Chemical weathering over the last 1200 years recorded in the sediments of Gonghai Lake, Lvliang Mountains, North China: a high-resolution proxy of past climate

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Increasing interest in global climate change has led to attempts to understand and quantify the relationship between chemical weathering processes and environmental conditions, especially climate. This interest necessitates the identification of new climate proxies for the reconstruction of two important Earth surface processes: physical erosion and chemical weathering. In this study, an AMS 14C-dated 2.8-m-long sediment core, GH09B1, from Lake Gonghai in north-central China was subjected to detailed geochemical analyses to evaluate the intensity of chemical weathering processes in the catchment. Multivariate statistical analysis of major and trace elemental data of 139 subsamples revealed that the first principal component axis PCA1 explained ∼53% of the variance in the assemblage of elements/oxides with significant positive correlations between PCA1 scores and the separation of mobile and soluble elements/oxides from the immobile and resistant elements/oxides, which is thus able to indicate the chemical weathering in the catchment. These results are supported by the down-core trends of other major and trace elemental ratios of chemical weathering intensity as well as by pollen data from the same core. Variations in PCA1, chemical index of alteration (CIA), Rb/Sr ratio and other oxides ratios indicate stronger chemical weathering due to a wet climate during the Medieval Warm Period (MWP). However, the MWP was interrupted by an interval of relatively weaker chemical weathering conditions from AD 940–1070. Weak chemical weathering under a dry climate occurred during the Little Ice Age (LIA), and increased chemical weathering intensity during the Current Warm Period (CWP). Our proxy records of chemical weathering over the last millennium correlate well with the available proxy records of precipitation from Gonghai Lake as well as with the speleothem oxygen isotope record from Wanxiang Cave, but do not show a significant correlation with the temperature record in N China, suggesting that the chemical weathering intensity in the study area was mainly controlled by the amount of rainfall rather than by temperature. We conclude that high resolution lacustrine sediment geochemical parameters can be used as reliable proxies for climate variations at centennial-decadal time scales.

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At geological time scales, chemical weathering processes can buffer atmospheric carbon dioxide (CO₂) and thus moderate large fluctuations in global temperature and precipitation through the greenhouse effect (e.g. White & Blum 1995). On a regional scale, weathering processes are mainly controlled by environmental conditions such as precipitation and temperature, and thus knowledge of weathering processes inferred from geochemical data from lake and marine sediment cores can provide information on past climatic and environmental changes of the region under investigation. Previous studies have focused mainly on longer-term (millennial-scale and greater) chemical weathering responses to global climate change and atmospheric CO₂ variability (e.g. Brady & Carroll 1994; Lasaga et al. 1994; McFarlane 1994; Taylor & Lasaga 1999; Beukema et al. 2011). However, few studies have addressed the question of whether or not variations in the chemical constituents of weathered products from a single watershed could be used as proxies for climate change, especially at shorter (centennial-decadal) time scales (Selvaraj et al. 2007; An et al. 2011; Beukema et al. 2011). Several studies have attempted to reconstruct the chemical weathering history since the Little Ice Age (LIA) using low-resolution records from Dahei Lake in N China; however, they used an age model based on ¹⁴C dates of bulk sedimentary organic carbon, which may potentially be affected by the radiocarbon reservoir effect (Jin et al. 2001a, b; Zhou et al. 2009). In addition, these studies paid less attention to the mechanism of the chemical weathering-climate link at shorter time scales and thus little is known about catchment weathering processes over the last millennium in the mid-latitude region of N China, where the environment is characterized by semi-arid to semi-humid conditions.

