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Alkenone-based reconstruction of late-Holocene surface temperature and salinity changes in Lake Qinghai, China

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[1] Few proxies can provide quantitative reconstructions of past continental climatic and hydrological changes. Here, we report the first alkenone-based reconstruction of late Holocene temperature and salinity changes in Lake Qinghai, China. The alkenone-temperature proxy ($U_{37}^{k'}$) indicates up to a 1°C change in mean annual air temperature or a 2°C change in summer lake water temperature during the late Holocene. Oscillating warm and cold periods could be related to the 20th century warm period, the Little Ice Age, the Medieval Warm Period, the Dark Ages Cold Period, and the Roman Warm Period. The relative importance of $C_{37:4}$ alkenone to total C_{37} alkenone production ($\%C_{37:4}$) fluctuated between 15–45%, with higher values during warm periods, suggesting that lake water was also fresher during these periods. The coupled late Holocene surface temperature and salinity changes suggest that Asian monsoons strongly influenced the climate of the Lake Qinghai region. **Citation:** Liu, Z., A. C. G. Henderson, and Y. Huang (2006), Alkenone-based reconstruction of late-Holocene surface temperature and salinity changes in Lake Qinghai, China, *Geophys. Res. Lett.*, *33*, L09707, doi:10.1029/2006GL026151.

1. Introduction

[2] The Qinghai-Tibetan Plateau of central Asia occupies the highest elevation on the continental Earth and is renowned for its extraordinary monsoonal climate [*An et al.*, 2001; *Porter*, 2001]. It is one of the places that will exhibit an unambiguous climate response to anticipated greenhouse warming [*Hansen et al.*, 1988]. Ice core records from this region have already witnessed a unanimous warming trend in the 20th century [*Thompson et al.*, 1993, 2003]. Precipitation in this region is strongly influenced by Asian monsoons that are driven by the thermally induced pressure gradient between ocean and land. An increase in precipitation, probably due to a rise in air temperatures, has been observed since 1987 in northwestern China [*Shi et al.*, 2002]. Because of the high sensitivity of this regional climate to Asian monsoon variations and global change, paleoclimatic reconstructions from the Tibetan-Qinghai region are essential to our understanding of how complex forcing mechanisms could affect the regional climate.

[3] Holocene temperature and hydrological oscillations in this region have been reconstructed from ice cores, tree rings and lake sediments [*Ji et al.*, 2005; *Thompson et al.*, 2003; *Yang et al.*, 2002]. However, most proxies previously used to study the climate of the Qinghai-Tibetan region are either qualitative in nature or confounded by multiple climatic factors. For example, precipitation and ice core $\delta^{18}O$ in this region may represent an integrated effect of temperature and precipitation changes [*Davis et al.*, 2005; *Johnson and Ingram*, 2004]. Past hydrological changes have been much more difficult to reconstruct than temperature changes, with existing data showing considerable conflicts. For instance, inferred from relations of snow accumulation rate and ice core $\delta^{18}O$ values [*Yang et al.*, 2004], warm conditions are associated with increased precipitation, whereas pollen data suggest the opposite [*Liu et al.*, 1998].

[4] We report in this study a quantitative reconstruction of temperature and salinity changes over the past 3500 years, based on alkenone distribution patterns. Alkenones are biologically produced by a limited number of haptophytes present in ocean and some lakes [*D'Andrea and Huang*, 2005; *Li et al.*, 1996; *Marlowe et al.*, 1990; *Thiel et al.*, 1997; *Zink et al.*, 2001]. The alkenone unsaturation index U_{37}^{k} ($U_{37}^{k} = ([C_{37:2}] - [C_{37:4}])/([C_{37:2}] + [C_{37:3}] + [C_{37:4}])$, where $[C_{37:2}]$, $[C_{37:3}]$ and $[C_{37:4}]$ are concentrations of di-, tri- and tetra-unsaturated C_{37} alkenones) [*Brassell et al.*, 1986] and its simplified form $U_{37}^{k'}$ ($U_{37}^{k'} = [C_{37:2}]/([C_{37:2}] + [C_{37:3}])$) have been calibrated to growth temperature of marine alkenone producers [*Prahl et al.*, 1988]. This index has also been calibrated to temperature changes in lacustine settings on a regional scale [*Chu et al.*, 2005; *Zink et al.*, 2001]. In addition to temperature dependence, the percentage of $C_{37:4}$ ($\%C_{37:4} = [C_{37:4}]/([C_{37:2}] + [C_{37:3}] + [C_{37:4}])$) has recently been proposed as an indicator of salinity changes, since alkenone producers tend to produce more $C_{37:4}$ in cold and low salinity regions [*Rosell-Mele*, 1998]. This index has been successfully applied to studies of salinity variations in certain oceanic regions [*Harada et al.*, 2003; *Rosell-Mele*, 1998; *Seki et al.*, 2005; *Sicre et al.*, 2002].

