



Late Holocene Moisture Changes in the Core Area of Arid Central Asia Reflected by Rock Magnetic Records of Glacier Lake Kalakuli Sediments in the Westernmost Tibetan Plateau and their Influences on the Evolution of Ancient Silk Road

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Abstract: The evolution of Ancient Silk Road (ASR) was deeply influenced by late Holocene moisture changes in Arid Central Asia (ACA). Nevertheless, controversies in Holocene moisture change pattern of ACA and poorly-constrained age models of related studies have made the discussion about late Holocene moisture changes in ACA and their influences on the evolution of ASR difficult. Recently, a high-resolution age model during the late Holocene was established for Kalakuli Lake, a small glacier lake located in the core area of ACA. A thorough rock magnetic investigation was carried out on Kalakuli Lake sediments based on this age model. The magnetic mineral assemblage of Kalakuli Lake sediments is still dominated by primary magnetite despite minor diagenetic effects. Comparisons of rock magnetic records to parameters previously used as indicator of glacier fluctuations suggest that clastic input to Kalakuli Lake was high (low) and magnetic grain size is relatively larger (smaller), when glaciers on Muztagh Ata advanced (retreated). The ARM/SIRM ratio, a magnetic grain size proxy, is directly related to lake hydrodynamics, which are ultimately controlled by glacier fluctuations on Muztagh Ata as the result of regional moisture changes. Late Holocene moisture changes indicated by the ARM/SIRM ratio are consistent with cool/wet and warm/dry oscillations indicated by the unweighted average of biomarker hydrogen isotopic data of the C₂₆ and C₂₈ *n*-alkanoic acids in a previous study about Kalakuli Lake, most moisture change records of the core area of ACA and winter insolation of the Northern Hemisphere, but opposite to Asian monsoon evolution. Given Asian monsoon and the westerlies are mutually inhibited, we propose that late Holocene moisture changes in the core area of ACA were controlled by the intensity of Asian monsoon versus the westerlies under the governance of solar insolation. Generally increased moisture since the late Holocene indicated by the ARM/SIRM ratio favored cultural exchange and integration between the western and the eastern Eurasia, which paved the way for the formation of ASR. Coincidence between significant increase in moisture at ~200 BC suggested by the ARM/SIRM ratio and the formation of ASR indicates moisture as an important factor that facilitated the formation of ASR. The onsets of three prosperity periods of ASR in the history generally correspond to periods when moisture was relatively high, nevertheless, stagnant periods of ASR do not coincide with periods when moisture was relatively low in the core area of ACA. Disorganized correlations between stagnant periods of ASR and moisture changes in the core area of ACA suggest that moisture is not the decisive factor influencing the evolution of ASR.

Key words: moisture changes, rock magnetic records, Kalakuli Lake, Arid Central Asia, Ancient Silk Road

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1 Introduction

Ancient Silk Road (referred as ASR hereafter) was once the main commercial and cultural passage between the western and the eastern Eurasia (Hansen, 2012). Previous studies have indicated that the rise and decline of ASR was definitely influenced by climate change (Du et al., 1996; Zhong et al., 2000). Silk Road within Arid Central Asia (referred as ACA hereafter) (from the Hexi Corridor in the east to the Caspian Sea in the west) is considered

the key part of the whole ASR because of perilous natural environments of ACA (An et al., 2017). Changes in moisture, the key factor for ecosystem sustainability in ACA, have resulted in increased or shrunk and even completely disappeared rivers and lakes, expanded or contracted and even deserted oases, rise or decline of ancient kingdoms along ASR and hence route changes and even stagnation of ASR (Han and Xie, 2010; An et al., 2017). Numerous studies have been carried out to investigate moisture changes of ACA during the Holocene (Zhao et al., 2007; Chen et al., 2008; An et al., 2012; Wang et al., 2013; Huang et al., 2015; Zhang et al., 2018;

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Li et al., 2019). Although a few studies have discussed the relationship between Holocene moisture changes of ACA and the evolution of ASR (Zhong et al., 2000; An et al., 2017), spatially varying Holocene moisture change pattern within ACA owing to its complex climatic systems makes this work difficult. Moreover, different geological archives can yield different Holocene moisture change patterns even within the core area of ACA (35° – 53° N, 60° – 90° E, from the Xinjiang region in the east to the Caspian Sea in the west). For example, An et al. (2017) and Chen et al. (2016) suggested a generally increasing moisture during the Holocene in the core area of ACA based on an integrated investigation on several pollen records of lake sediments and magnetic properties and soil color studies on four loess–paleosol sequences, respectively. On the contrary, a speleothem oxygen isotope record (Cheng et al., 2012) and a lake sediment pollen record (Li et al., 2011) also from the core area of ACA indicated a generally decreasing moisture during the Holocene. In addition, wet and dry oscillations reflected by Holocene moisture change records from An et al. (2017) and Chen et al. (2016) show distinct discrepancies, which may be the result of their poorly-constrained age models and low time resolutions. Constrained by one to three ^{14}C ages during the late Holocene, the period during which ASR formed and evolved, age models of most of these moisture change records are too poor to be used in discussions about detailed late Holocene moisture changes in ACA and their influences on the evolution of ASR.