In recent years, considerable attention has been paid to the variation of moisture conditions over the last millennium in eastern China; this region is heavily influenced by the East Asian monsoon (EAM) circulation, which is significantly interlinked with economic activity and cultural development (Zhang et al. 2008;
Cook et al. 2010). However, there is no consensus regarding the monsoon moisture conditions over the last millennium in eastern China, because variations in monsoon strength reflected by different climatic records spanning this interval show apparent discrepancies (Zheng et al. 2006; Zhang et al. 2008; Man 2009). In addition to possible chronological uncertainties, this could also be related to the fact that different proxies may have different palaeoclimatic implications, or that the strength of the Asian monsoon may have different effects on precipitation in different regions of eastern China. According to conventional concepts, the abnormal northward extension of the southerlies into N China and the associated increased precipitation could be indicative of a strengthened Asian summer monsoon (Wang et al. 2008; Liu et al. 2010). It is therefore important to provide additional reconstructions with a reliable chronology and one or more high-resolution climate proxies for the last millennium in N China.

Here we chose the site of Gonghai Lake, a closed-basin alpine lake located at the northern boundary of the modern Asian summer monsoon in N China, to investigate the relationship between chemical weathering conditions and climate change during the last millennium. As the lake is hydrologically closed, the history of chemical weathering in the watershed is expected to be recorded in the lake sediments. Based on AMS $^{14}$C dating of terrestrial plant macrofossils, which provides excellent chronological control, the specific aims of this study were to reconstruct the high-resolution history of weathering intensity in the catchment and to assess its usefulness as a potential proxy for climatic change over the last 1200 years.

**Study site**

Gonghai Lake (latitude 38°54′N, longitude 112°14′E, altitude 1860 m a.s.l.) is located in Ningwu County, Shanxi Province, on the northern margin of the Chinese Loess Plateau (CLP) (Fig. 1A). It has a surface area of $0.36$ km$^2$ with a maximum water depth of around $10$ m and a flat bottom (Fig. 1B). Gonghai Lake is a freshwater alpine lake formed on a plateau of the watershed between the Sanggan and Fenhe rivers. As the lake is a hydrologically closed basin, the water source is mainly precipitation (Fig. 1C). The Ningwu County area is located in a transitional zone between semi-arid and semi-humid conditions, falling into the typical fringe of the modern Asian summer monsoon (Fig. 1A). The mean annual precipitation in Ningwu (1500 m a.s.l.) is about 468 mm, with about 65% of the annual precipitation occurring in summer (from June to August). The regional vegetation in the nearby Lvliang Mountains is dominated by *Larix principis-rupperechtii*, *Pinus tabulaeformis* and *Populus davidiana* forest, whereas on the plateau (including the drainage basin of Gonghai Lake), *Hippophae rhamnoides* scrub, *Bothriochloa ischaemum* grassland and *Carex* spp. are widely distributed. The exposed bedrock of the zonal ground surfaces was mainly formed during the Archaean to Cenozoic, and is comprised mainly of sandstone, such as Huoshan sandstone (Meng et al. 2007; Liu et al. 2011). The origin of Gonghai Lake and the distinctive provenance of its lake sediments have been discussed elsewhere (Zhu et al. 2006; Meng et al. 2007; Chen et al. 2013; Wang et al. 2014). In the study area, the last tectonic activity occurred $16$ ka (Wang et al. 2014), which played an important role in formation of the lake basin. No known crustal uplift or tectonic event has been documented during the Lateglacial and Holocene periods and thus the effect of erosion or denudation in the source area on the weathering rates is unlikely to be very significant during the Lateglacial–Holocene interval.

