Climate-driven desertification and its implications for the Ancient Silk Road trade

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Abstract

The Ancient Silk Road played a crucial role in cultural exchange and commercial trade between western and eastern Eurasia during the historical period. However, the exchanges were interrupted in the early 16th century AD, during the Ming dynasty. Various causes for the decline of the Ancient Silk Road have been suggested. Among them, natural factors have not been adequately discussed as social aspects. In this study, we use evidence from a sedimentary site (XSW) in Dunhuang oasis, together with analysis of historical archives, to demonstrate the occurrence of extreme droughts and desertification events in the Dunhuang area post ~1450 AD and persisted for decades at least. The desertification may have closely associated with the accessibility of the ancient Silk Road in the area, which was responsible for a steep fall in the volume of trade as well as political chaos and mass migrations. Therefore, besides socio-economic factors, climate change may have played an important role in trade exchange between the Ming government and the West, and may even have influenced the rise and decline of the ancient Silk Road.

Keywords: Dunhuang; desertification; trade exchange; climate change; Ming dynasty

1. Introduction

The Ancient Silk Road was the most important link between nations in Eurasia from the 2nd century BC to the 16th century AD, and thus it indirectly shaped the politics, cultures and economies of populations across the Eurasian continent. The route not only linked commercial trade between the East and West but it also facilitated the spread of religion, technology and even diseases such as the plague (Jones et al., 2011; Chen et al., 2015; Schmid et al., 2015; Frankopan, 2015; An et al., 2017; Dong et al., 2017a; Hao et al., 2019; Afzaal, 2020). The Chinese section of the Ancient Silk Road passes through one of the driest regions on Earth and the logistical operation of the road depended directly on the oases that developed along the foot of the high mountain ranges (the Qilian, Kunlun and Tianshan), mainly as a result of precipitation supplied as streamflow from the highlands. Cities and towns emerged and developed in association with oases, such as Jiayuguan, Dunhuang, Hami and Ruoqiang, which functioned as logistical stations for trade between East and West along the Ancient Silk Road. The Jiayuguan Pass is at the western end of the Great Wall in the Ming dynasty. Located at the narrowest point of the Hexi Corridor, the Jiayuguan Pass was also a critical location on the primary routeway between the western Gobi Desert and the domains of the Ming dynasty. Dunhuang commandery was 300 km from the Jiayuguan Pass and the traffic hub which constituted the historic junction of several routes along the Ancient Silk Road in Central Asia (Huang, 2008). It passed to the control of the central government in 1372 AD, in the early Ming dynasty. As a routeway, the Ancient Silk Road reached a peak in the Tang dynasty (618–907 AD), but its importance declined substantially in the 16th century AD with the closure of the Jiayuguan Pass by the central government in China and the abandonment of Dunhuang city in the Ming dynasty (1368–1644 AD). This event was an important marker in terms of the severance of cultural exchange and trade between East and West, and the decline of the Ancient Silk Road as an historically important routeway.

Socioeconomic-related hypotheses have been proposed to explain the decline of the Ancient Silk Road during the later Ming Dynasty. For example, frequent wars in the Dunhuang area have been suggested (Chen, 2011; Li and Zheng, 2013). The Ming governor successively established seven garrisons, from the early Ming dynasty onwards, in the Jiayuguan-Dunhuang area and transferred the leadership to Mongolia which governed the seven garrisons in order to consolidate the frontier territory (Chen, 2000). In the Middle and Late Ming dynasty, national power declined due to political corruption and financial stresses, but the bordering nations such as Oirat and Turpan continued to expand (Zhang, 1974). Agri-nomadic wars (conflict between agriculturalists and nomads) and conflict between the seven garrisons and invasions by nomadic tribes in the Hexi

Corridor were frequent. The border policy of the administration weakened and there was a gradual isolation of the governance (Research Institute of History and Language of the Central Academy of Taiwan, 1962a; Zhang, 1974), and as consequence the seven-garrisons region, including Dunhuang city, was abandoned. The re-opening of the Maritime Silk Road in the southern part of Ming territory was suggested to be another cause of the interruption of the Ancient Silk Road on land (Xie et al., 2007; Qian and Jin, 2010; Zhai, 2017).