2. Materials and Methods

[5] Lake Qinghai (37°N, 100°E) is a saline and closed-basin lake in China (Figure 1). The lake is at the margin of the Asian summer-monsoon influence today [*Johnson and Ingram*, 2004]. Annual precipitation is ~400 mm in this region, primarily falling in the summer. Potential evaporation greatly exceeds precipitation. Modern salinity is ~15‰

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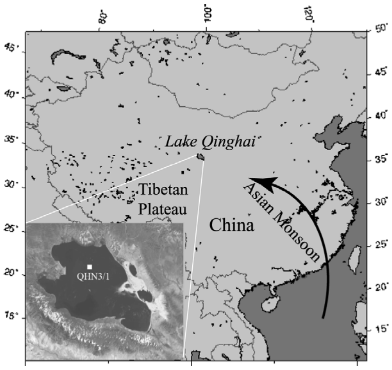

Figure 1. Location map of Lake Qinghai, China, modified from an online map creation (http://www.aquarius.geomar.de/omc/). The inset is a satellite image of Lake Qinghai, where our sediment site is indicated.

[*Lister et al.*, 1991]. The lake is stratified in the summer but overturns and becomes ice covered in the winter. Seasonal air temperature varies from −10°C to 12°C at the northern margin of the lake [*Henderson*, 2004].

[6] An 83 m sediment core (QHN3/1) was retrieved from the northern basin of the lake in May 2001 using a mini-Mackereth corer [*Henderson*, 2004]. It was sampled continuously every 0.5 cm for the top 30 cm and then every 1 cm for the remainder of the core. Samples were extracted with dichloromethane (DCM) and then saponified with 1M KOH in methanol/water (90/10) solution at 80°C to remove alkenonates that normally interfere with alkenones. Samples were further treated with silica gel chromatography. $U^{k'}_{37}$ and $\%C_{37:4}$ determinations were made using gas chromatography. Analytical error is within 0.01 units for both proxies.

[7] The chronology for this core is based on two ^{14}C dates. Plant debris was found at 32–33 cm in this core, and dated at 1049 ± 130 calendar year before present (cal yr BP). An additional ^{14}C control point, dated on bulk organic carbon, was taken from a nearby core [*Henderson*, 2004]. A close correlation of carbonate $\delta^{18}O$ generated from both cores (not shown) allows us to assign an age of 1822 ± 65 cal yr BP (after carbon reservoir correction) at 49–50 cm. Linear interpolation was applied between ^{14}C dates, which yields a sedimentation rate of 0.2–0.3 mm/yr throughout this core.

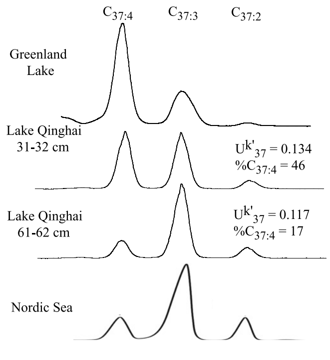

Figure 2. C_{37} alkenone distribution patterns from Greenland lakes [*D'Andrea and Huang*, 2005], Lake Qinghai (this study), and the Nordic Sea [*Sicre et al.*, 2002]. The two representative Lake Qinghai samples indicate a unique positive $\%C_{37:4} - U^{k'}_{37}$ relationship. See further discussion in the text.