**Material and methods**

In January 2009, a 9.42-m-long sediment core, designated GH09B, was retrieved from the centre of Gonghai Lake at a water depth of 8.96 m (Fig. 1B) using a Uwitec Piston Corer. The 2.8-m-long first section of core GH09B, designated GH09B1, was used for the present study. In the laboratory, the core was sliced at 1-cm interval for detailed geochemical analysis. After drying at $105^\circ$C, $3$ g powdered samples were compressed (at $30$ T pressure) into a 32-mm-diameter pellet and then stored in desiccators. Concentrations of $32$ major, trace and rare earth elements/oxides (Cl, S, P, As, Ba, Ce, Co, Cr, Cu, Ga, Hf, La, Mn, Nb, Nd, Ni, Pb, Rb, Sr, Th, Ti, Tl, V, Y, Zn, Zr, Fe$_2$O$_3$, SiO$_2$, Al$_2$O$_3$, CaO, Na$_2$O, K$_2$O) were determined at the Key Laboratory of Western China’s Environmental Systems, Ministry of Education (MOE), Lanzhou University. We used a PANalytical PW2403/00 X-ray fluorescence (XRF) spectrometer equipped with a Super Sharp Tube for the Rh-anode, with the following settings: $4.0$ kW, $60$ kV, $160$ mA, and a $75$ $\mu$ UHT Be end window. We used version 5 of the company’s SuperQ software for the XRF analysis. The accuracy of the analytical method was established using six internationally recognized standard reference materials (SRMs): MAG-1, BCSS-1, PACS-1, MESS-1, NIES-2 and GBW 07314. Following the manufacturer’s instructions, we calibrated the equipment and found that the analytical uncertainties (relative standard deviations) were less than $\pm5\%$ for most elements and oxides. The reproducibility and accuracy of XRF using blank samples was better than $\pm10\%$. Details of the XRF method have been described by Selvaraj & Chen (2006) and Selvaraj et al. (2010). In addition to the sediment core, six bedrock samples (sandstones) from the catchment of Gonghai Lake were analysed to calculate the Sr
fraction that is associated exclusively with the silicate fraction in the sediment core. To calculate the chemical index of alteration (CIA), a suitable proxy to infer chemical weathering of source rocks in the catchment, we used the carbonate content obtained from Loss on Ignition (LOI) measurements to derive the CaO content associated with the silicate fraction only (CaO*). However, we obtained a wide range of CaO* values (1.56–6.80%) and most CaO* values are higher than the Na2O values in the respective subsamples. The CIA was therefore calculated using the formula excluding CaO: molar Al2O3/(Al2O3+Na2O+K2O). Similarly, based on the carbonate content (range: 3.82–8.90%) in the sediment core, we apportioned the total Sr content obtained from the XRF method to Sr associated with silicate and carbonate, and the former Sr values were used to calculate Rb/Sr ratios of all sediment subsamples. We also selected 29 subsamples for pollen analysis, which were processed using the procedure described in Xu et al. (2007); the analyses were conducted in the laboratory of Hebei Normal University.

**Sediment lithology and chronology**

The lithology of core GH09B1 is uniform and consists mainly of silty clay with occasional plant fragments. Terrestrial plant macrofossils were selected from five depths for accelerator mass spectrometry radiocarbon (AMS 14C) dating (Table 1) to avoid the reservoir carbon effect that commonly occurs in the lacustrine sediments of arid China. The bottom four dates from core GH09B1 have been published in Liu et al. (2011). All AMS 14C samples were prepared using the standard pretreatment (alkali–acid–alkali) and then measured at the AMS Dating Laboratory of the Institute of Earth Environment, Chinese Academy of Sciences, Xi’an, China, and at Beta Analytic, USA. All dates were calibrated to calendar years using OXCAL4.1 software (Bronk 2009) with the IntCal04 calibration data set.

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*Fig. 1. A. Location of Gonghai Lake in the Chinese Loess Plateau (modified from Liu 1985). Also shown are Wanxiang Cave, sandy desert, mountain systems and the modern Asian summer monsoon limit (MASML, dashed line, from Chen et al. 2008). B. Bathymetry of Gonghai Lake. The dot indicates the location of core GH09B investigated in the present study. C. Panoramic view of Gonghai Lake and its catchment (modified from Chen et al. 2013). This figure is available in colour at http://www.boreas.dk.*
The calendar ages obtained are precise enough to resolve the intervals of important climatic events in the past millennium, such as the Medieval Warm Period (MWP), Little Ice Age (LIA) and the Current Warm Period (CWP). The ages of other samples were estimated by linear interpolation and the age at the bottom of core GH09B1 is AD 880 (Fig. 2). There is no significant change in the silty-clay lithology of core GH09B1; however, the sediments are somewhat coarser grained within two limited depth intervals: ∼1.0–2.0 m and 2.5–2.8 m. Therefore, it is unlikely that there are any significant changes in the density of mineral grains affected by changes in either water depth or the energy of sediment deposition. The sediment accumulation rate is relatively high (∼239 cm ka\(^{-1}\)) (Fig. 2) and the time resolution of the sampling interval ranges from ∼8–18 years, enabling us to assess changes in weathering intensity on decadal to centennial time scales.