On the other hand, a pollen record from the sediments of Lake Tian'E in the Qilian Mountains reveals the occurrence of a distinctly drier climate during 1350–1600 AD, and therefore an environmental-related hypothesis has also been suggested for the decline of the Ancient Silk Road (Zhang et al., 2018). Previous high-resolution tree-ring records from the Qilian Mountains revealed the occurrence of drought in the Hexi Corridor during 1450–1550 AD (Gou et al., 2015a, b; Yang et al., 2014), corresponding to the onset of a cold climate during the Little Ice Age (LIA), during AD 1450–1850 (Mann et al., 2009). However, these tree ring and lake sediment records are from the eastern part of the Hexi Corridor, and there are no reliable paleoclimatic records from the Dunhuang area in the western part. Throughout human history, climate change has been regarded as an important and sometimes critical trigger for the rise and fall of ancient civilizations (Wang et al., 2018; Tan et al., 2021), such as in the cases of Mesopotamia (Weiss, 1993), the Maya (Kennett et al., 2012; Medina-Elizalde and Rohling, 2012; Nooren et al., 2018), Angkor (Buckley et al., 2010), and the decline of the Loulan Kingdom on the Ancient Silk Road (Fontana et al., 2019; Fig. 1).

In the present study, we focused on the role that paleoenvironmental variations may have played on the ancient Silk Road in the Duanhuang-Jiayuguan area, which in terms of the physical environment is the most inhospitable section of the Ancient Silk Road, being dominated by sandy and Gobi deserts. First, the results of a detailed sedimentary investigation of Xishawo site (near Dunhuang city) are presented and the paleoenvironmental change are evaluated. Second, the relevant available literature is reviewed and a sociopolitical analysis of the historical archives in Dunhuang and the surrounding areas and in Ming China are used to determine environmental and sociopolitical changes in the area during the study period. Finally, the influence of the natural environment on the trade exchange between the Ming dynasty and western countries, on the abandonment of the Dunhuang area, and on the official closure of the Ancient Silk Road in the early 16th century AD are reviewed.

2. Study area

The Hexi Corridor (92°21′to 104°45′E, 37°15′ to 41°30′N) is located to the north of the Qilian Mountains and south of Beishan Mountain. It is long and narrow and stretches for over 1,000 km from Wushaoling Mountain in the east to the boundary of Gansu and Xinjiang provinces in the west, but it extends for only tens to some hundreds of kilometers in the North-South direction (Fig. 1). The area corresponds to the zone of climatic interaction between arid Central Asia and monsoonal Asia and is climatically characterized by a continental-monsoon climate influenced by both the westerlies and the monsoon. The annual precipitation is no more than ~200 mm but the evaporation ranges from 1,500 mm to 3,000 mm (Huang et al., 2017). The annual temperature is ~0–10 °C. The Hexi Corridor consists of three independent landlocked river systems: the Shule River Basin, the Heihe River Basin, and the Shiyang River Basin, from west to east. The flow of the three rivers is generated by the glaciers of the Qilian Mountains and is consumed in the middle and lower reaches of Owase Lake or in the deserts within the basin. Diverse landscapes of mountains, oases, deserts and Gobi are alternately distributed in the area. The unique topography and location of the Hexi Corridor were largely responsible for its great strategic and military importance to historical dynasties over the past 2,000 years. It was also known as the key routeway (the Ancient Silk Road) for cultural and merchandise exchanges between Chinese and western countries for thousands of years ago until the present.

[Fig. 1 is near here]

The oasis ecological system in arid areas is fragile because of the closed environment, sparse vegetation and water scarcity. However, the bead-like distribution of oases played a crucial role in the exchange of merchandise in Eurasia. Jiayuguan city was the northwestern gateway of the Ming domain and a key fortress along the routeway of East-West economic exchange. Dunhuang city and Guazhou city (~120 km northeast of Dunhuang) are located in the eastern Gobi Desert to the west of the Jiayuguan pass (Fig. 1). The Ancient Silk Road split into three branches in a westerly direction from the region. The northern branch led to the northwest of Hami oasis and the oasis cities of Turfan, Yanqi, Qiuci and Gumo, and then to Central Asia. The central branch passed through Loulan city (300 km west of Dunhuang) which was abandoned in ~330 AD because of eolian activity (Yuan and Zhao, 1999; James, 2007; Fontana et al., 2019). The southern branch connected many cities along the southern edge of the Taklimakan Desert, such as Ruoqiang, Qiemo, and Yutian, on the northern piedmont of the Altyn-Tagh and the

Kunlun Mountains (Fig. 1). As can be seen in Fig. 1, the location of Dunhuang oasis led to its importance as the only logistical station between Hami oasis/Ruoqiang oasis and Jiayuguan oasis during the Ming dynasty.

