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Calibration of the $U_{37}^{K'}$ index of long-chain alkenones with the *in-situ* water temperature in Lake Qinghai in the Tibetan Plateau

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Long-chain alkenones (LCAs) can potentially be used as indicators to understand past variations in lacustrine environments. Previous research has suggested that the relationship between the temperature and the unsaturation index of LCAs should be calibrated individually, because of the possible variations in the alkenone-producing algal species in the lacustrine environment. In this work, we have calibrated $U_{37}^{K'}$ of water filter samples against the *in-situ* water temperature in Lake Qinghai, Tibetan Plateau. There are significant relationships between $U_{37}^{K'}$ and the water temperature, a non-linear relationship was derived. Because the $U_{37}^{K'}$ values did not respond sensitively at lower temperatures, we suggested that a quadratic regression ($U_{37}^{K'}$=0.0011×T^2–0.0201× T+0.1959, n=15, r^2=0.74) was appropriate than linear regression to represent the relationship between the *in-situ* temperatures and $U_{37}^{K'}$. Meanwhile, the U_{37}^{K} correlation relationship was not more significant than $U_{37}^{K'}$ index in our study. Because of the $C_{37:4}$ effects by salinity change, we suggest U_{37}^{K} is not as robust as the $U_{37}^{K'}$ index as a temperature proxy, at least for the salt lake in the Tibetan Plateau. The calibration of the $U_{37}^{K'}$ index in this work has provided a new understanding of historic climatic changes in the Tibetan Plateau.

$U_{37}^{K'}$ index, *in-situ* temperature, Lake Qinghai

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The unsaturation index of long-chain alkenones (LCAs) has been widely used as an organic geochemical proxy to reconstruct past sea-surface temperatures (SST) in marine environments [1–9]. LCAs have also been discovered in lacustrine environments and much research has been conducted to establish a relationship between the unsaturation index of LCAs and lake temperatures or salinity [10–22]. Determining the relationship between temperature and the unsaturation index of lacustrine LCAs, however, is not as straightforward as in marine environments, in which a relatively fixed relationship is exhibited; this is because in lacustrine environments, the relationship seems to be specific to the lake and the conditions.

Zink et al. [13] suggested that the $U_{37}^{K'}$ index of lake sediments correlates best with lake-surface summer temperatures in Germany. Better correlation was found between the $U_{37}^{K'}$ index and the mean annual air temperature in China [15]. Sun et al. [16] successfully separated the LCA producers (*Chrysotila lamellosa*) in Lake Xiarinur (Inner Mongolia, China) and through a culture experiment showed that U_{37}^{K} was strongly correlated with the culture temperature over the range 10–22°C. However, in some lakes, where the LCA distribution is dominated by C_{38} homologues, traditional LCAs cannot be used to calibrate the temperature. Pearson et al. [18] found the strongest relationship was between temperature and the new U_{3738}^{K} index, which represents the combination of all C_{37} and C_{38} alkenone homologues. Through the use of *in-situ* water filter calibration, Toney et al. [20] reported that the U_{37}^{K} index was linearly correlated to water temperature in Lake George, but the $U_{37}^{K'}$ index did not exhibit any correlation. D'Andrea et al. [23] also calibrated U_{37}^{K} to temperature in Lake Braya Sø by

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combining data from filtered water samples with the previous core top calibration in Germany [13]. In general, the temperature calibrations differed for each lake. This is attributed to the presence of different haptophyte producers, which is in turn related to the complex lake-water conditions [16,24,25].