Kalakuli Lake ($38^{\circ}15'30''$ – $38^{\circ}16'33''$ N, $75^{\circ}1'22''$ – $75^{\circ}2'30''$ E; 3645 m altitude) is a small glacier lake located in the Pamir–Karakoram–Tien Shan–Himalayan mountain ranges at the westernmost of the Tibetan Plateau, within the core area of ACA (Fig. 1). The Muztagh Ata (7546 m altitude), a glacier massif that lies about 20 km to the south of Kalakuli Lake (Fig. 1), is the only glacial meltwater source of Kalakuli Lake. Using 17 reservoir-corrected ^{14}C ages, Liu et al. (2014) established a high-resolution age model for the Kalakuli Lake sediments and further reconstructed late Holocene glacier fluctuations on Muztagh Ata from grain size, volume-specific magnetic

susceptibility, Zr content, and Zr/Rb and Rb/Sr ratios. Over the last 2000 years, the reconstructed glacier fluctuations on Muztagh Ata are in good agreement with reconstructed temperatures of China (Yang et al., 2002) and the Northern Hemisphere (Christiansen and Ljungqvist, 2012), which indicates that centennial scale glacier fluctuations are sensitive to temperature changes in the western Tibetan Plateau. Based on the age model established by Liu et al. (2014), Aichner et al. (2015) carried out an investigation on compound-specific carbon and hydrogen isotopic compositions of the C_{24} , C_{26} and C_{28} *n*-alkanoic acids of Kalakuli Lake sediments, and reconstructed late Holocene cool/wet and warm/dry oscillations of the western Tibetan Plateau. Since the biomarker isotopic analysis is too labor consuming, this cool/wet and warm/dry oscillation record is not very high in time resolution. In addition, the influences of late Holocene moisture changes on the evolution of ASR still have not been discussed.

Since magnetic measurements are generally easy, fast, non-destructive and economical friendly (Thompson and Oldfield, 1986), it is feasible to reconstruct high-resolution paleoclimate records using magnetic parameters. Rock magnetic parameters have been suggested as effective approaches in extraction of paleoprecipitation information using lake sediments from monsoon regions (Zhang et al., 2007; Liu et al., 2011; Su et al., 2013; Duan et al., 2014; Hu et al., 2015; Wang et al., 2018). For example, the ARM/SIRM ratio, a magnetic grain size parameter (Thompson, 1986; Oldfield, 1994; Li and Wang, 2012) can reflect lake hydrodynamics more accurately than grain size distribution of bulk clastic materials because magnetic minerals, such as magnetite, maghemite and hematite, are all heavy minerals difficult to be suspended again once they were deposited (Morton and Hallsworth, 1999). As glacial meltwater is normally the dominant water source of glacier lakes, we consider that the ARM/SIRM ratio of Kalakuli Lake sediments may be a potential indicator of glacier fluctuations on Muztagh Ata and hence moisture changes in the core area of ACA.

In this article we present a high-resolution moisture change (glacier fluctuation) record during the late Holocene via rock magnetic investigations on a sediment core from Kalakuli Lake, in order to discuss late Holocene moisture changes in the core area of ACA and their influences on the evolution of ASR.

2 Geological Settings

Kalakuli Lake is a small glacier lake located at the westernmost of the Tibetan Plateau (Fig. 1). The Muztagh Ata massif, which is adjacent to the ranges of the Pamir Plateau, Karakorum and Tien Shan, is the only glacial meltwater source of Kalakuli Lake. There is a small outflow of Kalakuli Lake at its northern margin draining to the Kangxiwa River. Kalakuli Lake has an area of ca. 10 km^2 , a maximum water depth of 20 m and an average water depth of 15 m (Liu et al., 2014). The 48-year (1961–2009) meteorological data from the Tashikuergan weather station that lies ca. 75 km to the south of Kalakuli Lake suggest a mean annual temperature of 0.7°C and a

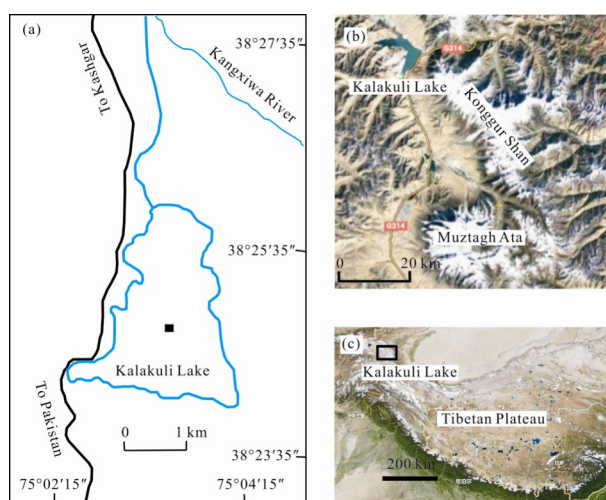


Fig. 1. Locations of (a) the coring position (■), (b) the Muztagh Ata and Kalakuli Lake in (c) the western Tibetan Plateau.

mean annual precipitation of 127 mm (Liu et al., 2014). The highest precipitation occurs in spring (from March to May) in response to the penetration of the midlatitude westerlies (Liu et al., 2014), which suggests the midlatitude westerlies as the dominant climate system concerning moisture supply to this region (Yao et al., 2012).

3 Samples and Methods

During October 2008, two long sediment cores were collected from the central part of Kalakuli Lake (Fig. 1) at a water depth of 16 m (38°15'50"N, 75°2'4"E) using Umwelt- und Wissenschaftstechnik coring equipment. Volume-specific magnetic susceptibility (κ) was measured for these two cores using a Bartington MS2C loop sensor at 2 cm interval. An 8.30 m long composite section was constructed by κ correlation between these two cores (Liu et al., 2014).