The XSW section in this study is located near the ancient city of Xishawo in the modern Gobi Desert area of the Shule River Basin. The site is in the middle of the Dunhuang and Guazhou oasis, ~50 km northeast of Dunhuang city (Fig. 1). The Xishawo site was previously an ancient oasis with cultural sites, ancient cities and beacon towers. Relict river channels are present at several locations, although most of them are buried by sand dunes (Li, 1990; Cheng, 2007). The modern annual mean precipitation and annual mean temperature of the area are 45.3 mm and 8.8° C, respectively. Previous research has revealed that the Xishawo site was occupied during ~900–1400 AD, and the inhabitants consumed barley, broomcorn and foxtail millet during this period (Li et al., 2017). Wind-eroded landforms are common in the region as a consequence of the arid climate, sparse vegetation cover and frequent sandstorms. The exposed part of the XSW section is ~3-m thick and consists mainly of a sand dune which is fixed by the dead roots of *Salix* and therefore preserved. The surface of the profile was cleaned to remove contamination by modern sediments and plant roots. The stratigraphic description of XSW section from the top to 270-cm depth is as follows: (1) 0–10 cm, fine sand. (2) 10–46 cm, dark-gray paleosol, with a 4 cm–thick black cultural layer at 30–34 cm. (3) 46–100 cm, light-yellowish loess. (4) 100–125 cm, loess-like paleosol. (5) 125–185 cm, dark gray clay with Fe-Mn nodules. (6) 185–250 cm, yellow fine sand. (7) 250–270 cm, black silty clay. A total of 135 samples were collected at a 2-cm interval for measurements of weight loss-on-ignition (LOI), grain size, and element contents. One wood sample (at the depth of 10 cm, labeled XSW-10) and one charcoal sample (from the cultural layer at 32 cm, labeled XSW-32) were collected for accelerator mass spectrometry radiocarbon (AMS ^{14}C) dating. Two eolian samples for optically stimulated luminescence (OSL) dating from the fine yellow sand layer (188 cm and 248 cm, labeled XSW-188, XSW-248, respectively) were collected by hammering stainless-steel cylinders into the section vertically, which were immediately sealed with opaque tape after removal.

3. Methodology

3.1 Laboratory analyses

(1) Chronology

AMS ^{14}C and OSL dating were used to establish a chronological framework for the XSW section. The charcoal and wood samples for AMS ^{14}C dating was prepared by the acid-base-acid procedure at the MOE Key Laboratory in Lanzhou University and measured at the AMS ^{14}C dating laboratory of Peking University. The IntCal13 curve, Libby half-life of 5,568 years and OxCal 4.2 were used to calibrate all of the dates (Reimer et al., 2013). All ages reported are relative to 1950 AD (referred to as “cal BC” and “cal AD”).

OSL dating was conducted at the OSL Laboratory at the MOE Key Laboratory of Western China’s Environmental System, Lanzhou University. Two OSL dating samples were collected from the XSW section. The pretreatment procedure followed that described in Aitken (1998). OSL measurement of coarse-grained (90–125 μm) quartz were performed using an automated Risø TL/OSL DA-20 reader. Laboratory irradiation was carried out using $^{90}Sr/^{90}Y$ sources. The quartz OSL signal was detected by a photomultiplier tube through two 3-mm-thick Hoya U-340 filters and the K-feldspar IRSL signal was detected using a package of Corning7-59 and BG-39 filters. The purity of the quartz extracts was checked using the IR depletion ratio test (Duller et al., 2003). A single aliquot regenerative protocol (Murray and Wintle, 2003) was applied to quartz samples to obtain the equivalent dose (De). The concentrations of the radioactive elements uranium (^{238}U), thorium (^{232}Th) and potassium (^{40}K) were measured by neutron activation analysis (NAA) to calculate the dose rate. The cosmic ray contribution was calculated according to the burial depth and altitude of the samples (Prescott and Hutton, 1994). A water content of 10 ± 5 % was used to the calculate ages of sand-loess sediments.

(2) Analysis of climatic proxies

Measurements of LOI, grain size and element contents were made at the MOE Key Laboratory of Western China’s Environmental System Lanzhou University. LOI measurements were used to determine the organic matter content of the sediments. The measurements were made at a 2-cm interval and calculated as LOI_{550} (%)=$(m_{105}-m_{550})/m_{105}\times100\%$, where m_{105} is the sample weight after oven drying at 105°C, and m_{550} is the sample weight after combustion at 550°C for 4 hr in a muffle furnace.