The Tibetan Plateau has a profound influence on the atmospheric circulation in the Northern Hemisphere because it acts as the main driving force of the Asian monsoon system [26,27]. The numerous salt lakes in the Tibetan Plateau provide an extensive source of sedimentary records, and previous studies have tried to link LCA indexes to environmental factors. For example, Li et al. [9] were the first to report the presence of LCAs in Lake Qinghai, the biggest inland lake of China; they suggested that the alkenones in the lake could be used for paleoclimatic studies. Later studies confirmed that LCAs are widely distributed throughout the salt lakes of the Tibetan Plateau [14,28]. A study of the general relationship between $U_{37}^{K'}$ in lake sediments in China and the mean annual air temperature was performed, in which the salt lakes in the Tibetan Plateau were included [15]. However, the potential LCA-producing algae in the studied lakes may differ significantly because of variations in the salinity [15]. Liu et al. [17,21] found that the proportion of tetra-unsaturated ketones (%$C_{37:4}$) was controlled by the water salinity and suggested that the $U_{37}^{K'}$ index was a more appropriate temperature proxy for lakes in the northern Qinghai-Tibetan Plateau. As *in-situ* water filters or culture temperature relationships for this region had not been reported, previous temperature reconstructions using LCAs in the Tibetan Plateau had to use calibration results from other sites [29], although it was not clear whether they were suitable for this study area.

In this study, we have measured the $U_{37}^{K'}$ values in water filters in Lake Qinghai and calibrated it with the *in-situ* water temperature. Our aim is to provide a reliable temperature calibration to reconstruct exact temperature variations over the history of the study area.

1 Materials and methods

1.1 Sample site

The Lake Qinghai (36°32′–37°15′N, 99°36′–100°47′E) is a closed-basin saline lake in northwest China at an altitude of 3193 m and with an area of 4400 km^2. Rivers draining into Lake Qinghai lie mainly to the north and northwest, with Buha River being the largest of them [30]. The maximum depth is ~27 m and the average depth is 21 m. Based on 10-year instrumental records (1994–2004), the mean annual and summer (July and August) air temperatures are 0.24 and 11.4°C, respectively [17].

Suspended matter samples were collected from the water column and surface water at different sites by filtering lake water (Figure 1), and the *in-situ* water temperature was measured at the same time. After filtering the lake waters with a glass fiber filter (Waterman GF filter, 0.47 μm), the samples were taken in Whirl-Pak containers cooled with dry ice, and then stored in the dark at −20°C in the Institute of Earth Environment, CAS.

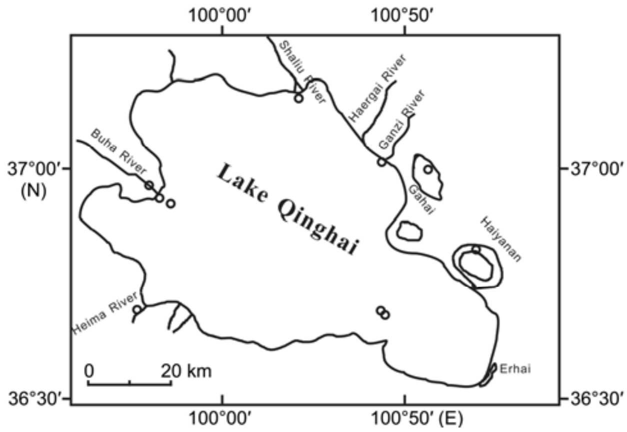

Figure 1 The water suspended samples in Lake Qinghai.

1.2 Analysis methods

(i) Extraction and separation of long chain alkenones. Each of the filter samples (10 L or more of lake water) was freeze-dried and extracted with a mixture of dichloromethane (DCM) and methanol (MeOH) (9∶1, v/v) for 20 min using an ultrasonic method. The extraction process was repeated at least three times. The extracted lipid compounds were blown down to dryness under a soft N_2 stream, and then saponified with 1 mol/L KOH in methanol solution (5% water) at room temperature for more than 12 h. Finally, a 5% aqueous solution of NaCl (2 mL) was added to each tube. The mixture was extracted three times with hexane to obtain the organic compounds, including the LCAs. A hexane extraction was performed by silica gel chromatography using hexane as the eluent. The second fraction, including the LCAs, was obtained after elution with a DCM solution.

(ii) Gas chromatography analysis. Gas chromatography (GC) analysis was performed with an Agilent 6890 Series instrument equipped with a split-injector, an Agilent HP1-MS GC column (60 m length, 0.32 mm×0.25 mm), and a flame ionization detector. For quantification, peak areas were compared with those from an external standard (n-C_{36} alkane). The detailed GC conditions are the same as those in Liu et al. [17]. Extraction and GC analysis was carried out at the stable isotope laboratory of the Institute of Earth Environment, CAS.