Results

Principal component analysis (PCA) of the Gonghai Lake geochemical data

In this study, ordination analysis was used to extract combinations of variables that are correlated with the distribution of elements/oxides. Prior to the analysis, an indirect ordination approach, i.e. detrended correspondence analysis (DCA), was performed to determine whether a linear or unimodal model was more appropriate. The results of the DCA with a gradient length of 0.24 (<3.0 standard deviations) suggest that a linear model is appropriate for the assemblage of elements/oxides. PCA was then conducted to identify the factors controlling the composition of elements/oxides. The first PCA axis (hereafter named PCA1) explains 53.3% of the variance within the geochemical data set (Fig. 3), and those elements/oxides usually considered as more soluble and mobile and that are mainly derived from chemical weathering due to abundant precipitation (e.g. CaO, Na\(_2\)O and Sr) (Mackereth 1966; Engstrom & Wright 1984) all showed strong positive loadings on PCA1. In contrast, elements/oxides that are considered as more insoluble and resistant (e.g. Al\(_2\)O\(_3\), SiO\(_2\) and Fe\(_2\)O\(_3\)) produced negative loadings on PCA1 (Fig. 3). Here, K\(_2\)O was excluded from the mobile and soluble group due to the abundance of potassium feldspar in the catchment that is relatively resistant to chemical weathering (Meng et al. 2007). Thus, the geochemically inert elements or oxides in the sediments of Gonghai Lake in general had negative loadings on PCA1. These relationships imply that PCA1 defines a synthetic geochemical gradient that separates mobile and soluble elements (or oxides) delivered to Gonghai Lake by catchment weathering processes from immobile and resistant elements (or oxides). Thus, when arranged stratigraphically (Fig. 6A), increasing PCA1 sample scores record the relative importance of soluble and mobile elements (or oxides) derived from chemical weathering to the overall geochemical record, suggesting a positive correlation between PCA1 and chemical weathering intensity. This also confirms that different degrees of stability of elements/oxides in the sediments of Gonghai Lake have been separated under different environmental conditions, suggesting that variations in the PCA1 score could be used as a proxy for chemical weathering intensity.

Rb/Sr ratio related to chemical weathering intensity in the sediments of Gonghai Lake

Strontium (Sr) is a trace element that behaves similarly to Ca in many geochemical processes. Rubidium (Rb) is incorporated mainly in potassium (K)-bearing silicates and displays a more inert geochemical behaviour than Sr.
during weathering processes. The strong contrast in weathering rates between the Ca- and K-containing minerals, especially Ca- and K-feldspars, leads to the fractionation of Rb and Sr during weathering (Dasch 1969; Chen et al. 1996), and this results in a significant increase in the Rb/Sr ratio in the residual weathered product (Brass 1975; Jin et al. 2001a). Lakes in general receive large amounts of weathering products from rocks and/or soils in the catchment. With the enhancement of chemical weathering, a greater amount of Sr is leached as dissolved Sr$^{2+}$ from rocks and soils and is transported into lakes, whereas Rb tends to remain in rocks and soils, resulting in a decrease of the Rb/Sr ratio in lake sediments. Analyses of the Gonghai Lake sediments show a negative relationship ($r=0.78$, $p<0.001$, $n=139$) between Sr concentration and Rb/Sr ratio (Fig. 4), which we attribute to an affinity of Rb (with K) for clay minerals and Sr loss (with Ca) to solution during weathering (Dasch 1969; Chen et al. 1998). Rb/Sr ratios of six rock samples from the catchment are uniform (Fig. 5A) and lower than that of the lake sediments (Fig. 5C). Thus, the variation in the Rb/Sr ratio in the sediments of Gonghai Lake can be used as an effective weathering proxy for the sediments of Gonghai Lake.