Samples for grain-size analysis were pre-treated with 10% H_2O_2 and 10% HCL to remove organic matter and carbonates, respectively. The samples were then dispersed by ultrasonication with the addition of 10% sodium hexametaphosphate. Grain-size distributions were measured with a Malvern MS 2000 laser grain-size analyzer.

Samples for the analysis of element contents were pretreated as follows. All samples were oven-dried for 24 hr and then pulverized into a powder. About 4 g of powder was then pressed into a 4–6 mm–thick and 30 mm–diameter pellet under 30 t/m^2 of pressure. The major, minor and trace element contents were measured with a Magix PW2403

Wavelength-Dispersive XRF Spectrometer. Elemental concentrations of 0.1 ppm to 100% could be analyzed. Rb/Sr ratios were calculated for paleoenvironmental reconstruction.

3.2 Analysis of published paleoenvironmental records and documentary evidence for the region

(1) Previous paleoclimatic records from the region

All available high-resolution paleoclimatic records for the study area and the adjacent region were reviewed and compared. They include records of regional temperature, precipitation, and river flow. In addition, documentary evidence of climate change in the region during the Ming dynasty was investigated.

(2) Sociohistorical archives

Sociohistorical records such as of the politics and economic and military activity of the Ming dynasty were analyzed (Zhang, 1974; Chinese Military History Writing Group, 2003; Yu, 2003), together with sociohistorical records of the Jiayuguan-Dunhuang area.

4. Results and discussion

4.1. Effects of warfare on the Ancient Silk Road

The Jiayuguan-Dunhuang area experienced frequent political turmoil and conflicts in Ming dynasty (Zhang, 1974). Warfare in the northwestern part of the Ming domain was suggested to be the main cause for the repeated (twice) closure of the Jiayuguan Pass and the severance of the Ancient Silk Road (Gao and Zhang, 1989; Chen, 2011). The Jiayuguan Pass was established in 1372 AD in the early Ming dynasty to resist the remaining elements of the Yuan dynasty (1271–1368 AD), and the Hexi Corridor was under the total control of the Ming government during the Ming dynasty. In addition, the Ming dynasty government established seven garrisons in the west of Jiayuguan Pass to reduce pressure on the border (Zhang, 1974). The Jiayuguan Pass was not only a military fastness, but also the primary pass on the Ancient Silk road to the Western Regions.

In order to investigate the relationship between conflict and the closure of the Jiayuguan Pass, the frequency of agri-nomadic conflict in the Dunhuang area was estimated based on historical archives (Chinese Military History Writing Group, 2003; Yu, 2003). The incidence of agri-nomadic conflicts in the Hexi Corridor was also summarized for comparison (Fig. 2a). The classification of agri-nomadic conflict was adopted because it directly reflects the conflict between the central government and nomadic peoples. The frequency of tribute trade and the number of tribute states in the Western Regions are illustrated in Fig. 2b and 2c (Chinese Military History Writing Group, 2003; Yu, 2003). All of the data were grouped into 5-year intervals. It is evident that conflicts between agriculturalists and nomads occurred constantly from 1368 AD, in the early Ming dynasty, until 1520 AD. However, conflicts ceased in the Dunhuang area after 1520 AD, which shows that the final closure of the Jiayuguan Pass in 1539 AD substantially reduced the frequency of nomad incursions in the Dunhuang area. However, evidence is still needed to prove that agri-nomadic conflicts were responsible for the closures of the Jiayuguan Pass in 1524 AD and 1539 AD, and the decline of the Ancient Silk Road. For example, it is unclear why—if agri-nomadic conflicts no longer occurred after 1520 AD—the Jiayuguan Pass was closed decades later in 1539 AD. It is also unclear why there was a lull in political unrest and violence in the Dunhuang area from 1450 AD.

[Fig. 2 is near here]

Reference to Fig. 2b and 2c shows that tribute exchange between the Ming government and the Western Regions has no obvious relationship with the frequency of conflicts. The tribute trade frequency and the number of tribute states both reached a peak during 1400–1450 AD, but then decreased sharply after 1450 AD and subsequently maintained a low level. As Fig. 2a demonstrates, there were frequent agri-nomadic conflicts during 1400–1450 AD, which were followed by a truce which lasted for about 20 years. However, the tribute trade declined substantially during the truce (1450–1470 AD) and there was no obvious revival until the collapse of the Ming dynasty (Fig. 2b and Fig. 2c).

