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13 authors, including:

Guoqiang Ding
Lanzhou University

Jianhui Chen
Lanzhou University

Feiya lv
Hunan University of Arts and Science

Shengqian Chen
Institute of Tibetan Plateau Research Chinese Academy of Science

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Precipitation variations in arid central Asia over past 2500 years: Possible effects of climate change on development of Silk Road civilization

Guoqiang Ding [a,b], Jianhui Chen [a,*], Yanbin Lei [c], Feiya Lv [d], Rui Ma [a], Shengqian Chen [c], Shuai Ma [a], Yuanhao Sun [a], Yuecong Li [e], Haipeng Wang [f], Zhilin Shi [g], Heikki Seppä [b], Fahu Chen [a,c,h]

[a] MOE Key Laboratory of Western China's Environmental System, College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, PR China
[b] Department of Geography and Geosciences, Faculty of Science, University of Helsinki, Helsinki 00014, Finland
[c] Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, PR China
[d] College of Geography and Tourism, Hunan University of Arts and Science, Changde 415000, PR China
[e] School of Geographical Sciences, Hebei Normal University, Shijiazhuang 050024, PR China
[f] State Key Laboratory of Cryospheric Science, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, PR China
[g] Institute of Dunhuang Studies, School of History & Culture, Lanzhou University, Lanzhou 73000, PR China
[h] CAS Center for Excellence in Tibetan Plateau Earth Sciences, Chinese Academy of Sciences, Beijing 100101, PR China

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ABSTRACT

The ecological environment of arid central Asia (ACA) is fragile and sensitive to long-term climate change. Recent palaeoclimatological studies have mainly focused on northwestern China, which is located on the eastern side of the region. Holocene palaeoclimate records from the western region of ACA are scarce, thus hindering the exploration of the relationship between climate change and Silk Road civilization. In this study, we conduct a pollen analysis of Lake Sasikul on the Pamir Plateau in Tajikistan and use pollen data to quantitatively reconstruct the precipitation history over the last 2500 years. The results show that herbaceous pollen is primarily represented by *Artemisia* and Amaranthaceae, thus suggesting the persistent dominance of grassland in the vicinity of Lake Sasikul. Amaranthaceae, which is the most drought-tolerant pollen type, shows the highest values during the Medieval Warm Period (MWP, 950–1300 CE). The values of *Artemisia* and cold-wet-adapted *Picea* pollen are higher during the Little Ice Age (LIA, 1550–1900 CE). The quantitative reconstruction shows that during the MWP, the mean annual precipitation is 120 mm, which is approximately 15% lower than the level of modern precipitation; meanwhile, during the LIA, the average annual precipitation is 160 mm (up to 210 mm), which is approximately 20% higher than the present value. We combine our results with regional temperature records and archaeological data to discuss the possible effects of climate change on the development of Silk Road civilization. The hydrothermal configuration may have altered water resources and thus affect human activities in ACA. From 580 to 900 CE, i.e. during the Sui and Tang Dynasties, ice and snow meltwater increased under warm climate, whereas the amount of precipitation was average. Additionally, human settlements intensified along with urbanization, and the Silk Road civilization was prosperous and well-developed. From 1270 to 1650 CE, i.e. during the Yuan and Ming Dynasties, under overall colder and drier conditions and due to insufficient freshwater input, the intensity of local human settlement weakened, and the Silk Road civilization declined. Therefore, owing to global warming and increasing precipitation, new development opportunities have emerged for the development of agriculture and social economy in ACA.

1. Introduction

Arid central Asia (ACA) is the largest non-zonal arid region worldwide. The climate is mainly controlled by the westerly circulation, and the region is characterised by fragile ecosystems and water resources that are sensitive to global climate change (Aizen et al., 2001; Shi et al., 2007; Chen et al., 2008). Chen et al. (2008) proposed the term 'westerlies-dominated climate regime' for ACA, emphasizing that the climate

* Corresponding author.
E-mail address: jhchen@lzu.edu.cn (J. Chen).

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history of ACA is detached from the evolution of the East Asian monsoon region on the Holocene timescale. The results of Chen et al. (2008) revealed that ACA had the most arid climate in the early Holocene, i.e. when most lakes had the lowest water levels or even dried up, and that lake water levels increased in the Mid and Late Holocene. Additionally, in the core area of the 'westerlies-dominated climate regime', loess-palaeosol records show that the humidity increased during the Holocene, which is opposite to the Holocene trend during the Indian monsoon (Chen et al., 2016). On the centennial scale, In China and its surrounding areas, a spatial pattern of 'dry west and humid east' (drought in ACA and wet conditions in the East Asia monsoon region) was indicated during the MWP in north of 34°N, whereas the opposite pattern was indicated during the LIA (Chen et al., 2015a). However, other palaeoclimatic records indicate humidity during the MWP and aridity during the LIA in ACA (Ma et al., 2008; Zhang et al., 2009; Hong et al., 2014). These records are primarily based on humidity indicators, which are controlled by temperature and precipitation. For example, the humid state during the LIA was caused by an increase in precipitation or a decrease in temperature. Therefore, for investigations pertaining to climate change in ACA, quantitative reconstruction of precipitation through sensitive indicators is expected to improve the understanding of the issues above and promote further understanding regarding the 'westerlies-dominated climate regime'.

The ACA is a key component of the Silk Road, which is an important pathway for human migration and cultural diffusion between Europe and China. In recent years, the possible coupling between civilization and environmental changes along the Silk Road has received significant attention (Chen et al., 2017a, 2019a; An et al., 2017; Opała-Owczarek and Owczarek, 2019; Yang et al., 2019; Tan et al., 2021). The history of East-West exchanges along the Silk Road can be traced back to prehistoric times (Dong et al., 2021a, 2022). A dry period in Central Asia from to 5920–5180 cal yr BP resulted in a transition in early agricultural and pastoral population diffusion pathways from oases to Eurasian grasslands, which changed the direction of the ancient Silk Road (Tan et al., 2021). Dong et al. (2022) investigated the crop-livestock and geographical-temporal variation of subsistence in prehistory based on a review and analysis of published archaeobotanical, zooarchaeological, and carbon-stable isotopic data of human bones from Neolithic-Early Iron Age sites in areas along the Steppe and Silk Roads. Moreover, studies of arid areas in ACA showed that high precipitation and extensive melting of ice and snow in the mountains around the Qaidam Basin increased the runoff of the river and expanded the oasis in the basin, thus promoting the development and prosperity of the Nuomuhong culture, which is an ancient civilization that originated from the Qaidam Basin in China (~3400–2450 BP) (Dong et al., 2016, 2021b). The Silk Road was officially opened to public during the Han Dynasty (~202 BCE to 220 CE). Previous studies showed that sufficient water resources promoted the development and prosperity of Tuyuhun, which is an ancient civilization that originated from the eastern Qaidam Basin in China (~313 to 663 CE) (Dong et al., 2016, 2021b). The dearth of water resources is speculated to have caused the disappearance of the Loulan Kingdom (from ~176 BCE to 630 CE) in Xinjiang and the Guge Kingdom (from ~900 to 1630 CE) in the Qinghai-Tibet Plateau (Qin et al., 2012; Cai et al., 2017; Kathayat et al., 2017; Mischke et al., 2017; Shi et al., 2018). However, these studies only focused on certain periods of civilization during the Silk Road, and did not cover the entire Silk Road period. Meanwhile, quantitative reconstruction of precipitation in ACA is insufficient, which limits our understanding regarding the relationship between climate and civilization development.