2 Results and discussion

2.1 Calibration of $U_{37}^{K'}$ with *in-situ* temperatures in Lake Qinghai

In this study, water filter samples were collected at different depths in Lake Qinghai to calibrate the LCA $U_{37}^{K'}$ values with the *in-situ* water temperatures (Table 1). The water filters samples has been widely used to explore the relationship between LCAs and temperature when it is unclear what the alkenone-producing species in the study area is, and thus, culture experiments cannot be performed [20,31,32].

Sample collection was mainly carried out from late-June to late-August, 2010. Water-temperature stratification in Lake Qinghai is complex, and many factors influence this, such as the direction of flow, wind speed, and air temperature [30]. The water temperatures at different depths at north-western lake basin maintained a relatively constant temperature of 13–13.9°C, and the $U_{37}^{K'}$ values also changed only negligibly. However, at the south lake basin, the *in-situ* temperature of the water column varied from 9.5 to 14.9°C in July and from 11.8 to 18.0°C in August. The site in the northwest of the lake was close to the estuary of the Buha River, we assumed that the mixing associated with the flow from the estuary resulted in the insignificant temperature stratification there.

As the water temperature varied from 9.5 to 18°C, the $U_{37}^{K'}$ changed from 0.088 to 0.182. The calibration of $U_{37}^{K'}$ vs. the *in-situ* temperature was found to be $U_{37}^{K'}=0.0011\times T^2-0.0201\times T+0.1959$ by quadratic regression (number of samples, n=15; regression coefficient, r^2=0.74) or $U_{37}^{K'}=0.0105\times T-0.0182$ by linear regression (n=15, r^2=0.69). The relationship between the *in-situ* temperatures and $U_{37}^{K'}$ was more likely to be that of the quadratic regression rather than the linear regression, because the $U_{37}^{K'}$ values did not respond sensitively at lower temperatures (Figure 2). In previous research, Sun et al. [16] also reported that the slope of the regression ($U_{37}^{K'}$ vs. temperature) clearly decreased when the culture temperature was lower. It was because the ability of adjusting the relative LCA abundance decreased when the environment temperature exceeded the optimum growth temperature of the alkenone-producing algae [33].

Meanwhile, we noticed that $U_{37}^{K'}$ values changed greatly at higher water temperature (17–18°C). Because in our study some filters samples were collected from surface lake water, we inferred that one possible reason was the significant diel cycles in lake surface water temperature lead to the deviation between the $U_{37}^{K'}$ and *in-situ* temperature. In general, the lake temperature profile below 5 m was relative constant throughout the summer [34]. However, the diel cycle in surface water had great variation due to the different lake

Table 1 Long-chain alkenone distribution of filter samples and different *in-situ* water temperature in Lake Qinghai[a)]