Although K$_2$O is not excluded from the mobile and soluble group because of the abundance of potassium feldspar in the Gonghai Lake basin that is resistant to chemical weathering, the CIA and Rb/Sr records (including records of the Rb/Sr ratio calculated using the total Sr content and Sr that are only associated with silicates) are still highly correlated (Fig. 5B, C), further supporting the view that the Rb/Sr ratio can be an effective weathering proxy for the sediments of Gonghai Lake.
Significance of oxide ratios in the sediments of Gonghai Lake

The major oxides, such as CaO and Na₂O, are usually considered more soluble and mobile and derived from chemical weathering and abundant precipitation, whereas Al₂O₃, SiO₂ and Fe₂O₃ are considered as more insoluble and resistant (Mackereth 1966; Engstrom & Wright 1984). Thus, molar ratios of (CaO+Na₂O)/Al₂O₃, (CaO+Na₂O)/SiO₂ and (CaO+Na₂O)/Fe₂O₃ in Gonghai Lake could also reflect the chemical weathering intensity in the catchment. Higher ratios of major oxides indicate the predominant input of soluble and mobile elements into Gonghai Lake during intervals of elevated hydroclimatic regime in the lake catchment and thus intense chemical weathering.

Discussion

Origin of weathering products and comparison of different sedimentary chemical weathering records from Gonghai Lake

As Gonghai Lake is located in a transitional zone between the East Asian monsoon system and the loess-desert area of N China (Fig. 1), both soil erosion via catchment runoff and wind-blown dust could be the major sources of detrital sediment to the lake basin. On the Chinese Loess Plateau (CLP), the average loess accumulation rate was 7 cm ka⁻¹ during the Brunhes epoch, varying with climate and being roughly four times higher during glacial periods than during interglacials (Heller & Evans 1995). In marginal areas
of the CLP, the loess accumulation rate may be as high as ~20 cm ka⁻¹ (Chen et al. 1991). However, the average accumulation rate in core GH09B1 is ~250 cm ka⁻¹ (Fig. 2), which is significantly higher than the maximum deposition rate even during glacial periods on the CLP. This implies that almost all of the detrital sediments in core GH09B1 are derived from intense soil erosion from the catchment, whereas the proportion of wind-transported particulates is likely to be negligible compared to the proportion of sediment derived from runoff. Moreover, previous study of the mineral magnetic properties of core GH09B1 has revealed that the detrital sediment component is mainly composed of eroded soil material rather than eolian dust (Chen et al. 2013). Thus, in the closed-basin of Lake Gonghai, chemically weathered materials derived from rocks and soils in the catchment are delivered to the lake predominantly via runoff and thus must be related to monsoon intensity. Therefore, the PCA of geochemical data, CIA values, Rb/Sr ratios and other major oxide ratios in sediments, which are positively correlated with each other over the last 1200 years (Fig. 6A–F), can potentially be used as effective geochemical proxies for the intensity of chemical weathering of rocks and soils in the catchment of Gonghai Lake.

To further verify our proposed geochemical result, subsamples from core GH09B1 were also selected for pollen analysis and the results are shown in Fig. 6G. The modern vegetation in the catchment area of Gonghai Lake consists mainly of grassland and shrubs. A mixed coniferous and broad-leaved forest is located below the plateau on which Gonghai Lake is located. Thus the proportion of tree pollen in lake sediments from the area might be expected to reflect the amount of precipitation and hence the summer monsoon intensity. It is therefore of interest that the percentage of tree pollen in lake sediments below the plateau on which Gonghai Lake is located. This implies that almost all of the detrital sediments in core GH09B1 have revealed that the detrital sediment component is mainly composed of eroded soil material rather than eolian dust (Chen et al. 2013). Thus, in the closed-basin of Lake Gonghai, chemically weathered materials derived from rocks and soils in the catchment are delivered to the lake predominantly via runoff and thus must be related to monsoon intensity. Therefore, the PCA of geochemical data, CIA values, Rb/Sr ratios and other major oxide ratios in sediments, which are positively correlated with each other over the last 1200 years (Fig. 6A–F), can potentially be used as effective geochemical proxies for the intensity of chemical weathering of rocks and soils in the catchment of Gonghai Lake.