In recent years, pollen-based quantitative palaeoclimatic reconstructions combined with modern pollen databases have significantly improved our understanding regarding past precipitation histories and environmental changes in East Asia (Zhao et al., 2009; Xu et al., 2010; Leroy et al., 2014; Zheng et al., 2014; Li et al., 2017; Lu et al., 2018; Herzschuh et al., 2019; Zhao et al., 2021). The conventional pollen-palaeoclimate quantitative reconstruction utilizes a calibration set for modern climate conditions or the comparability of fossil samples with calibration set samples, which results in unclear criteria when reconstructing climate parameters at specific sites. Hence, Chen et al. (2017b) proposed a new idea for the quantitative reconstruction of pollen palaeoclimate parameters, which is based on the quantitative reconstruction significance test using random international data (Telford and Birks, 2011). This method can avoid the simultaneous reconstruction of multiple environmental factors and reduce the uncertainty of the quantitative reconstruction of pollen-palaeoclimate parameters for determining the most important environmental factors controlling the change in fossil pollen. Owing to these advantages, it has been widely used (Lv et al., 2021; Zhang et al., 2022).

In this study, we quantitatively reconstructed the history of precipitation in ACA by pollen from Lake Sasikul sediments on the Pamir Plateau in Tajikistan in the past 2500 years. We combine published regional temperature records and archaeological data to analyse the effect of regional precipitation-temperature changes on human activities and the evolution of the Silk Road civilization. This study promotes understanding regarding the interaction between climate change and human activities in ACA and provides an important scientific basis for understanding environmental changes in key areas of the Silk Road.

2. Study area

Lake Sasikul in Tajikistan (37°42′N, 73°11′E, 3816 m a.s.l.) is located in the middle of the Pamir Plateau, with an area of approximately 8 km^2 and a drainage area of approximately 300 km^2 ((Lei et al., 2014)Fig. 1). It is a closed lake that is mainly recharged by groundwater with salinity exceeding 50 g/L. Records from the nearby Dzhavshangoz weather station (37°26′N, 72°32′E, 3453 m a.s.l.) show that from 1935 to 1990, the annual mean temperature at this station was −1.9 °C and the annual precipitation was 135 mm. The climate in the study area is controlled by westerly circulation, and the precipitation in the winter and spring reaches 60% of the annual precipitation. The Hybrid Single Particle Lagrangian Integrated Trajectory (http://ready.arl.noaa.Gov/HYSPLIT.php) model was used to calculate the backward air mass trajectory. The results show that the moisture reaching the study site was mainly derived from the North Atlantic and Mediterranean Sea and transported to Lake Sasikul by westerlies during the winter (February to April). During summer (June to September), Lake Sasikul experiences minimum precipitation (14% of the annual rainfall), with moisture derived primarily from local sources (Lei et al., 2014). The Pamir Plateau is an Asian desert. At an altitude of 3600–3900 m, shrub deserts are mainly formed by *Ceratoides*. In the Intermountain Basin, desert steppes are composed of *Stipa glareosa*, *Allium fistulosum*, and *Carex* spp. (Xu, 2007).

3. Materials and methods

3.1. Sediment coring and chronology

In May 2010, a 74-cm surface core (SK-1) was obtained from the southern region of the lake basin at a water depth of 3 m using a gravity corer. The core was sampled at 0.5 cm intervals for the top 10 cm and at 1 cm intervals from 10 to 74 cm. The chronology of the core was determined via ^{210}Pb and ^{137}Cs analyses and AMS^{14}C dating. ^{210}Pb and ^{137}Cs were measured using HPGe gamma spectrometry (ORTEC-GWL) for surface sample dating. The ^{210}Pb activity was used to determine the sedimentation rate and age of the sediment by applying a constant rate of supply model (Appleby and Oldfield, 1978). ^{137}Cs was used to verify the ^{210}Pb-derived data. AMS ^{14}C dating was performed to date samples from the lower region. Owing to inadequate macrofossil plant remains, six bulk sediment samples were used to perform AMS^{14}C measurements, among which four samples were measured at the Accelerator Mass Spectrometry Laboratory at Peking University, China, and two samples were measured at the Beta Radiocarbon Dating Laboratory, USA.