It has been determined that the Jiayuguan Pass – Dunhuang city route was the crucial routeway connecting the Western Region to the domestic territory during the Ming dynasty (Zhang, 1974). The absence of a relationship between the frequency of wars in the Dunhuang area and variations in the amount of tribute trade demonstrates that warfare was likely not the primary or single cause of the collapse of trade along the Ancient Silk Road. Moreover, war was not solely responsible for the closure of the Jiayuguan Pass. The first closure of the Jiayuguan Pass in 1524 AD may have been a consequence of wars in the Dunhuang area, although wars also occurred frequently during periods when trade flourished (1400–1450 AD) (Fig. 2a). However, subsequently there was a continuous state of peace in the Dunhuang area which lasted for decades and the city was only abandoned by the final closure of the Jiayuguan Pass in 1539 AD. Therefore, we conclude that warfare is not a tenable explanation for the decline of the Ancient Silk Road.

4.2. Influence of climate change on the Ancient Silk Road

4.2.1 Paleoclimatic record of the XSW section

The paleoclimatic record of the XSW section in the Dunhuang area was used to assess the possible role of climate change in the decline of the Ancient Silk Road. The results of the analysis of various climatically-sensitive parameters, together with the ^{14}C and OSL chronology, are illustrated in Fig. 3. The ^{14}C dates for the fine sand layer (XSW-10) and the cultural layer (XSW-32) are 499±10 cal yr BP (1440–1460 cal AD) and 701±27 cal yr BP (1224–1278 cal AD), respectively. The two OSL samples from the sand layer are dated to 2.6±0.2 ka (800±300 BC) and 2.8±0.2 ka (600±200 BC) (Table 2). Profiles of grain size, LOI and Rb/Sr ratio are shown in Fig. 3a, 3b, 3c and 3d, respectively. The increase in median grain size and of the >63 μm fraction indicate an arid environment and intense wind activity in the Dunhuang area during 800-600 BC and at ~1450 AD. The LOI record reflects variation in organic matter content and the Rb/Sr ratio of eolian sediments is positively correlated with weathering intensity. The Rb/Sr ratio of the two sand layers is very low (Fig. 3), and therefore the effects of weathering are minor (Gallet et al., 1996; Chen et al., 1999), suggesting that precipitation in the Dunhuang area was low during ~800–600 BC and after ~1450 AD. A comparison of the LOI and Rb/Sr profiles indicates that during 800–600 BC and after ~1450 AD, the organic matter content of the section was low and chemical weathering was weak. These results suggest the occurrence of overall arid conditions, frequent dust storms, and associated desertification events during 800–600 BC, i.e. the Spring and Autumn period (771–476 BCE) of the Eastern Zhou Dynasty, and after ~1450 AD (the Ming dynasty). These conditions would have been very unfavorable for human habitation of the area.

[Fig. 3 is near here]

The two desertification events recorded in the XSW section were not solely local events. A cold and dry climate at these times is also evident in palaeoclimatic records from the nearby Qilian Mountains and the Tibetan Plateau. A tree ring record from the Qilian Mountains suggests that precipitation was low during 900–550 BC (Yang et al., 2014). A pollen record from Juyanze lake indicates the low representation of tree pollen at the same time (Herzschuh et al., 2004). The $\delta^{18}O$ record from the Agassiz ice cap in the high Arctic indicates relatively low temperatures during ~800–600 BC (Lecavalier et al., 2017), which is correlative with records from the Guliya ice core in the Tibetan Plateau (Thompson et al., 1997). The timing of the second desertification event in the Dunhuang area, in ~1450 AD, coincides well with changes in a tree-ring record from mountains in the western Hexi corridor, which suggests an interval of persistent low precipitation during 1430–1540 AD (Fig. 2f, Gou et al., 2015a). An interval of reduced precipitation during this time is also widely recorded in other high-resolution tree ring records from the northern Tibetan Plateau (Gou et al., 2015b; Yang et al., 2014), and in the laminated sediments of Sugan lake in the western Qaidam Basin (Qiang et al., 2005). A decrease in global temperature at ~1450 AD has also been widely detected in high-resolution paleoclimatic records from various locations (Thompson et al., 1997; Wilson et al., 2016; Lecavalier et al., 2017), and is also recorded in historical documentary records from China (Ge et al., 2003). This evidence indicates the occurrence of two desertification events in the Dunhuang area and elsewhere, during ~800–600 BC and after ~1450 AD, which were related to regional-scale climatic and environmental deterioration.