Date	Sample site	Latitude	Longitude	Water depth (m)	$\%C_{37:4}$	$\%C_{37:3}$	$\%C_{37:2}$	$\%C_{38:4}$	$\%C_{38:3}$	$\%C_{38:2}$	$U_{37}^{K'}$	U_{37}^{K}	C_{37}/C_{38}	*In-situ* water temp. (°C)
2010-06-30	Lake Qinghai	36°57′19″N	99°55′30″E	0	47.5	46.1	6.4	30	51	19	0.122	–0.411	6.2	13.0
2010-06-30	Lake Qinghai	36°57′19″N	99°55′30″E	4	48.5	45.1	6.4	30	51	19	0.125	–0.420	6.5	13.9
2010-06-30	Lake Qinghai	36°57′19″N	99°55′30″E	10	49.3	44.5	6.2	34	49	16	0.123	–0.431	6.5	13.5
2010-06-30	Lake Qinghai	36°57′19″N	99°55′30″E	16	48.1	45.6	6.3	28	51	21	0.122	–0.418	6.5	13.4
2010-06-30	Lake Qinghai	36°57′19″N	99°55′30″E	20	53.1	41.5	5.4	40	46	14	0.116	–0.476	4.9	13.5
2010-07-01	Lake Qinghai	36°36′42″N	100°31′34″E	0	47.1	46.0	6.9	30	52	18	0.130	–0.402	6.0	14.9
2010-07-01	Lake Qinghai	36°36′42″N	100°31′34″E	6	47.7	45.6	6.7	34	50	15	0.128	–0.410	4.6	14.2
2010-07-01	Lake Qinghai	36°36′42″N	100°31′34″E	16	50.5	43.8	5.7	31	51	18	0.115	–0.448	6.2	12.4
2010-07-01	Lake Qinghai	36°36′42″N	100°31′34″E	23	48.4	46.1	5.5	39	44	17	0.107	–0.429	5.6	9.5
2010-08-21	Lake Qinghai	36°36′17″N	100°32′08″E	0	34.4	53.7	11.9	nd	nd	nd	0.182	–0.225	–	18.0
2010-08-21	Lake Qinghai	36°36′17″N	100°32′08″E	10	36.3	54.2	9.4	29	46	25	0.148	–0.269	7.1	18.0
2010-08-21	Lake Qinghai	36°36′17″N	100°32′08″E	25	42.4	51.1	6.5	29	51	20	0.113	–0.359	7.4	11.8
2010-06-29	Ganzi River estuary	37°02′47″N	100°26′46″E	0	52.2	43.0	4.8	nd	nd	nd	0.101	–0.473	–	12.3
2010-06-29	Ganzi River	37°03′15″N	100°26′49″E	0	nd	nd	nd	nd	nd	nd	nd	nd	–	–
2010-06-29	Shaliu River estuary	37°11′09″N	100°15′01″E	0	nd	nd	nd	nd	nd	nd	nd	nd	–	10.7
2010-06-29	Shaliu River	37°11′11″N	100°14′50″E	0	nd	nd	nd	nd	nd	nd	nd	nd	–	11.6
2010-06-30	Shaliu River	37°19′43″N	100°07′26″E	0	nd	nd	nd	nd	nd	nd	nd	nd	–	8.8
2010-08-21	Buha River estuary	36°57′42″N	99°51′10″E	0	43.5	45.0	11.6	nd	nd	nd	0.204	–0.319	–	17.3
2010-06-30	Buha River	37°02′09″N	99°44′20″E	0	nd	nd	nd	nd	nd	nd	nd	nd	–	–
2010-08-21	Buha River	37°02′09″N	99°44′20″E	0	nd	nd	nd	nd	nd	nd	nd	nd	–	–
2010-06-30	Heima River	36°44′09″N	99°46′48″E	0	nd	nd	nd	nd	nd	nd	nd	nd	–	–
2010-06-29	Gahai(Lake Qinghai)	37°00′39″N	100°35′48″E	0	58.2	38.2	3.7	43	45	12	0.088	–0.545	0.7	12.6
2010-06-28	Haiyanwan	36°51′45″N	100°39′40″E	0	nd	nd	nd	nd	nd	nd	–	–	–	14.4

a) nd: not detected.

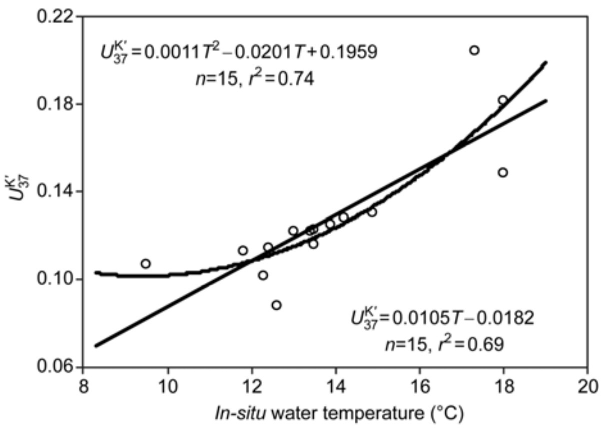

Figure 2 The LCA $U_{37}^{K'}$ calibration with *in-situ* water temperatures in Lake Qinghai (quadratic regression dashed line: n=15, r^2= 0.74; linear regression: n=15, r^2=0.69).