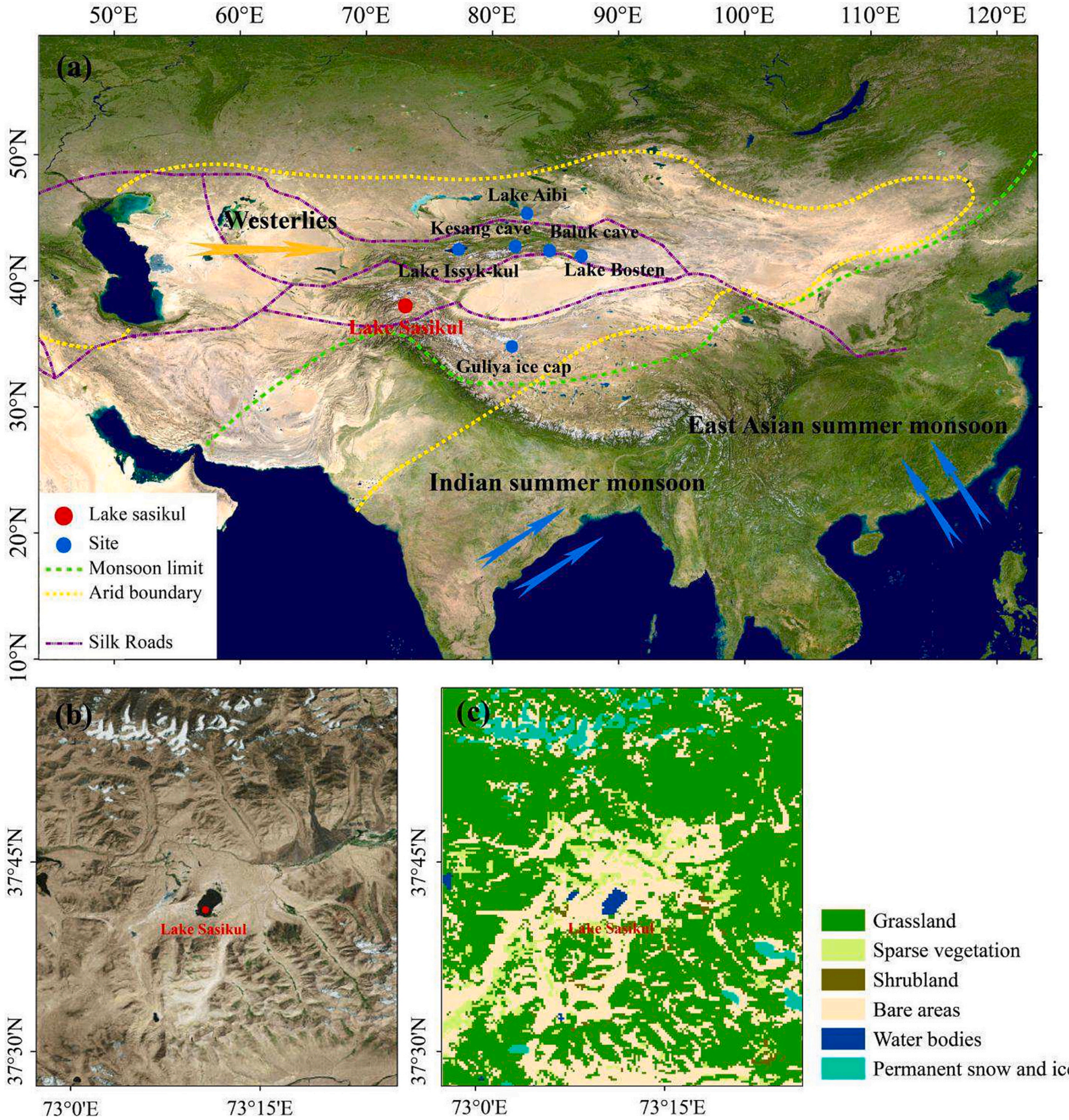

Fig. 1. (a) Location of Lake Sasikul and other sites referenced in the text. The modern Asian summer monsoon limit is shown by the dashed green line (MASML, from Chen et al., 2008). The area enclosed by the yellow dashed line is arid central Asia (modified from Feng and Fu, 2013). The prominent historical routes of the Silk Roads is shown by the dashed purple line. (b) The drainage basin of Lake Sasikul and the site of core SK-1. (c) The vegetation map of Lake Sasikul area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Pollen analysis

Pollen grains were extracted using the conventional HCl-NaOH-HF treatment (Faegri et al., 1989), which was conducted at the MOE Key Laboratory of Western China's Environmental System of Lanzhou University. Each sample weighed approximately 1 g, and one tablet of *Lycopodium* spores (10,315 spores) was added to calculate the pollen concentrations. The pollen grains were identified and counted using a Nikon ECLIPSE-80i optical microscope; at least 400 pollen grains were counted. To identify the pollen grains, the methods described by Wang et al. (1995) and Tang et al. (2016) were used. To separate crop from non-crop, Poaceae pollen was classified into two types, i.e. those with diameters ≥35 μm and < 35 μm, based on previous the results of previous studies (Lan and Xu, 1996). Among them, Poaceae with a diameter ≥ 35 μm is of the crop pollen type.

3.3. Quantitative reconstruction of environmental variables

The quantitative reconstruction method of the palaeoclimate is based on an idea proposed by Chen et al. (2017b). A modern calibration dataset comprising 2696 surface pollen samples, including 347 pollen taxa, was used for quantitative paleoenvironmental reconstruction. The following samples were excluded from the original dataset comprising 4175 samples (Lu et al., 2011; Xu et al., 2010; Zheng et al., 2014; Cao et al., 2021): samples from sites potentially affected by human disturbance (based on the original sampling notes); and samples from tropical rainforests, subtropical evergreen broadleaved forests, temperate coniferous forests, temperate broadleaved forests, and temperate coniferous, and broadleaved mixed forests (Editorial Board of Vegetation of China, 1980). The monthly average temperature and precipitation corresponding to each surface pollen type were extracted from the data space provided by Fick and Hijmans (2017). These data were interpolated from monthly temperature and precipitation (minimum, maximum, and average), solar radiation, vapour pressure, and wind speed data from 9000 to 60,000 meteorological stations worldwide between 1970 and 2000 using thin plate splines, which afforded a resolution of approximately 0.86 km. The pollen-based quantitative palaeoclimatic reconstruction was performed as follows: First, the most significant climatic variable controlling the changes in fossil pollen assemblages was identified by applying the random TF ignificance tests method (Telford and Birks, 2011) to the fossil data and the entire calibration dataset (2696 samples). Second, a calibration dataset used to infer the targeted variable (closest to the first axis of the PCA) was constructed by limiting the modern ranges of non-targeted variables (in this case, temperature, based on the results of the first step). Third, pollen-based quantitative palaeoclimatic reconstruction was performed and its statistical significance was assessed (Chen et al., 2017b). Weighted averaging partial least squares (WAPLS), which is one of the most widely used methods based on unimodal species responses with good empirical predictive power and efficient extraction of components (Birks, 1998), was used to establish regression and calibration functions. Further details regarding the procedure used for pollen-based quantitative palaeoclimatic reconstruction are available in papers by Chen et al. (2017b) and Lv et al. (2021).

3.4. Archaeological data analysis

Lake Sasikul on the Pamir Plateau is located between the middle and western sections of the Silk Road. We combined the archaeological sites and documents of Xinjiang in the middle section of the Silk Road and those of Central Asia in the western section of the Silk Road. The temporal and spatial distribution patterns of archaeological sites and documents can provide information for determining the relationship between human activity and climate. The National Bureau of Cultural Relics in Xinjiang Province (National Bureau of Cultural Relics, 2012) comprehensively records the status of existing and immovable cultural relics in China. It provides a scientific summary of the significant amount of data obtained from previous cultural relic surveys. Based on these data, we reconstructed the historical development of settlements in Xinjiang over the last two decades. The historical document entitled, History of Civilization of Central Asia (2010) was used to investigate the progression and decline of various cultures in Central Asia from the beginning of civilization to the present era by examining various archaeological materials, which we regard as key data for discussing the development of civilization in Central Asia.

4. Results

4.1. Chronology

The AMS ^{14}C dating results of six samples from core SK-1 are presented in Table 1. The procedure for correcting for the reservoir effect (1724 yrs) is explained in Lei et al. (2014). We used a Bayesian based Bacon model to establish a more reliable chronology for this study. The Bacon model implemented in R software was used to calculate and calibrate the six AMS ^{14}C ages. These ages were subsequently corrected using the Intcal20 calibration curve (Reimer et al., 2020) and utilized to establish the age-depth model (Fig. 2).

4.2. Pollen results

A total of 60 pollen types were identified from the 72 pollen samples in core SK-1, including 10 tree taxa, 14 shrub taxa, 32 herb taxa and 4 fern spore types. The average pollen concentration is 4630 grains/g (1498–9588 grains/g). The average resolution of pollen is 35 yrs./sample. Common tree and shrub taxa are *Pinus*, *Picea*, *Quercus*, *Betula*, *Ulmus*, Rosaceae, Elaeagnaceae, *Ephedra*, *Nitraria*, *Sarcozygium* and *Calligonum*; and common herb taxa are *Artemisia*, Amaranthaceae, Asteraceae, Poaceae, Lamiaceae, Caryophyllaceae, Apiaceae, Fabaceae, Polygonaceae, Cyperaceae and Ranunculaceae. Spores were present at low frequencies and only a small number of types were present. CONISS was used to conduct stratigraphically constrained cluster analysis on the pollen percentage data, which resulted in the definition of four pollen assemblage zones, which are described below (Fig. 3):

Zone 1 (74–50 cm; 520 BCE–600 CE). The average pollen concentration was 3876 grains/g. Herb pollen was dominant, with an average representation of 90.1% (84.1–94.5%), which was the lowest in the section. Among them, *Artemisia* (average of 47.6%) and Amaranthaceae (average of 33.1%) were the main ones; Asteraceae (average of 1.9%), Polygonaceae (average of 1.8%) and Poaceae (average of 1.2%) were more common; the average representation of wetland herb taxa was <1%. The average content of tree pollen was 2.8%, dominated by *Pinus* (average of 2.1%). The shrub pollen representation was the highest in the section, with an average of 7.1%, dominated by Elaeagnaceae (average of 1.5%), *Ephedra* (average of 1.2%) and *Calligonum* (average of 1.3%).