Anhyseretic remanent magnetization (ARM) was determined at 4 cm interval using a 2G-755 Enterprises Cryogenic SQUID magnetometer after imparting an ARM in a 100 mT alternating field with an attached degausser and a 50 mT biasing direct field. Isothermal remanent magnetization (IRM) was also determined at 4 cm interval using a Minispin magnetometer (Molspin) after inducing an IRM in a 1000 mT pulse field (IRM_{1000mT}, termed as the saturation IRM (SIRM) hereafter) and a 300 mT reverse pulse field (IRM_{-300mT}) using a MMPM9 pulse magnetizer. A simplified s-ratio was calculated as the ratio of IRM_{-300mT} to SIRM. Mass-specific low- (χ_{lf}) and high frequency (χ_{hf}) magnetic susceptibilities were determined for the same samples using a MFK1-FA Kappabridge at frequencies of 976 and 15616 Hz, respectively. Frequency dependent magnetic susceptibility percentage (% χ_{fd}) was calculated using the equation $\chi_{fd}\% = [(\chi_{lf} - \chi_{hf}) / \chi_{lf}] \times 100\%$. The temperature-dependence of magnetic susceptibility (χ -T) curves were determined for five representative samples in an argon atmosphere from room temperature to 700°C and back to room temperature using a KLY-3S Kappabridge with an attached CS-3 heating device. Hysteresis loops were determined for representative samples using a MicroMag 2900 alternating gradient field magnetometer (Lakeshore PMC) with a maximum field of 800 mT. Above magnetic measurements were all carried out in the Paleomagnetism Laboratory at University of Tübingen.

The methods for age model reconstruction, grain size analyses and element ratio determination have been described in a previous study about Kalakuli Lake (Liu et al., 2014).

4 Results

The temperature-dependent magnetic susceptibility (χ -T) curves all display quite similar behaviors (Fig. 2a). Relatively constant χ values and exclusive Curie temperatures at ~580°C detected in both heating and cooling curves suggest that magnetite is the main ferrimagnetic minerals in Kalakuli Lake sediments (Zeng et al., 2018). Gradual increase in χ values above ~400°C

and much higher levels of χ values in the cooling curves than in the heating curves indicate new formation of magnetite during heating (Deng et al., 2001). The characteristics of hysteresis loops (Fig. 2b) are typical for magnetite (Roberts, 1995; Tauxe, 1996), which is consistent with the implication of χ -T curves.

Variations of χ_{lf} determined on individual samples are completely consistent with variations of volume-specific magnetic susceptibility (κ) obtained through continuous core logging in the previous study of Liu et al. (2014) (Fig. 3), which indicates that both measurements are reliable. Among the magnetic concentration-dependent parameters, χ_{lf} ranges from 20.66 to 36.69 $\times 10^{-8}$ m³/kg (average 27.84 $\times 10^{-8}$ m³/kg), ARM varies from 1.78 to 5.32 $\times 10^{-4}$ Am²/kg (average 3.15 $\times 10^{-4}$ Am²/kg), and SIRM fluctuates from 21.98 to 45.92 $\times 10^{-4}$ Am²/kg (average 32.40 $\times 10^{-4}$ Am²/kg). The ARM/SIRM ratio ranges from 0.06 to 0.17 (average 0.10), $\chi_{fd}\%$ varies from 1.2 to 10.6 % (average 5.9%), and the s-ratio ranges from 0.88 to 0.99 (average 0.96). It is noteworthy that high contents of silt fractions are generally related to high values of χ_{lf} and SIRM, but low values of ARM and the ARM/SIRM ratio (Fig. 4). In order to make comparisons of the content of silt fractions to χ_{lf} , SIRM, ARM and the ARM/SIRM ratio more obvious, linear correlation of the content of silt fractions with those four parameters were carried out. In accordance with the deduction from visual observations, the content of silt fractions is positively correlated with χ_{lf} and SIRM, but negatively correlated with ARM and the ARM/SIRM ratio (Fig. 5).

Based on down-core variations in rock magnetic parameters, the Kalakuli Lake sediments can be divided into two subsections (Fig. 4). In the upper subsection (0–4.64 m, i.e. from 126 BC to the present), $\chi_{fd}\%$, ARM and ARM/SIRM values are all generally lower than their average values, while the s-ratio values are generally higher than its average value. In the lower subsection (4.64–8.30 m, i.e. from 2224 to 126 BC), $\chi_{fd}\%$, ARM and ARM/SIRM values are all generally higher than their average values, while the s-ratio values are generally lower than its average value, especially at the bottom of the lower subsection, the s-ratio values are much lower than its average value. Values of χ_{lf} and SIRM fluctuate considerably and do not show any regularity relative to their average values.