As mentioned earlier, the oasis ecological system in arid regions is relatively fragile, with the major limiting factor being water availability (Qian and Jin, 2010). At the present time, vegetation survival in the oasis of the Hexi Corridor depends mainly on runoff from the Qilian Mountains, which is derived firstly from precipitation in the highlands and secondly from glacier meltwater (Liu et al., 2010; Yang et al., 2011; Sakai et al., 2012). The prominent long interval of reduced precipitation and temperature in the Qilian Mountains and in the Tibetan Plateau during ~800–600 BC and at ~1450 AD caused a large decrease in runoff to the lowlands of the Hexi Corridor, which in turn caused vegetation degradation and the extension of Gobi and sandy desert. Compared to other oasis cities along the Ancient Silk Road, which were much closer to the high mountain glaciers (above 4,500 m.a.s.l., Fig. 1) which provided a constant supply of meltwater, Dunhuang oasis was located much closer to the center of the Gobi, and therefore it experienced severe desertification which may have resulted in its abandonment.

4.2.2 Archaeological evidence of climate change in the Dunhuang area

The relatively dense distribution of prehistoric sites in the Hexi Corridor reflects the past intensity of human settlement in the area as well as the habitability of the surrounding environment (Bureau of National Cultural Relics, 2011; Yang et al., 2019). The Hexi Corridor was extensively settled from the Majiayao period (3300–2000 BC) (Li, 2011), and foxtail millet and broomcorn millet, which were domesticated in north China, were cultivated (Zhou et al., 2016; Dong et al., 2018). Innovations in agricultural technology facilitated the rapid development of Bronze cultures in the Hexi Corridor and the surrounding areas in the succeeding millennium (Dong et al., 2016; Zhou et al., 2016). However, there is a gap in radiocarbon dates during ~850–650 BC in the western Hexi

Corridor and eastern Xinjiang Province (Fig. A1), which suggests a hiatus in cultural evolution and exchange during this period. This hiatus corresponds well to the desertification event in in the Dunhuang area of the western Hexi Corridor during ~800–600 BC (Fig. 3). However, even though the climate fluctuated substantially in northwest China during the Bronze Age, human settlement was continuous in the eastern Hexi Corridor at the same longitude (Fig. A1), which suggests that human occupation of the Hexi Corridor was primarily determined by the environmental conditions.

The second desertification event occurred at ~1450 AD and is recorded both in the sand layer of the XSW profile and in the historical and cultural literature. The drought in the Dunhuang area at this time was described as “The wind shakes the Tamarix in thousands of miles of uninhabited land” and “the moon shines on the quicksand on each departed day” (Huang and Wu, 2008). The Yugur minority ancestors, who originally settled in the Duanhuang area, after the abandonment of Dunhuang, sang folk songs about the human migrations through the Jiayuguan Pass during the Ming dynasty (Chen, 2011). An epic of the migration of the Yugur minority history contains the following passage: “Violent winds swept livestock away, sand dunes submerged tents and houses, rivers dried up, grassland was devastated” (Wang, 1992; Editorial Group of a Brief History of the Yugur minority, 2008). From these descriptions it can be deduced that the prolonged drought at ~1450 AD may have led to the disappearance of the oasis. The altered eco-environment would have reduced the productivity of agriculture and animal husbandry, which would have caused a local food shortage. The deteriorated environment was very likely another cause of mass migration in addition to warfare. The changing geopolitical situation in the western Hexi Corridor and eastern Xinjiang Province was an important factor in the abandonment of the Dunhuang area by the Ming government, and the extreme and the persistent drought event after ~1450 AD may have intensified the social upheaval and chaos (Fig. 2d, blue triangles highlight mass migrations), which triggered this significant historical event. Notably, a significant relationship has been observed between decreased precipitation, wars and the abandonment of cultivated land in the region during the last 2,000 years (Li et.al. 2019).