Zone 2 (50–34 cm, 600–1250 CE). The total pollen concentration was lower than in Zone 1, with an average of 3215 grains/g, which was the lowest in the section. The pollen assemblages were still dominated by herb pollen, with an average content of 93.5% (90.2–96%), among which the content of *Artemisia* (average of 45.1%) was lower than in the previous zone, while the content of Amaranthaceae was higher (average of 38.3%). Polygonaceae (average of 3%) and Asteraceae (average of 2.5%) both increased and pollen of wetland plants decreased. The content of tree pollen decreased slightly, with an average of 2.1%, among which *Pinus* (average of 1.6%) was the main one. The content of shrub pollen decreased to 4.8%, of which *Sarcozygium* (average of 1.2%) was the highest in the section, and *Ephedra* and *Calligonum* were also more common.

Zone 3 (34–9.5 cm, 1250–1770 CE). Compared with zone 2, the pollen concentration in the section was higher, with an average of 4224 grains/g. The average herb pollen value was 93.8% (89.1–97.1%), of which the content of Amaranthaceae rose to the highest (average of 39.6%) in the section. The average content of *Artemisia* is 45.4%, and the Polygonaceae (average of 2.8%) and Asteraceae (average of 1.9%) were more common. The content of Cyperaceae (average of 1%) was higher than zone 2. The average pollen content of trees was 2.9%, among which the content of *Picea* and *Abies* reached the highest in the section. The total content of shrub pollen (average of 3.4%) was slightly lower than that of the upper zone.

Zone 4 (9.5–0 cm; 1770 CE–present). The total pollen concentration was the highest in the section, with an average of 7059 grains/g. The herb pollen representation was the highest (average of 96.1%; 93–98.5%), among which *Artemisia* (average of 62.1%), Cyperaceae

Table 1
AMS ^{14}C ages and reservoir-corrected and calibrated ages for the SK-1 core (Lei et al., 2014).

Sample no.	Lab no.	Depth (cm)	Material dated	AMS^{14}C (yr BP)	Corrected ^{14}C age (yr BP)	Calibrated age	Laboratory
SK-1-8	357,072	4	Bulk organic	1440 ± 30	–		Beta
SK-1-23	BA110201	12.5	Bulk organic	1900 ± 30	176 ± 30	1650–1830 CE	Peking
SK-1-41	BA110202	30.5	Bulk organic	2355 ± 35	631 ± 35	1280–1410 CE	Peking
SK-1-60	BA110203	46.5	Bulk organic	3005 ± 35	1281 ± 35	660–880 CE	Peking
SK-1-81	BA110204	66.5	Bulk organic	3900 ± 35	2176 ± 35	370–100 BCE	Peking
SK-1-84	355,028	69.5	Bulk organic	4130 ± 30	2406 ± 30	660–360 BCE	Beta

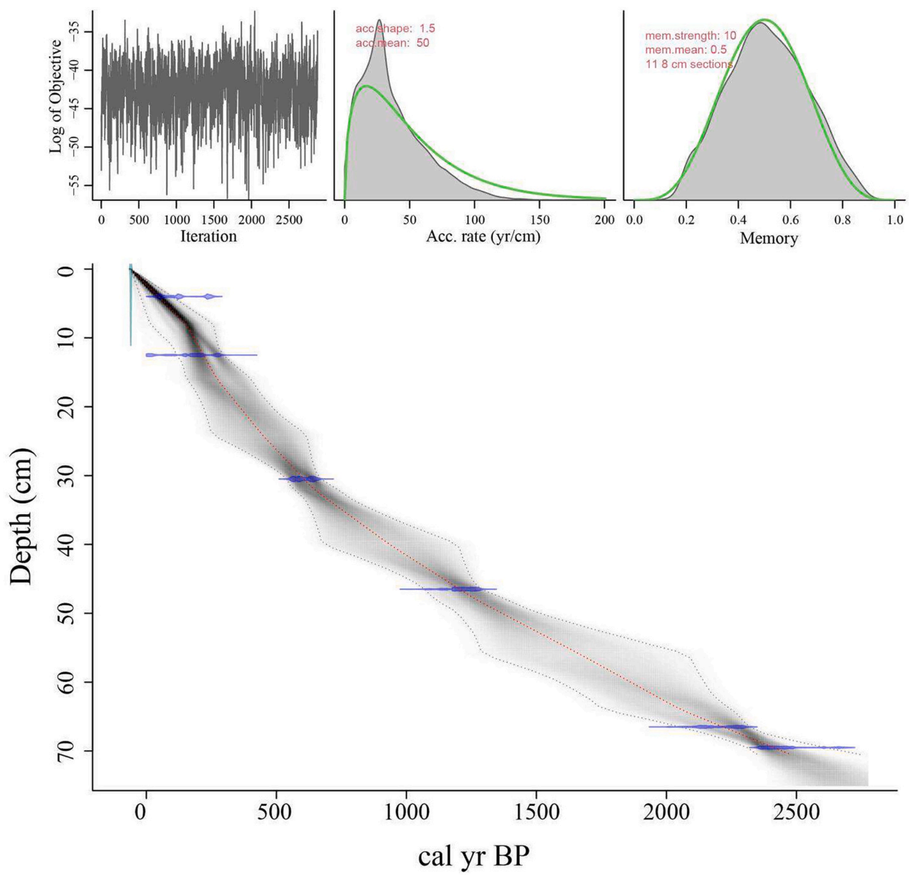

Fig. 2. Lithology and age-depth model for core SK-1.

