to lake-level change when the lake was relatively full. By contrast, the crenarchaeol'/crenarchaeol ratios suggest group I.1b Thaumarchaeota being an important source of isoGDGTs and the lake level was low during the YD cold event. After filtering for the influence of isoGDGTs derived from soils in the surrounding catchment and methanogens, the TEX_{86} paleothermometry revealed that the LST of Lake Chenghai was similar to the present-day value during the YD cold event and experienced a substantial warming of ~4 ℃ from the early-Holocene to the mid-Holocene. Overall, our results show that the distribution of isoGDGTs in Lake Chenghai sediments do have potential for quantitative paleotemperature reconstruction once potential underlying biases are properly constrained.

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Data availability.

All data in this study will be made available on request.

Author contributions.

W.S and E.Z designed the study, W.S performed the fieldwork and lab analysis. W.S and E.Z led the writing of the paper, J.C, J. S, M.I.B, C.Z, Q.J and J.S contributed to data interpretation and paper writing. All authors contributed to discussions and writing of the manuscript. The authors declare that they have no competing financial interests.

Competing interests.

The authors declare that they have no conflict of interest.

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Figure captions

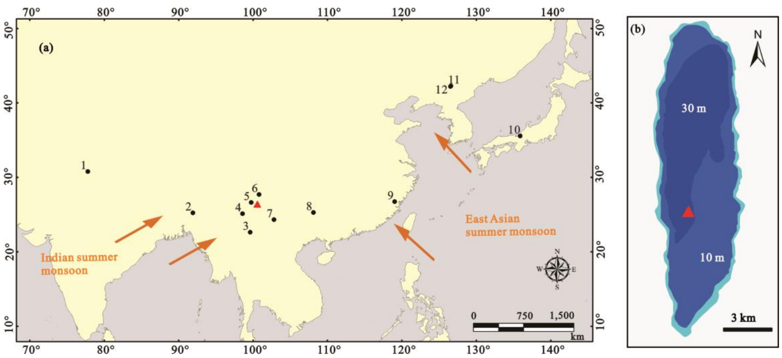

Fig. 1. (a) Map showing the location of Lake Chenghai in southwest China (triangle) and other sites (circles) mentioned in the text: 1. Bittoo Cave (Kathayat et al., 2016); 2. Mawmluh Cave (Dutt et al., 2015); 3. Lake Ximenglongtan (Ning et al., 2019); 4. Lake Tengchongqinghai (Zhang et al., 2017b; Li et al., 2018; Tian et al., 2019); 5. Lake Tiancai (Zhang et al., 2017a, 2019); 6. Lake Lugu (Wang et al., 2014); 7. Lake Xingyun (Wu et al., 2015, 2018); 8. Dongge Cave (Dykoski et al., 2005); 9. Peat bog Shuizhuyang (Wang et al., 2017b); 10. Lake Suigetsu (Nakagawa et al., 2003, 2006); 11. Lake Sihailongwan (Stebich et al., 2015; Sun et al., 2018), 12. Gushantun peat bog (Zheng et al., 2018). Arrows indicate the dominant atmospheric circulation systems in the region. (b) The triangle in panel b indicates the location of core CH2016 in Lake Chenghai.

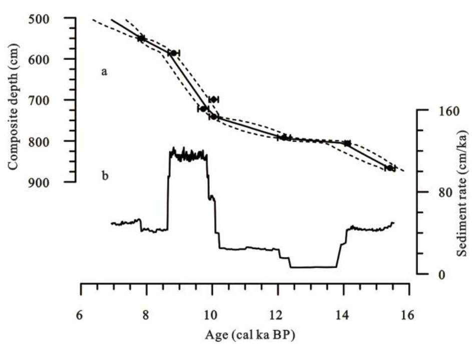

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Fig. 2. (a) Age-depth model of the Lake Chenghai sediment core produced ~~by~~ Bacon software (Blaauw and Andres Christen, 2011~~; Sun et al., 2019~~). Dotted lines indicate the 95% confidence range and the solid line indicates the weighted mean ages for each depth, error bars indicate the standard deviation range (2σ) of the calibrated radiocarbon dates. (b) estimated sedimentation rate (Sun et al., 2019).