3. Results and Discussion

3.1. C_{37} Alkenone Distribution in Lake Qinghai

[8] In contrast to the exceptional dominance of $C_{37:4}$ alkenones in most lakes [*D'Andrea and Huang*, 2005; *Thiel et al.*, 1997; *Zink et al.*, 2001], Lake Qinghai sediments are characterized by relatively low $\%C_{37:4}$ values. In fact, the alkenone distributions in Qinghai are more similar to those from northern high-latitude oceans than to those in lakes (Figure 2). $\%C_{37:4}$ in Lake Qinghai varies between 15–45%, similar to the range found in the Nordic Sea [*Sicre et al.*, 2002].

[9] The alkenone distributions in Lake Qinghai are also unique in terms of the relationship between $\%C_{37:4}$ and $U^{k'}_{37}$ (Figure 2). In ocean and other lakes, $U^{k'}_{37}$ is negatively correlated with $\%C_{37:4}$ [*Sicre et al.*, 2002; *Thiel et al.*, 1997; *Zink et al.*, 2001] However, in Lake Qinghai, $U^{k'}_{37}$ is positively correlated with $\%C_{37:4}$. In other words, the relative importance of $C_{37:4}$ to $C_{37:3}$ increases or decreases

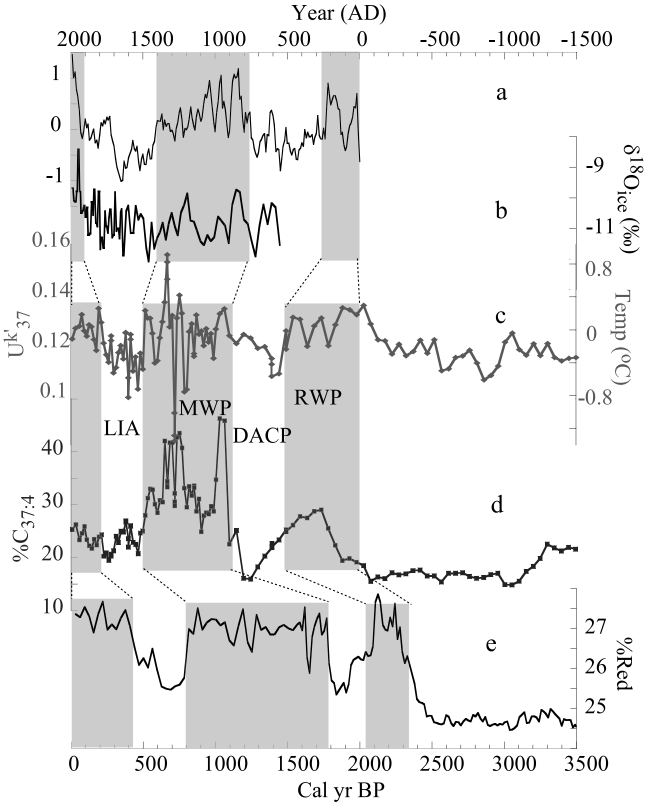

Figure 3. Comparison of late Holocene climatic records in China: (a) the composite temperature record in China [*Yang et al.*, 2002], (b) the Dunde ice core $\delta^{18}O$ record [*Thompson et al.*, 2003; *Yao and Thompson*, 1992], (c) alkenone-based temperature record from Lake Qinghai, using the *Chu et al.* [2005] calibration, (d) alkenone-based salinity record from Lake Qinghai, and (e) the wetness record from Lake Qinghai [*Ji et al.*, 2005].

in concert with that of $C_{37:2}$ to $C_{37:3}$. Such an anomalous behavior may suggest that the salinity effect overprints the opposite temperature effect on the $\%C_{37:4}$ signal in Lake Qinghai.

3.2. Surface Temperature Changes

[10] Our temperature record based on $U_{37}^{k'}$ clearly shows oscillating warm/cold periods (Figure 3c). Periods at 0–200 yr BP, 500–1100 yr BP and 1500–2000 yr BP were relatively warm, which could be related to the 20th century warm period, the Medieval Warm Period (MWP), and the Roman Warm Period (RWP) [*Hughes and Diaz*, 1994; *Lamb*, 1985]. Cold periods at 200–500 yr BP and 1100–1500 yr BP corresponded to the Little Ice Age (LIA) and the Dark Ages Cold Period (DACP) [*Lamb*, 1985]. Shown in Figures 3a and 3b are a composite temperature record from several localities in China [*Yang et al.*, 2002] and the $\delta^{18}O$ record from Dunde (near to Lake Qinghai) ice cores [*Thompson et al.*, 1993; *Yao and Thompson*, 1992]. Our alkenone-temperature record generally resembles these records. Discrepancies between these records can be attributed to uncertainties in chronology, regional climate differences in China [*Yang et al.*, 2002], and influence of multiple climatic factors on ice core and composite records.