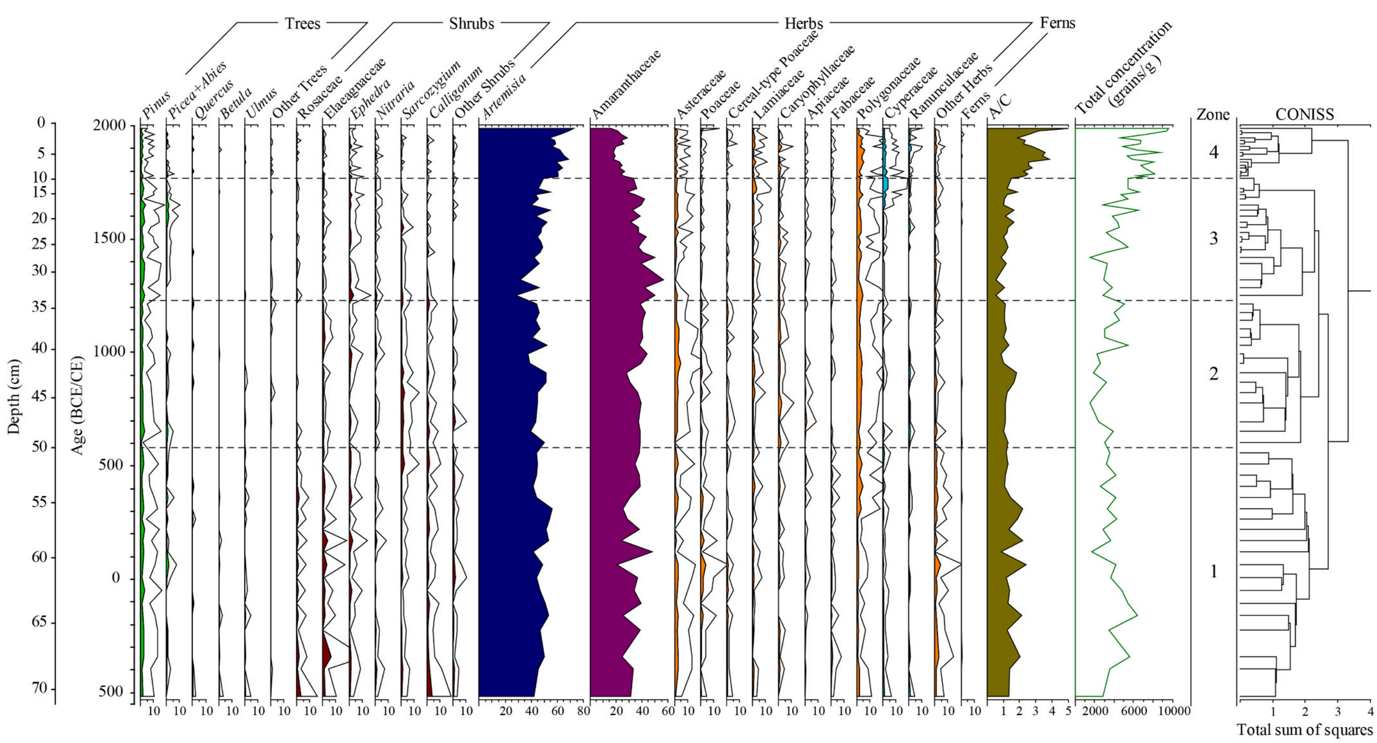

Fig. 3. Pollen diagram for core SK-1 from Lake Sasikul (only selected taxa are shown), together with the total pollen concentration, CONISS results, and the pollen zones.

(average of 1.8%) and other wetland pollen content rose to the highest in the section. In addition, the pollen content of Cereal-Poaceae also reached the highest in the section. Amaranthaceae was lower than that zone 3, with an average content of 22.8%, which was the lowest in the section. The pollen content of tree (average of 1.7%) and shrub (average of 2.2%) was the lowest in the section.

4.3. Pollen-inferred precipitation change

An assessment of the statistical significance of the reconstructions of various climatic variables using the SK-1 fossil pollen data and 2696 samples (Fig. S1a) from the calibration dataset indicated that the mean annual precipitation (Pann) was the most important factor determining the changes in the fossil pollen assemblages (Fig. 4a). We imposed a limit on the mean annual temperature (Tann). The amplitude of the Tann variation during the Holocene was <5 °C (Fang and Hou, 2011; Wang et al., 2001) and that of the Tann was 2–3 °C higher during the Holocene Thermal Maximum than the present value (Wang et al., 2001; Jiang et al., 2012). Considering the amplitude of temperature variation in the Holocene and the number of modern samples, the range of temperature change was limited to ±2.5 °C, based on the Tann of the Pamir Mountain Area. The calibration data set was composed of 927 samples (Fig. S1b) within the large precipitation range of 30–750 mm and a relatively small temperature range of −4.4-0.6 °C. The calibration dataset comprised 927 samples. All sampling points from Lake Sasikul fell into the "Good" region, indicating that the fossil samples from Lake Sasikul have a good match with the selected training set. This provides a reliable foundation for subsequent analyses and reconstructions (Fig. S2). The WAPLS-2 model was selected for precipitation reconstruction owing to its high coefficient of determination (r^2) and low root mean square error of prediction (Table S1, Birks, 1998). In addition, the proportions of variance based on the Pann reconstructions were higher compared with those obtained using the entire calibration dataset (Fig. 4a and b).

The quantitative reconstruction results showed that the average annual precipitation in the study area was 150 mm (60–220 mm), which is slightly higher than the level of modern (1935–1990) precipitation (135 mm). The reconstruction results agreed well with the changes in the pollen assemblages. Based on the CONISS analysis of the pollen data, the study area can be categorised into four zones (Fig. 5):

Zone 1 (74–50 cm; 520 BCE-600 CE). The annual precipitation typically exceeds 150 mm, with an average of 160 mm (70–220 mm). This is approximately 20% higher than the level of modern precipitation and is the second highest in the zone.

Zone 2 (50–34 cm, 600–1250 CE). Compared with the case of Zone 1, the annual precipitation decreased to the lowest level in this zone, with an average of 135 mm (65–170 mm), which is similar to the level of modern precipitation.

Zone 3 (34–9.5 cm, 1250–1770 CE). Compared with the case of Zone 2, the annual precipitation increased, with an average level of 140 mm (60–210 mm). Precipitation fluctuated during this period, and wet and dry fluctuations were evident.

Zone 4 (9.5–0 cm, 1770 CE): The annual precipitation increased compared with the case of Zone 3, with an average level of 165 mm (130–210 mm), which was approximately 1/4 higher than the level of modern precipitation and was the highest in the zone.

5. Discussion

5.1. Comparison of precipitation changes on Pamir Plateau over past 2500 years and climate records of ACA

The results of Lake Sasikul on the Pamir Plateau over the last 2500 years showed that herbaceous pollen dominated the pollen assemblages, with a proportion exceeding 80%. The herbaceous pollen comprised mainly *Artemisia* and Amaranthaceae; the shrub pollen was mainly xerophytic shrubs, with a proportion of approximately 10%; and the proportion of pollen content of trees was typically <5%, indicating that the regional vegetation was dominated by grassland throughout the study period (Fig. S3). The results of the quantitative climate reconstruction show that the modern Pann is 150 mm, which is slightly higher than the observed level of modern precipitation; however, dry and wet fluctuations are indicated in the record.

5.1.1. MWP and LIA (950–1900 CE)

The reconstructions show a generally drier period from 950 to 1300 CE, which corresponds to the MWP, and a wetter period from 1550 to 1900 CE, which corresponds to the LIA. Earlier results from ACA revealed similar changes in humidity over the past 1000 years. The grain size, chemical elements, and other sedimentary indicators from Lake Sasikul suggest a drier climate during the MWP and wetter conditions during the LIA (Lei et al., 2014) (Fig. 6d). These results are similarly supported by Chen et al. (2010), who integrated temporal and spatial changes in the effective humidity recorded by 17 different environmental indicators in ACA and established an effective humidity change sequence. Their results showed that ACA was generally warm and dry during the MWP but cold during the LIA (Fig. 6e). The same climatic development was reflected in the accumulation record of the Guliya ice