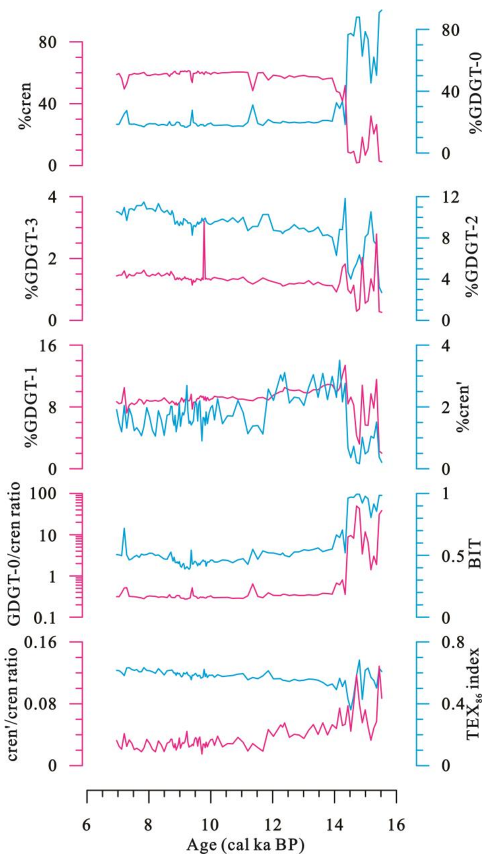

Fig. 3. Variations in the relative isoGDGT distribution and isoGDGTs-based proxies of the Lake Chenghai ~~sediments~~.

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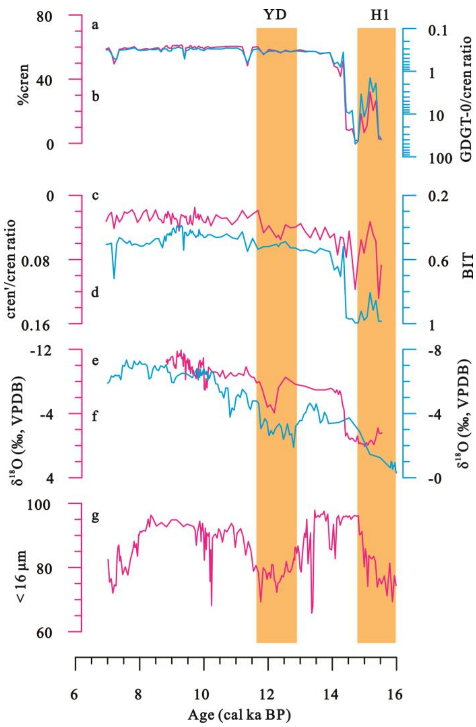

Fig. 4. Comparison of the isoGDGT-based lake-level record from Lake Chenghai (a-d) with the $\delta^{18}O$ record of carbonate finer in grain size than 63 µm from Lake Chenghai (e, Sun et al., 2019), the stalagmite $\delta^{18}O$ records from Mawmluh Cave in northeast Indian (f, Dutt et al., 2015); and grain-size record from Lake Tengchongqinghai (g, Zhang et al., 2017). The shading is utilised to represent 'cold' events in the North Atlantic.

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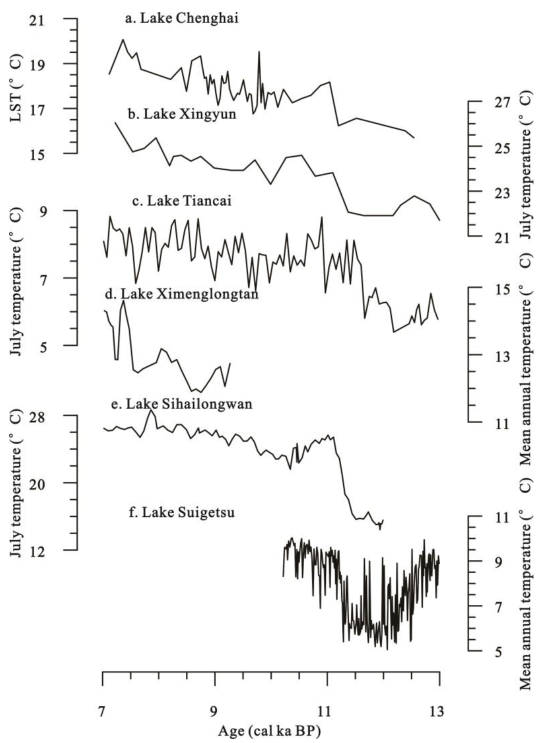

Fig. 5. A comparison of TEX_{86}-based lake surface temperature of Lake Chenghai (a) with other paleotemperature records. July temperature reconstructed from pollen record from Lake Xingyun (b, Wu et al., 2018) and subfossil chironomids from Lake Tiancai (c, Zhang et al., 2017a, 2019); mean annual temperature reconstructed from Lake Ximenglongtan based on brGDGTs (d, Ning et al., 2019); July temperature reconstructed from pollen record from Lake Sihailongwan (e, Stebich et al., 2015); and pollen reconstructed mean annual temperature from Lake Suigetsu (f, Nakagawa et al., 2003).