Evolution of chemical weathering over the last millennium

The base of core GH09B1 is dated at AD 880, thus enabling us to reconstruct ~1200 years of weathering history in arid China. Based on the PCA1 and other oxide ratios (CIA and Rb/Sr ratio), the record can be divided into two types of geochemical zone: (i) with high values of PCA1 and the other oxides (and low values of CIA and Rb/Sr ratio) and (ii) with low values of PCA1 and the other oxides (and high values of CIA and Rb/Sr ratio) (Fig. 6A–F). Intervals of type (i) occurred from AD 880 to 1230 and from AD 1880 to the present and roughly correspond to the time intervals of the MWP and the Current Warm Period (CWP; i.e. 20th-century warm period), respectively (Moberg et al. 2005) (Fig. 7A). An interval of type (ii) lasted from AD 1230 to 1880, corresponding to the LIA (Moberg et al. 2005) (Fig. 7A). Therefore, these intervals correlate well with the most distinctive climatic fluctuations during the last millennium in the Northern Hemisphere. The PCA1 and other oxide ratios (CIA and Rb/Sr) exhibit high (low) values in sediments deposited from AD 880 to 1230 with larger fluctuations, suggesting stronger chemical weathering of source rocks during the MWP in the study area. In contrast, in sediments accumulated from AD 1230 to 1880, low values of CIA and Rb/Sr ratio with an increasing trend suggest that the intensity of chemical weathering was probably weaker during the LIA, but increased towards the later part of the LIA. Finally, high values of these proxies since AD 1880 indicate an increased chemical weathering intensity during the CWP. Although the chemical weathering intensity was generally stronger during the MWP, a pattern of
shorter term oscillations is superimposed on it, of which the most pronounced lasted from AD 940 to 1070 (Fig. 6A–F). During this period, the values of PCA1 and other oxide ratios were relatively low but the CIA and Rb/Sr ratio were relatively high, indicating that the chemical weathering intensity was reduced at this time.