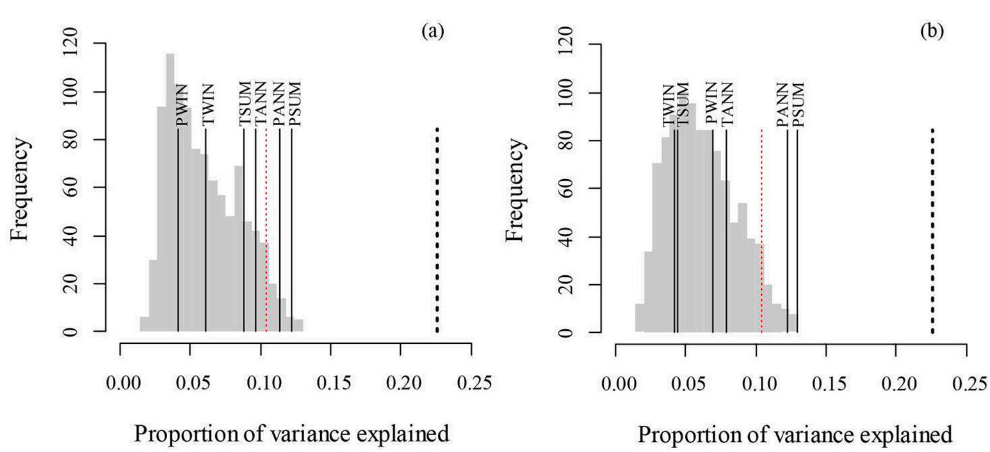

Fig. 4. Histogram of the proportion of the variance in the pollen records in cores SK-1 from Lake Sasikul which are explained by 999 calibration functions trained with a random environmental data set: Solid black lines indicate the proportion of the variance explained by different environmental variables. The red dotted line indicates the proportion of the variance below which 95% of the random data-trained calibration functions could explain. The black dotted line indicates the proportion of the variance explained by the first axis of a principal components analysis (PCA) of the fossil pollen data, representing the maximum proportion of the variance in the fossil data that could be explained by a single reconstruction. (a) using the SK-1 fossil data from Lake Sasikul and the entire 2696-sample calibration data set, (b) using the SK-1 fossil data from Lake Sasikul and the 927-sample subset (for the Pann reconstruction). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

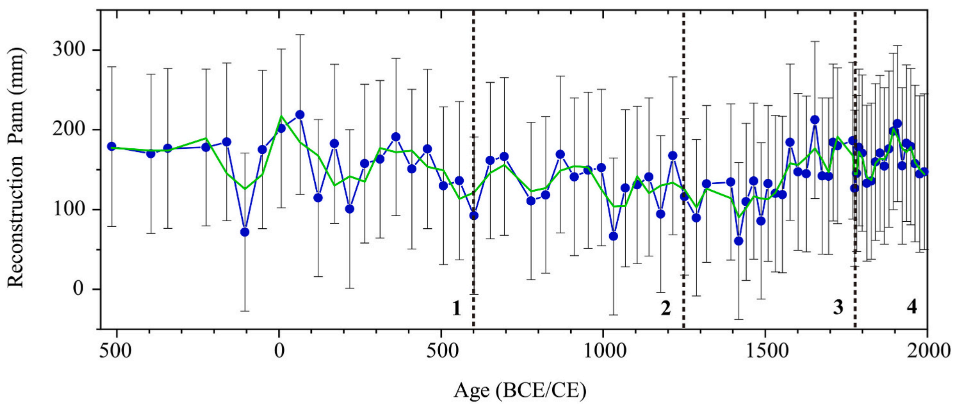

Fig. 5. Pollen-based Pann records (blue line) using SK-1 core fossil pollen and calibration data limited the average of Tann in Lake Sasikul to a range of ±2.5 °C; the green line is the five-point sliding result. The error bar is a line segment drawn in the direction representing the size of the reconstructed value, with the reconstructed precipitation amount as the midpoint, and half of the length of the line segment representing the uncertainty of the reconstruction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

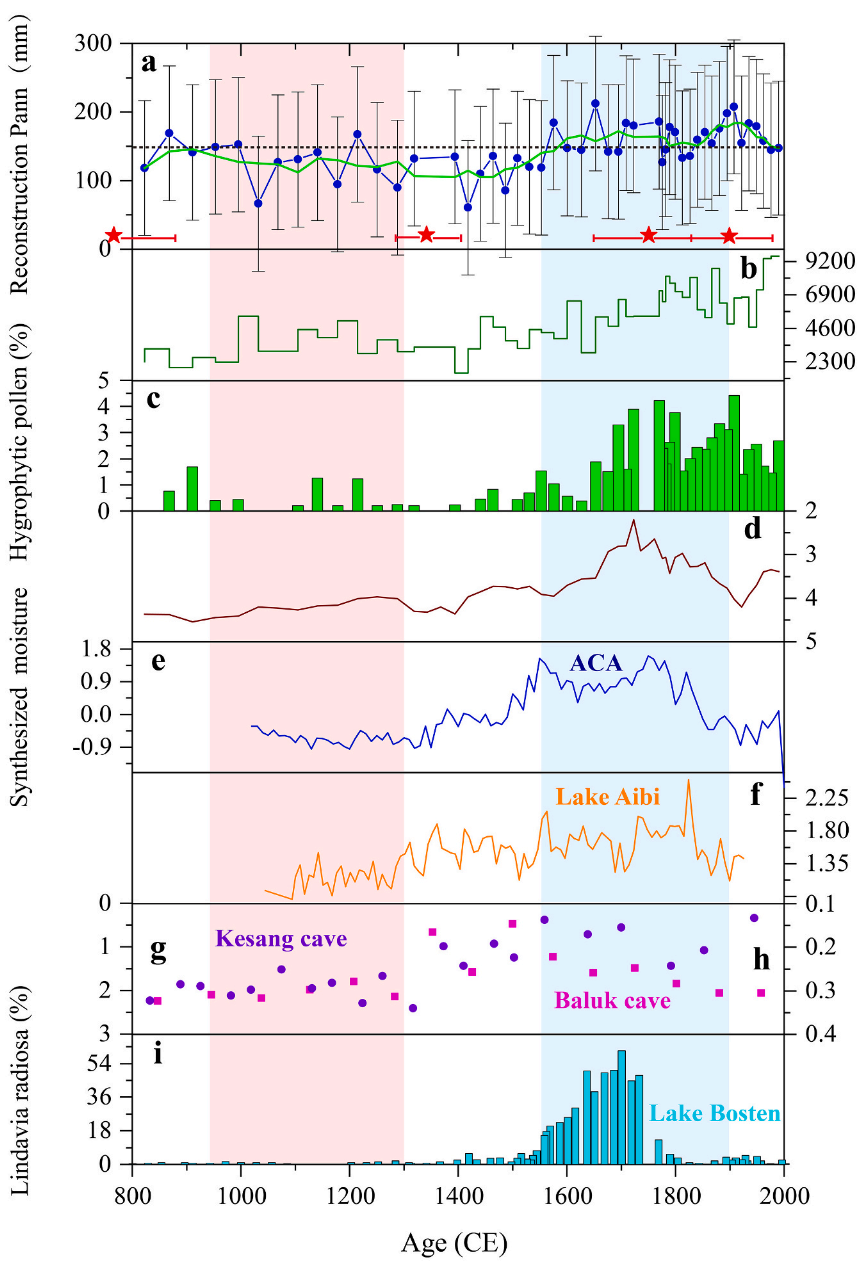

Fig. 6. (a-c) Pollen-based quantitative annual precipitation, the total pollen concentration and the percentage of hygrophytic herbaceous pollen of Lake Sasikul. (d) The total inorganic carbon content of Lake Sasikul (Lei et al., 2014). (e) Integrated water integration data for arid central Asia (Chen et al., 2010). (f) A/C ratio of Lake Aibi (Wang et al., 2013). (g) Speleothem Sr/Ca ratio (purple) from Kesang cave (Cheng et al., 2016). (h) Speleothem Sr/Ca ratio (pink) from Baluk cave (Liu et al., 2020). (i) Lindavia radiosa of Lake Bosten (Fontana et al., 2019). The red pentagram represents the location of the dating point in this study, and the red line represents the range of age error. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

core in the western Kunlun Mountains (Thompson et al., 1997), the A/C ratio of the pollen of Lake Aibi (Fig. 6f), the Sr/Ca ratio of Kesang Cave (Fig. 6g) and Baluk Cave (Fig. 6h), and the percentage of cold-adapted diatoms (*Lindavia radiosa*) in Lake Bosten, all of which are located in Xinjiang (Fig. 6i).