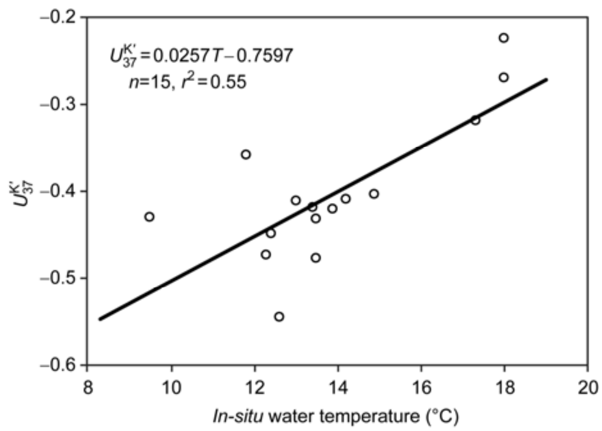

Figure 3 The LCA U_{37}^{K} at different *in-situ* water temperatures.

environment conditions and the diel variations were up to 2°C in some Swiss alpine lakes when the lake average temperature was below 20°C [35]. Therefore, the surface *in-situ* water temperature would lead to some error of calibration. However, some researchers also suggested that the lake water temperature was relative stable in late evening or early morning on most days [36,37]. So the most surface samples collections in this study were in the morning to avoid more *in-situ* temperature error.

2.2 LCA U_{37}^{K} and the *in-situ* water temperatures in Lake Qinghai

The LCA U_{37}^{K} values varied from −0.545 to −0.225 with the temperature ranging from 9.5 to 18°C (Figure 3). The calibration of U_{37}^{K} vs. the *in-situ* temperature was U_{37}^{K}= 0.0257×T−0.7597 (n=15, r^2=0.55). However, the U_{37}^{K} correlation relationship was not more significant than $U_{37}^{K'}$ index. The U_{37}^{K} index calculation depends mainly on the abundance of the $C_{37:4}$ alkenone. Because of the effects of salinity, a higher percentage of $C_{37:4}$ appeared in lakes with a low salinity, and *vice versa* [17,21,38,39]. Therefore, the U_{37}^{K} index may be sensitive to variations in salinity, especially in the more saline lakes. In this study, we did not measure the salinity of each water sample. However, the previous study indicated that water salinity at different sites in the Lake Qinghai varies from 4.6% to 17.2% and causes %$C_{37:4}$ to fluctuate by over 20% [17]. The significant variations in %$C_{37:4}$ values could influence the calculation of U_{37}^{K} index greatly. Previous research has detailed the relationship between the salinity and %$C_{37:4}$ in salt lakes in the Tibetan Plateau [17,21], and thus, it will not be discussed further here.

Therefore, we inferred that water salinity changes caused some error in the calibration of U_{37}^{K} vs. *in-situ* temperature in the Lake Qinghai. Meanwhile, our results emphasize that the U_{37}^{K} is not as robust as the $U_{37}^{K'}$ index as a temperature proxy for the salt lakes in the Tibetan Plateau, as it mentioned in previous study [21].

2.3 Assessment of the $U_{37}^{K'}$ calibration equation in Lake Qinghai

Here, the $U_{37}^{K'}$ temperature calibration of Lake Qinghai is compared with previous results [2,13,15,16,32,40]. Figure 4 shows that calibrations of water filter vs. *in-situ* temperature are more similar, including our study (Lake Qinghai, $U_{37}^{K'}$= 0.0011×T^2−0.0201×T+0.1959, *in-situ* water temperature, 9.5–18°C), Sun et al. [16] (*C. lamellosa*, $U_{37}^{K'}$=0.0011×T^2−0.0157×T+0.1057, culture water temperature, 10–22°C), and Mercer et al. [32] (Chesapeake Bay, $U_{37}^{K'}$=0.013×T−0.040, *in-situ* water temperature, 12–26°C). The calibration between the $U_{37}^{K'}$ values of sediments and the summer lake surface temperature ($U_{37}^{K'}$=0.02×T−0.0121, 13–24°C) [13] is also included. On the other hand, the calibrations from the lakes of China (sediment, $U_{37}^{K'}$=0.0328×T+0.126, mean annual air temperature, 0–22°C) is similar to the equations widely used to reconstruct the SST [2,40]. They have significant