**Comparison with other climatic records**

Climate plays a major role in chemical weathering processes. The major climatic variables, temperature and precipitation, either individually or in combination, act as the first order control on the initiation of major chemical reactions and therefore determine the chemical weathering intensity of rocks (White & Blum 1995; Blands & Rolls 1998). The inferences drawn above, based on our proxy records of chemical weathering from Gonghai Lake, are consistent with several other published monsoon reconstructions in N China. For example, Fig. 7 compares proxy records of chemical weathering from Gonghai Lake (Fig. 7C–E) with the Asian summer monsoon reconstructed using S_{300}, a mineral magnetic rainfall proxy from Gonghai Lake (Liu et al. 2011) (Fig. 7F), and the oxygen isotope record of speleothems from Wangxiang Cave (Zhang et al. 2008) (Fig. 7G), which is also located on the northeastern margin of the modern Asian summer monsoon. The correlation coefficient between PCA1 and S_{300} is 0.65 (p<0.001, n=139). It is apparent that, on a multichenial time scale, the proxy data for the monsoon (rainfall) variability from different locations show a consistent pattern with changes in chemical weathering intensity inferred from geochemical records from Gonghai Lake over the last millennium. In particular, the stronger Asian monsoon during the MWP indicated by high values of S_{300} in the Gonghai Lake sediments and the lighter oxygen isotope values recorded in speleothems from Wanxiang Cave, as well as the strong chemical weathering intensity indicated by the high values of PCA1 and oxide ratios and low values of CIA and Rb/Sr ratio in the sediments of Gonghai Lake, all indicate a stronger chemical weathering process under a wet climate during the MWP. The situation was roughly the opposite during the LIA and consistent since AD 1880. On decadal to centennial time scales, the secondary weakening of chemical weathering intensity during AD 940–1070, against the background of an overall strong chemical weathering period during the MWP, is also evident in the monsoon rainfall proxy reconstruction from Gonghai Lake. In addition, this short-term episode of weaker chemical weathering is also reflected in the high-resolution oxygen isotope record from Wangxiang Cave. Therefore, changes in chemical weathering intensity evident in the sediments of Gonghai Lake seem to respond sensitively to rainfall variability on submillennial and even shorter time scales. However, there is no correlation between the geochemical proxy records of Gonghai Lake and the temperature record reconstructed from historical documentation (Ge et al. 2003) in north-central China, given that the correlation coefficient between PCA1 and temperature in north-central China is 0.05 (n=139) (Fig. 7B). This suggests that chemical weathering in the Gonghai Lake region over the last 1200 years was mainly controlled by variations in the amount of precipitation delivered by the Asian summer monsoon, rather than by temperature. This possibility is consistent with the fact that over the past 1200 years, temperatures in north-central China only fluctuated by ±1°C. Clearly, further work on additional sites in N China is needed to confirm the suggested dominant role of precipitation in controlling the rate of chemical weathering during the last millennium. Finally, we suggest that sediments from lakes in N China are more suitable for chemical weathering
studies than those from lakes in arid China, where the geochemistry of sediments is largely influenced by carbonate precipitation.

Conclusions

- In the closed-basin of Gonghai Lake, the weathering products in the lake sediments are mainly derived from rocks and soils in the catchment and are largely supplied to the lake basin via runoff with minimal aeolian inputs. Such conditions offer the opportunity of using the sediment geochemical record to investigate the relationship between weathering rate in the catchment and climate.
- The first component of a PCA of the geochemical data set of core GH09B1 from Gonghai Lake defines a synthetic geochemical gradient separating mobile and soluble elements/oxides delivered to the lake by catchment processes from that of immobile and resistant elements/oxides. This suggests that variations in the PCA1 score can be used as a proxy for chemical weathering intensity. In addition, the negative relationship between Sr concentration and Rb/Sr ratio, due to an affinity of Rb (with K) for clay minerals and Sr loss (with Ca) to solution during weathering, suggests that the variation of Rb/Sr ratios in sediments of Gonghai Lake can also be used as a proxy of chemical weathering intensity. These records of chemical weathering intensity, together with the CIA and other oxide ratios, are all positively correlated over the last 1200 years.
- High resolution geochemical data combined with a reliable chronology of sediment accumulation in core GH09B1 enabled us to study the evolution of chemical weathering in the montane region of N China for the first time. The results indicate more intense chemical weathering under a warm and wet climate during the MWP (AD 880–1230); weaker chemical weathering with an increasing trend under a cold and dry climate during the LIA (AD 1230–1880); and finally increased chemical weathering intensity during the CWP (AD 1880 to present). In addition, an interval (AD 940–1070) of relatively weak chemical weathering occurred within the context of generally strong chemical weathering during the MWP.
- The major characteristics of chemical weathering over the last millennium correlate well with other proxy records of monsoon rainfall derived from Gonghai Lake as well as with other records from the monsoon region. All of these reconstructions, including the reconstruction of chemical weathering in the sediments of Gonghai Lake and summer monsoon rainfall, are comparable even on decadal–centennial time scales. However, we found no correlation between chemical weathering in the catchment of Gonghai Lake and a coeval temperature record from north-central China, suggesting that chemical weathering in the Gonghai Lake region over the last 1200 years was not controlled by air temperature, but rather was largely controlled by the intensity of East Asian summer monsoon rainfall. Our study demonstrates the value of geochemical records from Gonghai Lake as additional, reliable proxies for exploring the past variability of Asian monsoon.

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References