4.2.3 Desertification events in the Ancient Silk Road area

Various indicators of climatic variations, wars and the tribute trade are plotted in Fig. 2 versus the chronological sequence of the Ming dynasty (1368–1644 AD). Under the premise that at ~1450 AD the environment was characterized by a cold and dry climate with intense sandstorms (Fig. 2e), low precipitation (Fig. 2f) and decreased streamflow (Fig. 2g), there is a possibility that climate change played a role on the tribute trade of the

Ancient Silk Road. There was an abrupt decrease in the frequency of tribute trade at ~1450 AD, but not during the two closures of the Jiayuguan Pass, in 1524 AD and 1539 AD (Fig. 2b and 2d). In addition, at this time there was a lull in conflicts in the Dunhuang area (Fig. 2a). Therefore, it is proposed that environmental deterioration likely contributed to the decline of the tribute trade and the cessation of hostilities. Climatic perturbations and environmental degradation may not necessarily be a direct trigger of a societal crisis, but they may instead result in institutional failure caused by the lack of a centralized response to an environmental crisis (Feng et al. 2019). Social disturbance associated with migrations and chaos in the Ming dynasty was likely an indirect consequence of environmental changes. For example, the consequences of a deteriorating environment would include the shrinkage of the habitat and farmland necessary for human survival, multiple waves of human migrations into the eastern part of the Hexi Corridor, and the shift of the frontier from Dunhuang to the Jiayuguan pass. Thus, the population decline in the Dunhuang area during the early Ming Dynasty was most probably a “domino effect” (Feng et al. 2019).

The influence of the desertification in ~1450 AD on the streamflow of the Qilian Mountains gradually decreased after the 1520s AD (Fig. g and Fig. h). However, the formation and evolution of an oasis is a long-term process (Stamp, 1961; Zhang and Hu, 2002; Li et al., 2016), and the ecological response of an oasis to climatic drying would not to be to disappear immediately (Fan, 1993). Moreover, it takes at least 15-20 years for the recovery of a degraded oasis following destruction by ~1-3 years of human activity (Zhang and Hu, 2002). Therefore, the regeneration of a degraded oasis would take much longer than a change in streamflow. Overall, it is suggested that the abrupt decrease in tribute exchange and prosperity, or even the decline of the ancient Silk Road, may have been affected by the deterioration of the environment along the routeway in the Ming dynasty (Fig. b and Fig. c).

We now address the issue of how the desertification at ~1450 AD in the Dunhuang oasis and adjacent regions may have affected the functioning of the Ancient Silk Road. First, trading in the arid environment of the Ancient Silk Road led to the increase in the importance of oasis cities. Camel caravans needed supplies of grain and water from an oasis as they traversed the extensive desert along the road. The desertification events recorded in the XSW section and in the adjacent regions indicate that Dunhuang oasis and Guazhou oasis were not functioning at ~1450 AD. This lengthened the distance from the Jiayuguan oasis in the Hexi Corridor to the western oasis in Xinjiang (Fig. 1). According to several researchers, camel caravans in deserts areas were able to travel a maximum distance of ~30 km/day (Shui, 1990; Wang et al., 2000). In addition, the metabolism of a domesticated camel will decrease within 20 days from the beginning of water deprivation (Chen, 1982). Under working conditions, camels can go for ~10–15 days without water under a mean ambient temperature of 35°C (Kataria et al., 2001). A camel caravan took 59 days to traverse the 1,400 km of the Taklimakan Desert in 1993 AD under modern climatic conditions, which are much more favorable than in ~1450 AD, and the maximum distance was 24 km in one day (Blackmore, 2000). The maximum distance for a caravan in the water-limited environment on the Silk Road was 30 km/day×15 days = 450 km. The distances of Hami, Ruojiang and Jiayuguan to Dunhuang, where are Gobi Desert without high mountains, are already close to or above this limit, which is barely sufficient for camel travel (shown by the dots in Fig. 1, near the Dunhuang and Shazhou oasis). On the other hand, the distances between the oases along the routes on the piedmonts of the high mountain ranges (Qilian, Kunlun and Tianshan) are generally less than 200 km as the high mountain ranges provide meltwater. After the desertification event, the distances between Jiayuguan and Hami oases (the northern route of the ancient Silk Road) and between Jiayuguan and Ruoqiang oases (the southern route) increased to ~600 km and ~1,000 km, respectively. This is close to the maximum distance that a camel caravan can achieve (~450 km) without a water supply, and would have substantially increased the difficulty of travel across the region and was likely to be the physical cause of the decline of the Ancient Silk road during the periods of desertification.

5. Conclusion

We have systematically investigated a possible climatic cause of the interruption of the operation of the Ancient Silk Road during the Ming Dynasty. A compilation of the results of absolute dating and high-resolution paleoclimatic records from the SXW site in the Dunhuang area, and historical archives, reveals that two desertification events occurred, at ~800–600 BC and ~1450 AD. The later desertification event was consistent with the immediate fall in tribute trade that occurred in ~1450 AD, which indicates that environmental deterioration may have disrupted the trading exchanges by draining the oases in Dunhuang and Guazhou city, which were strategic logistical stations in the vast Gobi Desert. This resulted in travelling distances between supply stations exceeding the physical limit for camel caravans and an irreversible decline in trade exchange. On the other hand, the incidence of agri-nomadic conflicts from historical archives suggests that warfare alone is not the best explanation for the severance of exchanges between Western countries and the Ming government. Hence, we propose that climate change also played a potentially important role in explaining the decline of the Ancient Silk Road trade.