5 Discussions

Despite the fact that χ_{lf} , ARM and SIRM are all magnetic concentration-dependent parameters, they are sensitive to different magnetic phases. χ_{lf} roughly reflects the concentration of all magnetic phases, and usually is an approximate measurement of ferrimagnetic minerals, including superparamagnetic (SP) particles (Thompson and Oldfield, 1986). Nevertheless, SP particles do not contribute to the remanence parameters ARM and SIRM (Maher, 1988). Compared with SIRM, ARM is particularly sensitive to single domain (SD) materials, thus, the ARM/SIRM ratio can be used to reflect variations in magnetic grain size (i.e., magnetic domain state), with relatively higher values of the ARM/SIRM

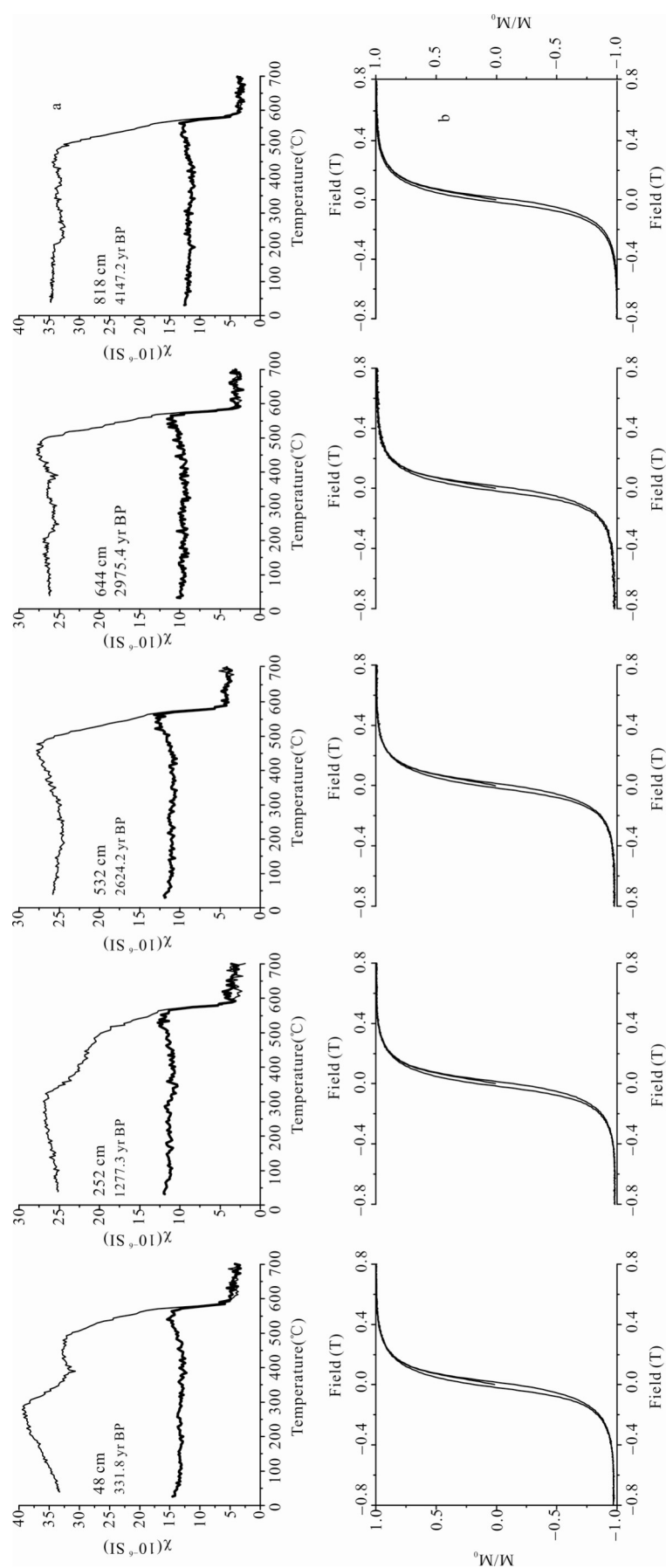


Fig. 2. (a) χ -T curves (bold and slim lines represent heating and cooling curves, respectively) and (b) Hysteresis loops (corrected for paramagnetism and diamagnetism) for representative samples.

ratio indicating higher abundances of fine-grained SD or SD-like materials and vice versa (Oldfield and Yu, 1994; Moskowitz et al., 2008). As magnetic particles in SP state do not contribute to χ_{hf} , $\chi_{\text{fd}}\%$ is usually used to reflect the abundance of SP materials (Maher, 1988; Jiao et al., 2020). The s-ratio is a reflection of the relative contribution of low to high coercivity magnetic components (Thompson and Oldfield, 1986).

5.1 The environmental significance of the ARM/SIRM ratio

At the boundary between the lower and the upper subsections, greatly decreased values of $\chi_{\text{fd}}\%$ and the ARM/SIRM ratio (Fig. 4) indicate a distinct decrease in abundances of SP, SD and SD-like materials, but increase in magnetic grain size (Maher, 1988; Oldfield and Yu, 1994). Consistent with this increase in magnetic grain size, the content of silt fractions also suggests increase in grain size of all clastic materials at the boundary between the lower and the upper subsections (Fig. 4). In the lower subsection, down-core gradual decrease in the s-ratio suggests progressively enhanced post-depositional diagenesis with depth (Wu et al., 2016). Nevertheless, variations of the magnetic concentration-dependent parameters are not smoothed, which indicates that the pristine magnetic mineral assemblage of Kalakuli Lake sediments was not severely modified by diagenesis. If the pristine magnetic mineral assemblage of Kalakuli Lake sediments was severely modified by diagenesis, preferential dissolution of fine magnetite particles would result in relatively lower values of s-ratio and $\chi_{\text{fd}}\%$ occur at the same time (Wu et al., 2016). Up-core generally opposite variation tendencies of $\chi_{\text{fd}}\%$ and the s-ratio indicates that primary magnetic minerals were still fairly well preserved in Kalakuli Lake sediments despite diagenesis. In additions, down-core roughly consistent variations between magnetic grain size indicated by the ARM/SIRM ratio and grain size of all clastic materials indicated by the content of silt fractions can serve as another evidence that primary magnetic minerals dominated the magnetic mineral assemblage of Kalakuli Lake sediments. Liu et al. (2014) have suggested that high values of volume-specific magnetic susceptibility and high contents of silt