[11] We applied two calibrations [*Chu et al.*, 2005; *Zink et al.*, 2001] to our $U_{37}^{k'}$ time series. *Chu et al.* [2005] calibrated $U_{37}^{k'}$ in Chinese lakes (including Lake Qinghai) to mean annual air temperature (MAAT). A MAAT change of up to 1°C in this region during the late Holocene could be inferred using this calibration (Figure 3c). *Zink et al.* [2001] found relations between $U_{37}^{k'}$ and summer surface water temperature, mainly in European lakes. We applied this relation to our $U_{37}^{k'}$ time series, which suggests a summer surface water temperature change of up to 2°C in Lake Qinghai during the late Holocene.

3.3. Salinity Variations

[12] $\%C_{37:4}$ varied between 15% and 45% during the late Holocene (Figure 3d). Higher $\%C_{37:4}$ values occurred at 500–1100 yr BP and 1500–1800 yr BP. There is a small increase in $\%C_{37:4}$ values since 200 yr BP. The most dramatic change in $\%C_{37:4}$ occurred at 1050 yr BP, where we observe an increase in $\%C_{37:4}$ from 23% to 45% within several decades, based on our chronology. At 2000–3500 yr BP, $\%C_{37:4}$ values were consistently within 15–20%. We applied three salinity-$\%C_{37:4}$ relations [*Harada et al.*, 2003; *Rosell-Mele*, 1998; *Sicre et al.*, 2002], based on field studies from northern high latitude oceans, to our $\%C_{37:4}$ record. These three calibrations yield up to 3.5, 0.75 and 2.75 psu of salinity changes respectively in Lake Qinghai during the late Holocene. A regional $\%C_{37:4}$-salinity calibration is needed to achieve a more robust quantification of salinity changes in Lake Qinghai.

[13] In order to evaluate the validity of $\%C_{37:4}$ as a salinity proxy, we compared our $\%C_{37:4}$ record with a wetness record [*Ji et al.*, 2005], also reconstructed from Lake Qinghai. *Ji et al.* [2005] suggested that the redness of sediments, primarily related to iron oxide mineral concentrations, is an indicator of dry/wet conditions in this region. More redness in sediments tends to occur during elevated rainfall which would have increased riverine runoff and thus the flux of iron oxide minerals into the lake. As shown in Figures 3d and 3e, the absolute ages of dry/wet conditions suggested by the two proxies disagree. We note that the warm/cold periods based on our chronology are consistent with those previously identified in this region [*Thompson et al.*, 1993; *Yang et al.*, 2002] and with those previously defined [*Lamb*, 1985], whereas the timing of the RWP inferred by *Ji et al.* [2005] is apparently too old. Despite the chronological discrepancy, the pattern of dry/wet (more/less saline) oscillations in both records is similar. For instance, the long duration of wet conditions in the MWP and dry conditions before the RWP is observed in both records.

3.4. Coupled Surface Water Temperature and Salinity Changes

[14] Our alkenone data indicate that late Holocene surface water temperature and salinity changes were tightly coupled in Lake Qinghai. Because our temperature and salinity reconstructions are derived from the same set of compounds, our inference of the coupled temperature and salinity responses is independent of chronology uncertainties. Warm conditions during the 20th century warm period, the MWP and the RWP were associated with freshening of lake waters, whereas cold conditions during the LIA, the DACP and before the RWP were accompanied by more saline lake waters (Figures 3c and 3d). The MWP represents an extended interval of warm and fresh conditions in our record. Within the MWP, higher-frequency (decadal or centennial) variations in warm/cold conditions also appear to correspond to changes in fresh/salty conditions. The RWP was also a period with substantial warmth and freshness of lake water. The lake water during the 20th century warm period was fresher and warmer than the three cold and salty periods, but the amplitude of salinity and temperature changes was smaller than the two proceeding warm periods.