5.1.2. Recent warm period (1900 CE-present)

Our records indicate that the highest Pann value was recorded over the last 100 years. This is consistent with the grain size and oxygen isotope data from Lake Sasikul, thus suggesting that the lake level increased in the second half of the 20th century, whereas the area of Lake Sasikul increased since the 1970s (Lei et al., 2014). Remote-sensing images from 1977, 1992, 2001, and 2005 show that the lake area continued to expand since the late 1970s. The increase in humidity and the expansion of Lake Sasikul over the past 100 years are consistent with the monitoring data of other large lakes in ACA, such as the Caspian Sea (Hoogendoorn et al., 2005), Lake Issyk-Kul (Wang et al., 2006) and Lake Bosten (Wang et al., 2003), thus indicating an increase in lake area during the last 50 years.

The effect of human activities on the pollen data in the Lake Sasikul record is likely to be insignificant. The lake is located on the Pamir Plateau at an altitude of 3.8 km, which is not conducive to cultivation owing to the extremely cold climate, and its topography is extremely steep and rough, which does not support permanent settlement apart from erratic pastoralism and nomadism (Robinson, 2005). Furthermore, the high similarity between the reconstructed and instrumental Pann data for the most recent past (1920–1990 CE) (Fig. S4) further demonstrate the robustness of the proposed Pann reconstruction.

5.2. Westerlies-dominated climate regime of precipitation changes in ACA

In recent years, climate change in ACA has been intensively investigated. For example, Chen et al. (2008) proposed a 'westerlies-dominated climate regime', which refers to the inconsistency with the humidity evolution in the monsoon region based on the integrated results of 12 lakes in ACA. Chen et al. (2015a) integrated 71 palaeoclimatic records of humidity changes in China and its surrounding areas with good chronological control over the past millennium. The result shows that the 'westerlies-dominated climate regime' in the past millennium is applicable on a hundred-year scale. However, some climate records show a 'humid in the MWP and arid in the LIA' trend in ACA (Ma et al., 2008; Zhang et al., 2009; Hong et al., 2014). These records were mainly based on humidity indicators, whereas humidity was jointly controlled by temperature and precipitation. Therefore, in investigations pertaining to climate change in ACA, climate parameters should be separated to aid further understanding into the issues above and the 'westerlies-dominated climate regime'.

We conducted a comparative study of the results of precipitation reconstruction using pollen from ACA and the East Asian monsoon regions. Our results indicate that the quantitative reconstruction precipitation of Lake Sasikul is consistent with the humidity evolution model in the core area of the 'westerlies-dominated climate regime' (Chen et al., 2019b). However, Lake Gonghai in the East Asian monsoon region (Chen et al., 2015b) showed the opposite characteristics (humid in the MWP and dry in the LIA). This indicates that the ACA and East Asian monsoon regions experienced anti-phase precipitation evolution patterns on a hundred-year scale since the Late Holocene. Therefore, our results based on the reconstruction of pollen precipitation in ACA support the 'westerlies-dominated climate regime' pattern proposed by Chen et al. (2008, 2009, 2019b). Additionally, the results indicate that the ACA and East Asian monsoon regions not only exhibit anti-phase evolution patterns in terms of humidity, but also exhibit the same evolution pattern in terms of precipitation.

5.3. Possible effects of climate change on development of Silk Road civilization

Historically, the Silk Road has been the main route for cross-continental cultural exchange in Central Asia and was pivotal in promoting the evolution of human civilization. The main region of the Silk Road is located in ACA, which is one of the regions that is the most sensitive to global climate and environmental changes (Chen et al., 2017a, 2019a; An et al., 2017; Opała-Owczarek and Owczarek, 2019; Yang et al., 2019). The Silk Road begins and ends with Chang'an (now Xi'an) in China in the East and Rome in the West. This channel is segmented into eastern, middle, and western sections and is the most important trunk channel for transportation between China and the West (Yong, 2015). Lake Sasikul on the Pamir Plateau is located between the middle and western sections of the Silk Road. We combined the archaeological sites and documents of Xinjiang in the middle section of the Silk Road and those of Central Asia in the western section of the Silk Road to discuss the effects of regional precipitation (Fig. S5) and temperature change on the intensity of human activities and the evolution of the Silk Road civilization (Fig. 7).

In ACA, Silk Road was formed mainly by connecting oasis towns (Zhang et al., 2011). The development of oases is closely related to the availability of water resources, which mainly originate from land surface runoff and the flow of surrounding rivers (Sun et al., 2005; Deng et al., 2015; Fang et al., 2018; Tan et al., 2018). Ice and snow meltwater from high mountains, precipitation in mid-mountain forests, and fissure water in low mountain areas converge in the mountains and constitute the surface water resources in arid areas. In the northwestern arid inland river basins of China, ice and snow meltwater are important components of runoff and river flow (Chen et al., 2015c, 2019c; Zhang et al., 2016; Yao et al., 2022). Runoff and river flow are not only controlled by precipitation in the surrounding mountains (Liu et al., 2010; Yang et al., 2011; Sakai et al., 2012; Ding, 2015; Wu et al., 2015), but are also affected by temperature. Temperature can regulate the amount of ice and snow meltwater in spring and summer and control the evaporation intensity of the basin (Li et al., 2020, 2021), particularly in Xinjiang. >80% of runoff is from glaciers and melting snow in mountainous areas (Yang, 1987). This indicates that the interaction between climate and hydrology is vital to the cultural development and human activities in arid and arid semi-areas (Wu et al., 2015). Therefore, climatic factors (temperature or precipitation) with a more profound effect on the selection of human settlements, as well as the forms and intensity of human activities during the evolution of the Silk Road civilization must be investigated.

From 680 to 900 CE, which corresponds to the Sui and Tang Dynasties in China, the number of archaeological sites in Xinjiang, which is located in the middle of the Silk Road, was the highest in history (274 archaeological sites) (Fig. 7d); this indicates that the human settlement density was high and the Silk Road civilization was prosperous. Palaeoclimate records (Fig. 7a and b) show that the temperature in the region was relatively high (Esper et al., 2002, 2003; Liu et al., 2014), whereas the precipitation level was average (Fig. 7c). Higher temperatures may have increased the meltwater of ice and snow, which consequently may have increased river flow and runoff along the middle section of the Silk Road, thus promoting the development of the Silk Road civilization. Precipitation during this period was at the average level and might not have limited the evolution of the Silk Road civilization, which promoted human settlement, particularly in oasis areas (Zhang et al., 2011). In addition, abundant water resources may increase agricultural production, the population, and societal stability (Fig. 7e). We discovered that the development of the Silk Road civilization and the rapid development of the Yangshao culture in the Central Plains of China occurr under both a warm climate and abundant water resources (Dong et al., 2012; Chen et al., 2015b). However, the water resources in the Yangshao culture in the monsoon area of China were from abundant summer monsoon precipitation (Chen et al., 2015b; Zhang et al., 2021), whereas the water