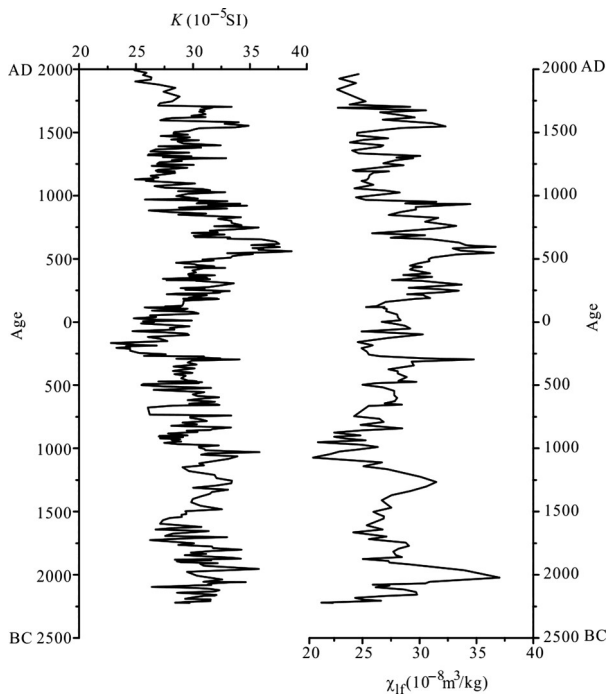


Fig. 3. Comparison between χ_{lf} from this study and volume-specific magnetic susceptibility (κ) from Liu et al. (2014).

fractions in sediments of Kalakuli Lake are related to glacier advances on Muztagh Ata, on the contrary, low values of volume-specific magnetic susceptibility and low contents of silt fractions are related to glacier retreats. Roughly consistent variations of χ_{lf} and SIRM with those of the content of silt fractions (Fig. 4) indicates that there was more clastic input to Kalakuli Lake when glaciers on

Muztagh Ata advanced and vice versa, while contrary variations of ARM and the ARM/SIRM ratio with those of the content of silt fractions (Fig. 4) indicate that magnetic grain sizes of Kalakuli Lake sediments are larger (less SD-like magnetite) when glaciers on Muztagh Ata advanced and vice versa. When glaciers on Muztagh Ata advances, shortened distance between the Muztagh Ata glacier massif and Kalakuli Lake would result in not only shortened transport distance of clastic materials, but also enhanced lake hydrodynamics, which would ultimately result in increased clastic input (high values of χ_{lf} and SIRM) and grain size of clastic materials (high contents of silt fractions), and thus accordingly increased magnetic grain size (decreased ARM/SIRM values).

Besides the ARM/SIRM ratio, $\chi_{fd}\%$ is also indicative of magnetic grain size (Blake et al., 2006). The up-core general decrease in both $\chi_{fd}\%$ and the ARM/SIRM ratio indicates that both SP, SD and SD-like particles stem from the same source, and there is a general increase in magnetic grain size because of roughly continuous glacier advance on Muztagh Ata (generally increasing moisture in the core area of ACA) since the late Holocene. However, variations of $\chi_{fd}\%$ are much smoother compared with those of the ARM/SIRM ratio, especially in the upper subsection (Fig. 4). Multi-domain (MD) particles are characterized by $\chi_{fd}\%$ values lower than $\approx 5\text{--}6\%$ (Fine et al., 1993). In the upper subsection, generally lower than 6% $\chi_{fd}\%$ values and smoother variations of $\chi_{fd}\%$ compared with those of the ARM/SIRM ratio (Fig. 4) indicates that there is hardly any SP material in the upper subsection of Kalakuli Lake sediments. Moreover, magnetic grain size estimation based on $\chi_{fd}\%$ values is complex because magnetic minerals of different grain size distributions may have the same $\chi_{fd}\%$ values even when magnetite is the