[15] We attribute the coupled surface temperature and salinity changes in Lake Qinghai to the influence of Asian monsoons. Intensified Asian monsoons would bring warmer and moister air masses to this region, resulting in warmer lake surface temperatures and more precipitation. Warm air temperatures could also result in increased melting of snow/ice in surrounding areas and thus more freshwater input into Lake Qinghai. Therefore, more riverine input, as a consequence of intensified Asian monsoons, must have outpaced potentially increased evaporation at the lake surface due to increased surface temperatures. Conversely, cold and salty conditions in the lake could have corresponded to intervals of weakened Asian monsoons.

4. Conclusion

[16] Alkenone proxies $U_{37}^{k'}$ and $\%C_{37:4}$ faithfully record temperature and salinity changes in Lake Qinghai, China. During the late Holocene, our $U_{37}^{k'}$ record indicates up to a 1°C change in mean annual air temperature or a 2°C change in summer lake water temperature. The 20th century warm period, LIA, MWP, DACP and RWP have been identified in our temperature record. As suggested by $\%C_{37:4}$, warm periods are associated with periods of lake water freshening. The coupled surface temperature and salinity changes in Lake Qinghai suggest that Asian monsoons strongly influ-

enced regional climate, and experienced significant changes in their strength during the late Holocene. Alkenones provide a rare opportunity to study the relationship between climatic and hydrological changes independently of chronology. The same approach can potentially be applied to the study of Asian monsoon behaviors on various timescales. A regional salinity calibration will allow a more robust quantification of salinity changes based on $\%C_{37:4}$ values.

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References

An, Z., J. E. Kutzbach, W. L. Prell, and S. C. Porter (2001), Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan plateau since Late Miocene times, *Nature*, *411*, 62–66.

Brassell, S. C., G. Eglinton, I. T. Marlowe, U. Pflaumann, and M. Sarnthein (1986), Molecular stratigraphy: A new tool for climatic assessment, *Nature*, *320*, 129–133.

Chu, G., Q. Sun, S. Li, M. Zheng, X. Jia, C. Lu, J. Liu, and T. Liu (2005), Long-chain alkenone distributions and temperature dependence in lacustrine surface sediments from China, *Geochim. Cosmochim. Acta*, *69*, 4985–5003.

D'Andrea, W. J., and Y. Huang (2005), Long chain alkenones in Greenland lake sediments: Low δ13C values and exceptional abundance, *Org. Geochem.*, *36*, 1234–1241.

Davis, M. E., L. G. Thompson, T. D. Yao, and N. L. Wang (2005), Forcing of the Asian monsoon on the Tibetan Plateau: Evidence from high-resolution ice core and tropical coral records, *J. Geophys. Res.*, *110*, D04101, doi:10.1029/2004JD004933.

Hansen, J., I. Fung, A. Lacis, D. Rind, S. Lebedeff, R. Ruedy, G. Russell, and P. Stone (1988), Global climate changes as forecast by Goddard Institute for Space Studies 3-Dimensional Model, *J. Geophys. Res.*, *93*, 9341–9364.

Harada, N., K. H. Shin, A. Murata, M. Uchida, and T. Nakatani (2003), Characteristics of alkenones synthesized by a bloom of emiliania huxleyi in the Bering Sea, *Geochim. Cosmochim. Acta*, *67*, 1507–1519.

Henderson, A. C. G. (2004), Late Holocene environmental change on the NE Tibetan Plateau: A palaeolimnological study of Lake Qinghai and Lake Gahai, China, based on stable isotopes, Unpublished Ph.D. thesis, 189 pp., Univ. of London, London, U. K.

Hughes, M. K., and H. F. Diaz (1994), Was there a Medieval warm period, and if so, where and when, *Clim. Change*, *26*, 109–142.

Ji, J. F., J. Shen, W. Balsam, J. Chen, L. W. Liu, and X. Q. Liu (2005), Asian monsoon oscillations in the northeastern Qinghai-Tibet Plateau since the late glacial as interpreted from visible reflectance of Qinghai Lake sediments, *Earth Planet. Sci. Lett.*, *233*, 61–70.

Johnson, K. R., and B. L. Ingram (2004), Spatial and temporal variability in the stable isotope systematics of modern precipitation in China: Implications for paleoclimate reconstructions, *Earth Planet. Sci. Lett.*, *220*, 365–377.

Lamb, H. H. (1985), *Climatic History and the Future*, 835 pp., Princeton Univ. Press, Princeton, N. J.