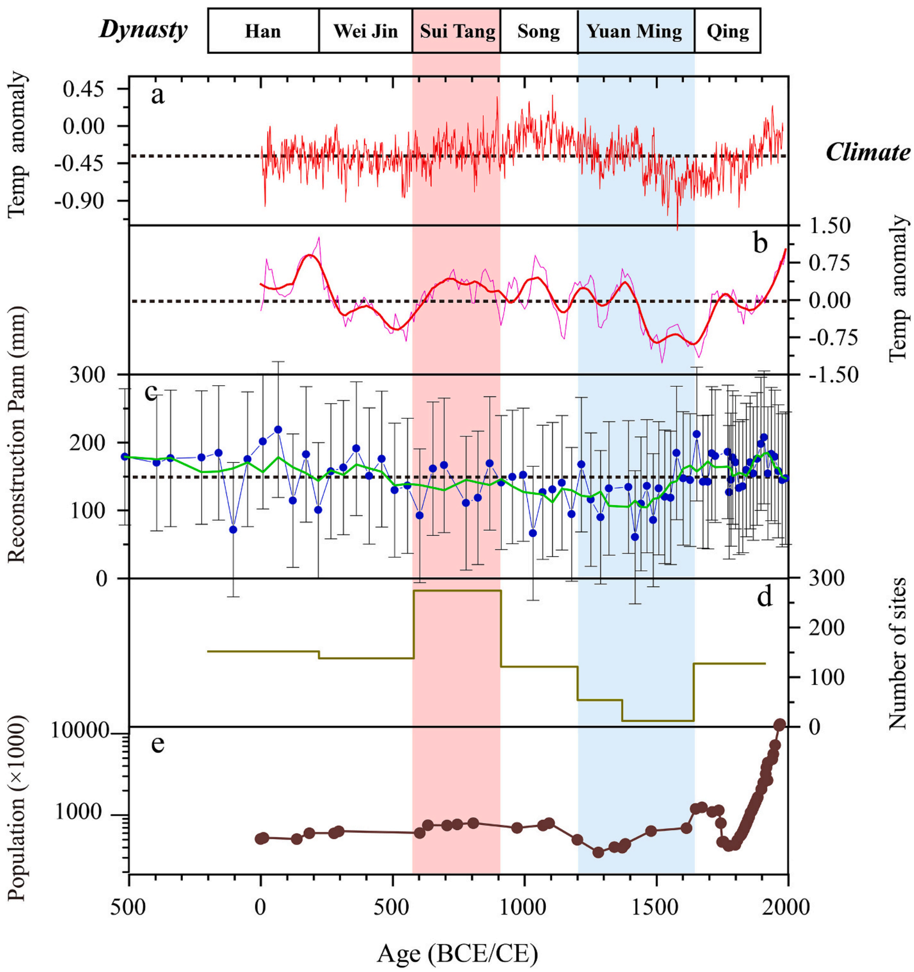

Fig. 7. (a) The temperature in the Northern Hemisphere reconstructed for the Northern Hemisphere for the past 2000 years by combining low-resolution proxies with tree-ring data (Moberg et al., 2005) and (b) The temperature in China (Yang et al., 2002), three alternate China-wide temperature composites covering the last 2000 years were established by combining multiple paleoclimate proxy records obtained from ice cores, tree rings, lake sediments and historical documents. (c) Pollen-based quantitative annual precipitation of Lake Sasikul. (d) Number of ancient archaeological sites of Xinjiang since 2 ka (National Bureau of Cultural Relics, 2012). (e) The population of in Xinjiang since 2 ka (Zhao and Xie, 1988).

resources in the Silk Road civilization were closely related to the meltwater of ice and snow. Additionally, many influential nomadic alliances were present on the vast grasslands in the western section of the Silk Road in Central Asia, whereas in the oasis-distributed areas, urbanization was highly developed, and the construction and handicraft industry had developed to a high level. Furthermore, the development of Islamic and Arab caliphs resulted in extensive cultural communication between civilizations (History of Civilization of Central Asia, 2010).

From 1270 to 1650 CE, i.e. during the Yuan and Ming Dynasties, the number of archaeological sites in Xinjiang decreased, representing the second lowest (54) and the lowest (12) in the historical period, respectively; this indicates that the density of human settlements in the region weakened and Silk Road civilization declined. At this time, the palaeoclimate records show that precipitation in the area was generally low (Fig. 7c) and the temperature (Fig. 7a and b) decreased (Esper et al., 2002, 2003; Liu et al., 2014). The decline in human settlements may have been due to the cold and dry climate and reduced river flow and runoff, which limited agricultural activity and increased social unrest and the frequency of wars, thus resulting in human migration and further weakening the intensity of local human settlements (Dong et al., 2017). At this time, Karez, which is a type of underground irrigation system in Central Asia, was required to provide irrigation, which significantly limited agricultural production and civilization development (History of Civilization of Central Asia, 2010). Inadequate water resources have affected human civilization in Asia. For example, the decline of the Harapa civilization in the Indus Valley in 4200 cal yr BP (Staubwasser et al., 2003) and the abandonment of the ruins of Panjikent on the Silk Road in northern Tajikistan from 900 to 1000 CE (Owczarek et al., 2018) are related to a continuous dry climate.

In addition to historical factors, water resources may be a key factor affecting the intensity of human settlement and the evolution of the Silk Road civilization. We believe that the precipitation and temperature conditions in climate factors have equally important effects on human activities and the evolution of the Silk Road civilization in ACA. In the context of global warming, precipitation in ACA will increase in the future, which can facilitate agricultural production and socioeconomic activities in the study area.

6. Conclusion

Based on the pollen analysis of Lake Sasikul on the Pamir Plateau and modern surface pollen data, we reconstructed precipitation over the last 2500 years in ACA using the WA-PLS method. The results were combined with regional temperature records and archaeological data to determine the possible effect of climate change on human activities and the development of the Silk Road civilization during the historical period. Our results showed that during the MWP, the pollen content of drought-tolerant Amaranthaceae reached its highest values. The average annual precipitation was 120 mm, which was approximately 15% lower than the level of modern precipitation, and the climate was relatively arid. During the LIA, the pollen contents of *Artemisia* and wetland herbs increased, the pollen content of coniferous trees such as *Picea* and *Abies* increased, and the average annual precipitation was 160 mm, which was approximately 20% higher than the level of modern precipitation. Thus, the climate was cold and humid. The results above showed that the ACA and East Asian monsoon regions not only exhibited anti-phase evolution patterns in terms of humidity, but also exhibited the same evolution pattern in terms of precipitation. The reconstruction of precipitation change of Lake Sasikul in the ACA is a typical 'westerlies-dominated climate regime' pattern.

Combining the above with regional temperature records and archaeological data, we discussed the possible effects of climate change on the development of Silk Road civilization. The results suggested that the effects of precipitation and temperature change on human activities and the development of the Silk Road civilization were equally important. The hydrothermal configuration might have altered the water resource and thus affected human activities in ACA. From 680 to 900 CE, i.e. during the Sui and Tang Dynasties, the Silk Road civilization flourished owing to the warm and moderately humid climate during that period. From 1270 to 1650 CE, i.e. during the Yuan and Ming Dynasties, the civilizations of the Silk Road declined gradually owing to the cold and dry climate during that period. Owing to global warming, regional precipitation has increased, which is conducive to the development of agriculture and social economy in ACA.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloplacha.2023.104142.

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