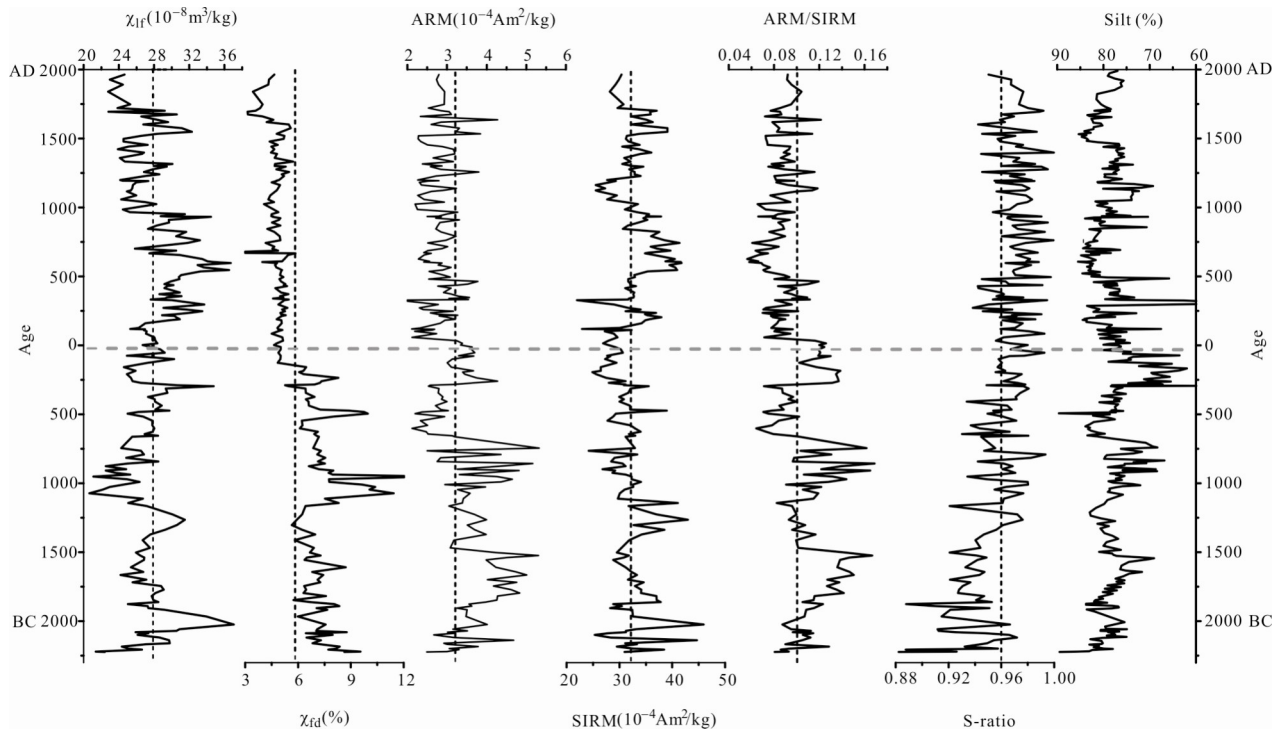


Fig. 4. Down-core variations in rock magnetic parameters (χ_{lf} , $\chi_{fd}\%$, ARM, SIRM, the ARM/SIRM ratio and the s-ratio) and content of silt fractions (Liu et al., 2014).

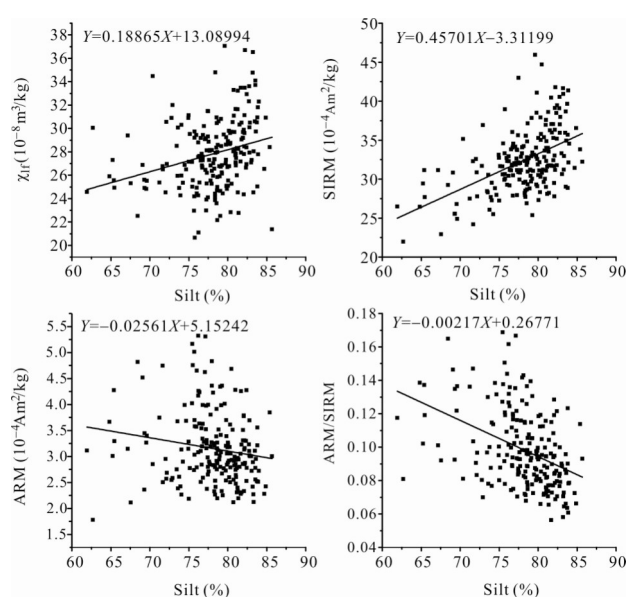


Fig. 5. Linear correlation of the content of silt fractions with χ_{fd} , SIRM, ARM and the ARM/SIRM ratio.

only magnetic mineral (Eyre, 1997; Worm, 1998). Thus, the ARM/SIRM ratio instead of $\chi_{fd}\%$ was chosen in this study to reflect magnetic grain size variations of Kalakuli Lake sediments, glacier fluctuations on Muztagh Ata and hence moisture changes in the core area of ACA.

Late Holocene moisture changes reconstructed using the ARM/SIRM ratio in this study are in good agreement with cool/wet and warm/dry oscillations reconstructed using the unweighted average of biomarker hydrogen isotopic data of the C_{26} and C_{28} *n*-alkanoic acids (Anicher et al., 2015) (Fig. 6), which indicates that the newly obtained moisture change record is credible. The content of silt fractions, which reflects the grain size of all clastic materials, also suggested moisture changes in good agreement with cool/wet and warm/dry oscillations suggested by the biomarker hydrogen isotopic data mentioned above. However, the content of silt fractions does not show an obvious general increasing trend since the late Holocene like the unweighted average of biomarker hydrogen isotopic data (Anicher et al., 2015) and the ARM/SIRM ratio (Fig. 6), which indicates that the ARM/SIRM ratio record may be of better capability in reflecting late Holocene moisture changes in the core area of ACA than the grain size of all clastic materials.

5.2 Climatic implications

The general increasing moisture since the late Holocene indicated by the ARM/SIRM ratio in this study (Fig. 7a) is consistent with implications of the $\chi_{ARM}/SIRM$ ratio of loess–paleosol sequences in Xinjiang and the simplified moisture change pattern for the core area of ACA (Fig. 7b) (Chen et al., 2016), a synthesized moisture change record for Xinjiang (Fig. 7c) (Wang and Feng, 2013), lake level fluctuation record of Wulungu Lake (Fig. 7d) (Liu et al., 2008), as well as an investigation on environmental changes and cultural exchange along the ASR (An et al., 2017). The loess–paleosol sequences used in Chen et al.