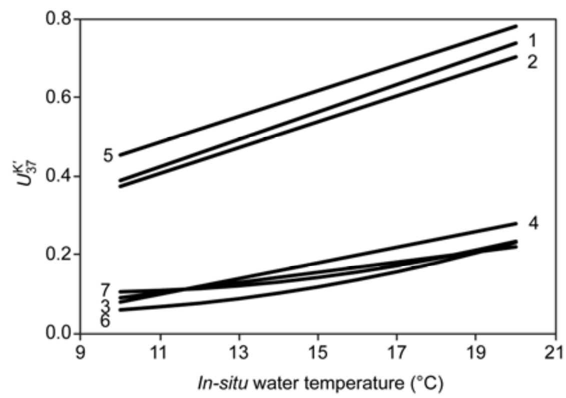

Figure 4 Comparison of the $U_{37}^{K'}$ calibration equation in the Lake Qinghai with previous researches [2,13,15,16,32,40]. 1, Prahl; 2, Muller; 3, Mercer; 4, Zink; 5, Chu; 6, Sun; 7, Lake Qinghai.

difference from calibrations of water filers. We conclude that differences in the equations are related to the calibration methods (sediment vs. surface temperature or water filter vs. *in-situ* temperature) and the algal producers (marine, coastal, and lacustrine species).

We propose that the LCA producers in the Chesapeake Bay [32], the Lake Xiarinur [16], and the Lake Qinghai probably belong to similar algal species because of the relative similar calibration relationships. In the Chesapeake Bay, the main alkenone-producing species includes the common marine species (*E. huxleyi*, *G. oceanic*) and a typical coastal species (*I. galbana*) [32,41]. The LCA producer in Lake Xiarinur, *C. lamellose*, belongs to the coastal marine strains [16,42]. Based on the distribution of $C_{37:4}$ and $C_{38:Me}$, Liu et al. [17] suggested that alkenone producers in Lake Qinghai are similar to all of the mentioned species. Our results further verify this assumption.

Meanwhile, $U_{37}^{K'}$ responding in lower temperature in the Lake Qinghai was more insensitive. It was similar to the previous results of *C. lamellose* culture experiment [16]. It would be the result of non-linear biological response of algae in lower temperature, or a little amount of LCA (*in-situ*) produced in lower temperature may be easier to be effect by LCA from not *in-situ* and other factors. The insensitive responding in lower temperature still need more research in the further.

3 Conclusions

In this study, we reported the calibration of the $U_{37}^{K'}$ index with the *in-situ* water temperature in Lake Qinghai, Tibetan Plateau. Since $U_{37}^{K'}$ changed insignificantly at lower temperatures, a quadratic equation was more appropriate in the Lake Qinghai ($U_{37}^{K'}$=0.0011×T^2−0.0201×T+0.1959, n=15, r^2=0.74).

The correlation between the U_{37}^{K} values and the *in-situ* water temperature was not more significant than $U_{37}^{K'}$ index. We inferred that salinity effect caused some error in the calibration of U_{37}^{K}, because of the %$C_{37:4}$-salinity relationship in the lakes of the Tibetan Plateau, Therefore, we suggest U_{37}^{K} is not as robust as the $U_{37}^{K'}$ index as a temperature proxy in the salt lake in the Tibetan Plateau.

We validated our calibration equation by comparison to similar $U_{37}^{K'}$ temperature calibrations for Lake Qinghai, Chesapeake Bay, and a *C. lamellose* culture. The results further verified a previous suggestion that the alkenone producers in these studies are similar. Meanwhile, $U_{37}^{K'}$ responding was more insensitive in lower temperature in Lake Qinghai, the reason still need more research in the further.