Li, J. G., R. P. Philp, F. Pu, and J. Allen (1996), Long-chain alkenones in Qinghai Lake sediments, *Geochim. Cosmochim. Acta*, *60*, 235–241.

Lister, G. S., K. Kelts, C. K. Zao, J.-Q. Yu, and F. Niessen (1991), Lake Qinghai, China: Closed-basin lake levels and the oxygen isotope record for ostracoda since the latest Pleistocene, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *84*, 141–162.

Liu, K.-B., Z. Yao, and L. G. Thompson (1998), A pollen record of Holocene climatic changes from the Dunde ice cap, Qinghai-Tibetan Plateau, *Geology*, *26*, 135–138.

Marlowe, I. T., S. C. Brassell, G. Eglinton, and J. C. Green (1990), Long-chain alkenones and alkyl alkenoates and the fossil coccolith record of marine-sediments, *Chem. Geol.*, *88*, 349–375.

Porter, S. C. (2001), Chinese loess record of monsoon climate during the last glacial-interglacial cycle, *Earth Sci. Rev.*, *54*, 115–128.

Prahl, F. G., L. A. Muehlhausen, and D. L. Zahnle (1988), Further evaluation of long-chain alkenones as indicators of paleoceanographic conditions, *Geochim. Cosmochim. Acta*, *52*, 2303–2310.

Rosell-Mele, A. (1998), Interhemispheric appraisal of the value of alkenone indices as temperature and salinity proxies in high-latitude locations, *Paleoceanography*, *13*, 694–703.

Seki, O., K. Kawamura, T. Sakamoto, M. Ikehara, T. Nakatsuka, and M. Wakatsuchi (2005), Decreased surface salinity in the Sea of Okhotsk during the last glacial period estimated from alkenones, *Geophys. Res. Lett.*, *32*, L08710, doi:10.1029/2004GL022177.

Shi, Y. F., Y. P. Shen, and R. J. Hu (2002), Preliminary study on signal, impact and foreground of the climatic shift from warm-dry to warm-humid in northwest China (in Chinese with English abstract), *J. Glaciol. Geocryol.*, *24*, 219–226.

Sicre, M. A., E. Bard, U. Ezat, and F. Rostek (2002), Alkenone distributions in the North Atlantic and Nordic sea surface waters, *Geochem. Geophys. Geosyst.*, *3*(2), 1013, doi:10.1029/2001GC000159.

Thiel, V., A. Jenisch, G. Landmann, A. Reimer, and W. Michaelis (1997), Unusual distributions of long-chain alkenones and tetrahymanol from the highly alkaline Lake Van, Turkey, *Geochim. Cosmochim. Acta*, *61*, 2053–2064.

Thompson, L. G., E. Mosley-Thompson, M. Davis, P. N. Lin, T. Yao, M. Dyurgerov, and J. Dai (1993), Recent warming—Ice core evidence from tropical ice cores with emphasis on central Asia, *Global Planet. Change*, *7*, 145–156.

Thompson, L. G., E. Mosley-Thompson, M. E. Davis, P. N. Lin, K. Henderson, and T. A. Mashiotta (2003), Tropical glacier and ice core evidence of climate change on annual to millennial time scales, *Clim. Change*, *59*, 137–155.

Yang, B., A. Braeuning, K. R. Johnson, and Y. F. Shi (2002), General characteristics of temperature variation in China during the last two millennia, *Geophys. Res. Lett.*, *29*(9), 1324, doi:10.1029/2001GL014485.

Yang, B., A. Braeuning, Y. F. Shi, and F. H. Chen (2004), Evidence for a late Holocene warm and humid climate period and environmental characteristics in the arid zones of northwest China during 2.2 ~ 1.8 kyr BP, *J. Geophys. Res.*, *109*, D02105, doi:10.1029/2003JD003787.

Yao, T., and L. G. Thompson (1992), Trends and features of climatic changes in past 5000 years recorded by the Dunde ice core, *Ann. Glaciol.*, *16*, 21–24.

Zink, K. G., D. Leythaeuser, M. Melkonian, and L. Schwark (2001), Temperature dependency of long-chain alkenone distributions in recent to fossil limnic sediments and in lake waters, *Geochim. Cosmochim. Acta*, *65*, 253–265.

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