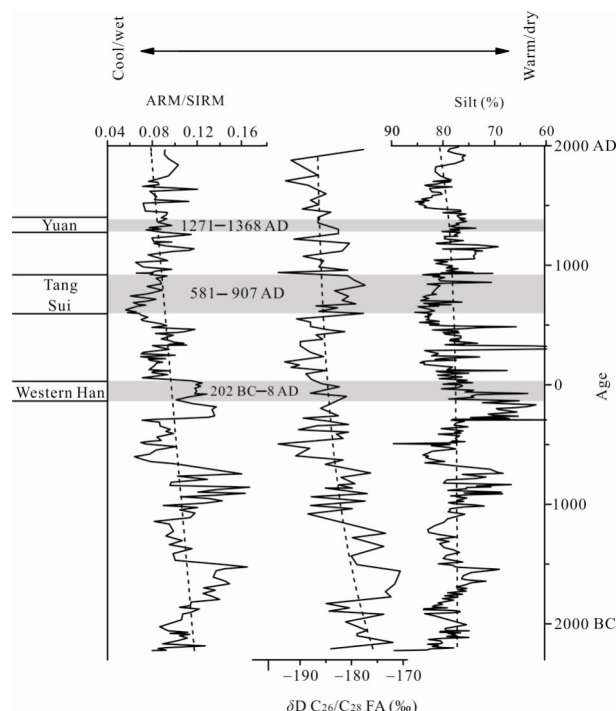


Fig. 6. Comparisons among moisture change records reconstructed using (a) the ARM/SIRM ratio in this study; (b) the unweighted average of biomarker hydrogen isotopic data of the C_{26} and C_{28} *n*-alkanoic acids in Anicher et al. (2015); (c) the content of silt fractions (Liu et al., 2014) (the dashed lines are exponential asymptotic fitting lines).

(2016), moisture change records used in the synthesized moisture change record for Xinjiang (Wang and Feng, 2013) and Wulungu Lake are all located within the core area of ACA. While moisture change records used in An et al. (2017) are mainly located within the core area of ACA, only a few are located outside but very close to the core area of ACA. Consistent increasing moisture during the late Holocene indicated by above studies suggest that environmental significance interpretation of the ARM/SIRM ratio is reasonable and that the general increasing moisture change pattern during the Holocene suggested by Chen et al. (2016) may be more suitable for the core area of ACA instead of the general decreasing moisture change pattern suggested by Li et al. (2011) and Cheng et al. (2012).

Liu et al. (2008), Wang et al. (2013) and Chen et al. (2016) all attributed general increasing moisture during the Holocene in the core area of ACA to a gradual enhancing strengthen of the westerlies. Liu et al. (2008) considered this gradual enhancing strengthen of the westerlies was the result of weakened Asian monsoon governed by decreasing solar insolation in the Northern Hemisphere and consequently enhanced precipitation but decreased temperature in the core area of ACA. While Chen et al. (2016) suggested this enhancing westerlies as the result of increasing winter insolation in the Northern Hemisphere and temperature gradient between the mid- and the high-latitudes, as well as weakening of the North Atlantic Oscillation or Arctic Oscillation. Wang et al.

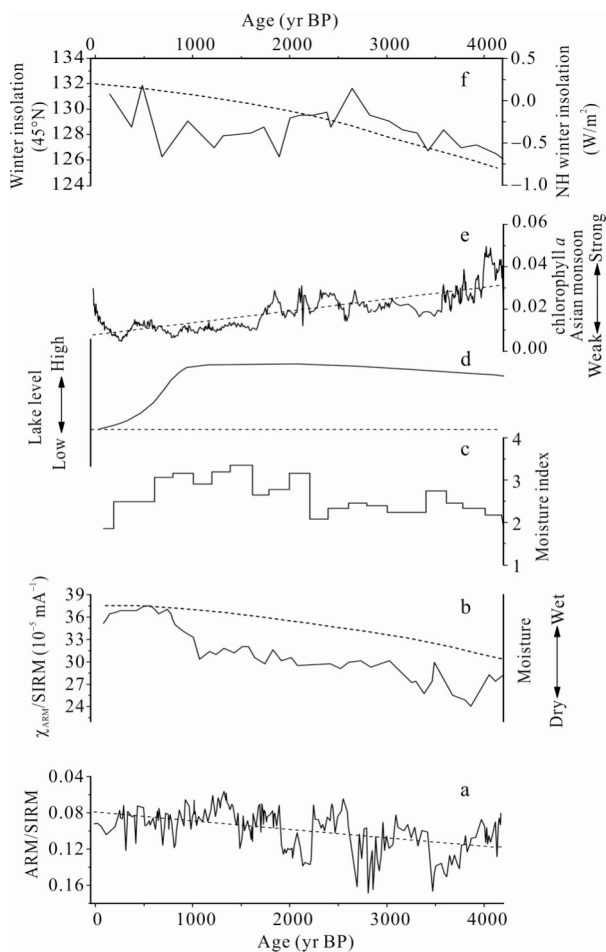


Fig. 7. Moisture changes indicated by (a) the ARM/SIRM ratio (the red dashed line is an exponential asymptotic fitting line) and its comparison to (b) the $\chi_{\text{ARM}}/\text{SIRM}$ ratio of loess-paleosol sequences in Xinjiang (the black line) and the simplified moisture evolution pattern for the core area of ACA (the dashed line) (Chen et al., 2016), (c) a synthesized moisture change record for Xinjiang (Wang and Feng, 2013), (d) lake level fluctuations of Wulungu Lake in northern Xinjiang (the dashed line represent the modern lake level) (Liu et al., 2008), (e) Asian monsoon intensity recorded by chlorophyll *a* of Huguangyan Maar Lake (Wu et al., 2012) (the dashed line is an exponential asymptotic fitting line), simulated winter insolation for the core area of ACA (Liu et al., 2009) (the black line) and winter insolation in the Northern Hemisphere (Berger and Loutre, 1991) (the dashed line).