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1 Brassell S C, Eglinton G, Marlowe I T, et al. Molecular stratigraphy: A new tool for climatic assessment. Nature, 1986, 320: 129–133

2 Prahl F G, Wakeham S G. Calibration of unsaturation patterns in long-chain ketone compositions for palaeotemperature assessment. Nature, 1987, 330: 367–369

3 Volkman J K, Barrerr S M, Blackburn S I, et al. Alkenones in Gephyrocapsa oceanica: Implications for studies of paleoclimate. Geochim Cosmochim Acta, 1995, 59: 513–520

4 Bard E, Rostek F, Sonzogni C. Interhemispheric synchrony of the last deglaciation inferred from alkenone palaeothermometry. Nature, 1997, 385: 707–710

5 Kienast M, Steinke S, Stattegge K, et al. Synchronous tropical south China Sea SST change and greenland warming during deglaciation. Science, 2001, 291: 2132–2134

6 Koutavas A, Lynch-Stieglitz L, Marchitto T M, et al. El Niño-like pattern in ice age tropical Pacific sea surface temperature. Science, 2002, 297: 226–230

7 Li L, Wang H, Li J R, et al. Changes in sea surface temperature in western South China Sea over the past 450 ka. Chin Sci Bull, 2009, 54: 3335–3343

8 Cranwell P A. Long-chain unsaturated ketones in recent lacustrine sediments. Geochim Cosmochim Acta, 1985, 49: 1545–1551

9 Li J, Philp R P, Pu F, et al. Long-chain alkenones in Qinghai Lake sediments. Geochim Cosmochim Acta, 1996, 60: 235–241

10 Thiel V, Jenisch A, Landmann G, et al. Unusual distributions of long-chain alkenones and tetrahymanol from the highly alkaline Lake Van, Turkey. Geochim Cosmochim Acta, 1997, 61: 2053–2064

11 Innes H E, Bishop A N, Fox P A, et al. Early diagenesis of bacteriohopanoids in recent sediments of Lake Pollen, Norway. Org Geochem, 1998, 29: 1285–1295

12 Sheng G Y, Cai K Q, Yang X X, et al. Long-chain alkenones in Hetong Qagan Nur Lake sediments and its paleoclimatic implications. Chin Sci Bull, 1998, 43: 1090–1094

13 Zink K G, Leythaeuser D, Melkonian M, et al. Temperature dependency of long-chain alkenone distributions in recent to fossil limnic sediments and in lake waters. Geochim Cosmochim Acta, 2001, 65: 253–265

14 Sun Q, Chu G Q, Li S Q, et al. Long-chain alkenones in sulfate lakes and its paleoclimatic implications. Chin Sci Bull, 2004, 49: 2082–2086

15 Chu G Q, Sun Q, Li S Q, et al. Long-chain alkenone distributions and temperature dependence in lacustrine surface sediments from China. Geochim Cosmochim Acta, 2005, 69: 4985–5003

16 Sun Q, Chu G Q, Liu G X, et al. Calibration of alkenone unsaturation index with growth temperature for a lacustrine species, Chrysotila lamellosa (Haptophyceae). Org Geochem, 2007, 38: 1226–1234

17 Liu W G, Liu Z H, Fu M Y, et al. Distribution of the C_{37} tetra-unsaturated alkenone in Lake Qinghai, China: A potential lake salinity indicator. Geochim Cosmochim Acta, 2008, 72: 988–997

18 Pearson E J, Juggins S, Farrimond P, et al. Distribution and significance of long-chain alkenones as salinity and temperature indicators in Spanish saline lake sediments. Geochim Cosmochim Acta, 2008, 72: 4035–4046

19 Jaraula C M B, Brassell S C, Morgan-Kiss R M, et al. Origin and tentative identification of tri to pentaunsaturated ketones in sediments from Lake Fryxell, East Antarctica. Org Geochem, 2010, 41: 386–397

20 Toney J L, Huang Y, Fritz S C, et al. Climatic and environmental controls on the occurrence and distributions of long chain alkenones in lakes of the interior United States. Geochim Cosmochim Acta, 2010, 74: 1563–1578

21 Liu W G, Liu Z H, Wang H Y, et al. Salinity control on long-chain alkenone distributions in lake surface waters and sediments of the northern Qinghai-Tibetan Plateau, China. Geochim Cosmochim Acta, 2011, 75: 1693–1703

22 Toney J L, Leavitt P R, Huang Y. Alkenones are common in prairie lakes of interior Canada. Org Geochem, 2011, 42: 707–712

23 D'Andrea W J, Huang Y, Fritz S C, et al. Abrupt Holocene climate change as an important factor for human migration in West Greenland. Proc Natl Acad Sci USA, 2011, 108: 9765–9769