(2013) also considered this enhancing westerlies as the result of gradual increase of winter insolation in the Northern Hemisphere, and hence enhanced evaporation in the North Atlantic Ocean and more moisture to the westerlies system. In accordance with Wang et al. (2013) and Chen et al. (2016), late Holocene general increasing moisture suggested by this study (Fig. 7a) is also opposite to the general weakening Asian monsoon indicated by the Chlorophyll *a* record of Huguangyan Maar Lake sediments (Fig. 7e) (Wu et al., 2012), but consistent with winter insolation in the Northern Hemisphere (Berger and Loutre, 1991) and simulated regional-average winter

insolation for the core area of ACA (Liu et al., 2009) (Fig. 7f). However, both meteorological data analyses (Ding et al., 1984; Sun et al., 2002) and paleoclimate studies (An Z S et al., 2012; Ma et al., 2014; Li et al., 2015; He et al., 2016) suggested that Asian monsoon and the westerlies are mutually inhibited, with strong Asian monsoon associated with retreated westerlies, and vice versa. Hence, explanations for moisture changes in the core area of ACA might be biased if they emphasized a little more about strengthening or weakening of Asian monsoon like Liu et al. (2008) or more about intensities of the westerlies like Wang et al. (2013) and Chen et al. (2016). In this article, we propose that moisture evolution in the core area of ACA was controlled by the intensity of Asian monsoon versus the westerlies that is ultimately governed by solar insolation.

5.3 Late Holocene moisture changes in the core area of ACA and their influences on the evolution of ASR

Benefited from progressively improved natural environments (progressive increasing moisture), the process of cultural exchange and integration between the western and the eastern Eurasia significantly accelerated after 2000 BC, especially in Xinjiang and Central Asia (An et al., 2017), an area that is termed as the core area of ACA by Chen et al. (2016). At ~200 BC, ASR formed thanks to continuous increasing moisture (An et al., 2017). Consistent with An et al. (2017), this study indicates progressive increasing moisture since the late Holocene in the core area of ACA as well (Fig. 6), which resulted in markedly enhanced cultural exchange and integration between the western and eastern Eurasia that paved the way for the ultimate formation of ASR. Significantly increased moisture at ~200 BC showed by this study (Fig. 6) coincides with the formation time of ASR, which is an important evidence that moisture facilitated the evolution of ASR. Du et al. (1996) and Zhong et al. (2000) have suggested that ASR was prosperous during the Western Han Dynasty (202 BC–8 AD), the Sui and Tang dynasties (581–907 AD) and the Yuan Dynasty (1271–1368 AD), but was stagnant during other periods. Besides, Zhong et al. (2000) also suggested that prosperity periods of ASR started during periods when the climate was relatively cold and wet, while stagnant periods of ASR roughly correspond to periods when the climate was relatively warm and dry in southern Xinjiang. In this study, we see that the onsets of three prosperity periods of ASR generally correspond to periods of relatively higher moisture in the core area of ACA (relatively lower ARM/SIRM values), however, stagnant periods of ASR do not coincide with periods of relatively lower moisture (higher ARM/SIRM values), and there are stagnant periods of ASR when moisture was even higher than that in the prosperity periods of ASR (Fig. 6). An et al. (2017) indicated that political factors primarily controlled the ASR during the historic periods, although environmental factors were not negligible. Disorganized correlations between stagnant periods of ASR and moisture changes in the core area of ACA imply that moisture may be not the decisive factor influencing the evolution of ASR.

6 Conclusions

(1) The magnetic mineral assemblage of Kalakuli Lake sediments is dominated by primary magnetite despite diagenesis, and changes in the ARM/SIRM ratio, a magnetic grain size parameter, are determined by regional moisture changes, with lower (higher) ARM/SIRM values indicating larger (smaller) magnetic grain size, enhanced (weakened) lake hydrodynamics and advanced (retreated) glaciers on Muztagh Ata as the result of higher (lower) regional moisture.

(2) Consistency in late Holocene moisture changes suggested by the ARM/SIRM ratio in this study, the unweighted average of biomarker hydrogen isotopic data in a previous study about Kalakuli Lake and most moisture change records for the core area of ACA suggests that the moisture change record reconstructed in this study is reliable. Late Holocene moisture changes in the core area of ACA are consistent with winter insolation of the Northern Hemisphere, but opposite to Asian monsoon evolution, which indicates that moisture changes in the core area of ACA were controlled by the intensity of Asian monsoon versus the westerlies that is ultimately governed by solar insolation given Asian monsoon and the westerlies are two climate systems that mutually inhibited.

(3) Markedly increased moisture at ~200 BC indicated by the ARM/SIRM ratio coincides with the formation of ASR, which indicates that moisture is an important factor that facilitated the formation of ASR. The onsets of three prosperity periods of ASR roughly correspond to periods of relatively higher moisture, however, stagnant periods of ASR do not coincide with periods of relatively lower moisture. Disorganized correlations between stagnant periods of ASR and moisture changes in the core area of ACA suggest that moisture may be not the decisive factor influencing the evolution of ASR.

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