24 Coolen M J L, Muyzer G, Rijpstra W L C, et al. Combined DNA and lipid analyses of sediments reveal changes in Holocene haptophyte and diatom populations in an Antarctic lake. Earth Planet Sci Lett, 2004, 223: 225–239
25 D'Andrea W J, Lage M, Martiny J B H, et al. Alkenone producers inferred from well-preserved 18S rDNA in Greenland lake sediments. J Geophys Res, 2006, 111: G03013
26 An Z S, Kutzbach J E, Prell W L, et al. Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan plateau since Late Miocene times. Nature, 2001, 411: 62–66
27 Herzschuh U, Kurschner H, Mischke S. Temperature variability and vertical vegetation belt shifts during the last ~50000 yr in the Qilian Mountains (NE margin of the Tibetan Plateau, China). Quat Res, 2006, 66: 133–146
28 Fu M Y, Liu W G, Li X Z, et al. The distribution of long-chain alkenones in modern lacustrine sediments in the Lake Qinghai and lakes from the Qaidam Basin (in Chinese). J Lake Sci, 2008, 20: 285–290
29 Liu Z, Henderson A G, Huang Y. Alkenone-based reconstruction of late-Holocene surface temperature and salinity changes in Lake Qinghai, China. Geophys Res Lett, 2006, 33: L09707
30 Lanzhou Branch of Chinese Academy of Sciences. Evolution of Recent Environment in Qinghai Lake and Its Prediction (in Chinese). Beijing: Science Press, 1994
31 Goni M P, Woodworth H L, Aceves R C, et al. Generation, transport, and preservation of the alkenone-based $U_{37}^{K'}$ sea surface temperature index in the water column and sediments of the Cariaco Basin (Venezuela). Glob Biogeochem Cycles, 2004, 18: 1–21
32 Mercer J L, Zhao M X, Colman S M, et al. Seasonal variations of alkenones and UK37 in the Chesapeake Bay water column. Estuar Coast Shelf S, 2005, 63: 675–682
33 Sun Q, Chu G Q, Liu G X, et al. The occurrence and distribution of long chain alkenones in lakes (in Chinese). Acta Geosci Sin, 2010, 31: 485–494
34 Livingstone D M, Lotter A F, Walker I R. The decrease in summer surface water temperature with altitude in Swiss Alpine lakes: A comparison with air temperature lapse rates. Arct Antarct Alp Res, 1999, 31: 341–352
35 Livingstone D M, Lotter A F. The relationship between air and water temperatures in lakes of the Swiss Plateau: A case study with palaeolimnological implication. J Paleolimnol, 1998, 19: 181–198
36 Wood T M, Hoilman G R, Lindenberg M K. Water-quality conditions in Upper Klamath Lake, Oregon, 2002-04: U.S. Geological Survey Scientific Investigations Report, 2006, 2006–5209: 54
37 Hoilman G R, Lindenberg M K, Wood T M. Water quality conditions in Upper Klamath and Agency Lakes, Oregon, 2005: U.S. Geological Survey Scientific Investigations Report, 2008, 2008–5026: 44
38 Rosell-Melé A. Interhemispheric appraisal of the value of alkenone indices as temperature and salinity proxies in high-latitude locations. Paleoceanography, 1998, 13: 694–703
39 Sicre M A, Bard E, Ezat U, et al. Alkenone distributions in the North Atlantic and Nordic sea surface waters. Geochem Geophys Geosyst, 2002, 3: 1013
40 Muller P J, Kirst G, Ruhland G, et al. Calibration of the alkenone palaeotemperature index $U_{37}^{K'}$ based on core-tops from the eastern South Atlantic and the global ocean (60–60°C). Geochim Cosmochim Acta, 1998, 62: 1757–1772
41 Marshall H G. Chesapeake Bay phytoplankton: I. Composition. P Biol Soc Wash, 1994, 107: 573–585
42 Rontani J F, Beker B, Volkman J K. Long-chain alkenones and related compounds in the benthic haptophyte *Chrysotila lamellosa* Anand HAP 17. Phytochemistry, 2004, 65: 117–126