Acknowledgements

We thank Dr. Teng Li and Dr Shengda Zhang for their suggestions and discussions which inspired this study. We also thank Dr Jan Bloemendal for improving the English. This work was supported by the National Key R&D Program of China (2018YFA0606402), the National Natural Science Foundation of China (41825001, 41971110, 41901098)

References

Afzaal, M.: Silk Road to Belt Road: reinventing the past and shaping the future. Asia Pac. Bus. Rev., 26, 104-107, 2020.

An, C. B., Wang, W., Duan, F. T., Huang, W., and Chen, F. H.: Environmental changes and cultural exchange between East and West along the Silk Road in arid Central Asia. Acta Geogr. Sin., 72, 875-891, 2017 (In Chinese).

Bureau of National Cultural Relics: Atlas of Chinese Cultural Relics-Fascicule of Gansu Province, Surveying and Mapping Press, Beijing, 2011 (In Chinese).

Blackmore, C.: Crossing the Desert of Death: Through the Fearsome Taklamakan. John Murray press, London, 2000.

Chen, C.: Annals of the western vassal states, China Publishing House, Beijing, 2000 (in Chinese).

Chen, F. H., Dong, G. H., Zhang, D. J., Liu, X. Y., Jia, X., An, C. B., Ma, M. M., Xie, Y. W., Barton, L., Ren, X. Y., Zhao, Z. J., Wu, X. H., and Jones, M. K.: Agriculture facilitated permanent human occupation of the Tibetan Plateau after 3600 BP, Science, 347, 248-250, 2015.

Chen, G. W.: Research on the abandonment of the Dunhuang during Ming Dynasty. J. Dunhuang Stud., 60, 111-118, 2011 (In Chinese).

Chen, J., An. Z. S., and Head, J.: Variation of Rb/Sr ratios in the loess-paleosol sequences of central China during the last 130,000 years and their implications for monsoon paleoclimatology, Quat. Res., 51, 215-219, 1999.

Chen, Z.: Determination of hunger and thirst tolerance of camel. Animal husbandry and veterinary, 2, 56-58, 1982 (in Chinese).

Chen, Z.L.: Ming Jing Shi Wen Bian, China Publishing House, 1962 (in Chinese).

Cheng, H.Y.: The Desertification of the Hexi Area in Historical Time. Lanzhou University, Doctoral Dissertation, 2007 (In Chinese with English abstract).

Chinese Military History Writing Group: Chronology of China’s Ancient War, People’s Liberation Army press, Beijing, China, 2003 (in Chinese).

Dreyer, E.L. Zheng He: China and the oceans in the early Ming dynasty, 1405-1433. Pearson Longman, 2006.

Dong, G. H., Ren, L. L., Jia, X., Liu, X. Y., Dong, S. M., Li, H. M., Wang, Z. X., Xiao, Y. M., and Chen, F. H.: Chronology and subsistence strategy of Nuomuhong Culture in the Tibetan Plateau. Quatern. Int., 426, 42-49, 2016.

Dong, G. H., Yang, Y. S., Liu, X. Y., Li, H. M., Cui, Y. F., Wang, H., Chen, G. K., Dodson, J., and Chen, F. H.: Prehistoric trans-continental cultural exchange in the Hexi Corridor, northwest China. Holocene, 28(4), 621-628, 2018.

Editorial Group of a Brief History of the Yugur minority: Brief history for Yugur minority, The Ethnic Publishing House, Beijing, 2008 (in Chinese).

Fan, Z.L.: A study on the formation and evolution of Oases in Tarim Basin, Acta Geographica Sinica, 48: 421-427, 1993.

Feng, Q., Yang, L., Deo, R. C., AghaKouchak, A., Adamowski, J. F., Stone, R., Yin, Z. L., Liu, W., Si, J. H., Wen, X. H., Zhu, M., Cao, S. X.: Domino effect of climate change over two millennia in ancient China’s Hexi Corridor, Nat. Sustain., 2, 957-961, 2019.

Fontana, L., Sun, M. J., Huang, X. Z., and Xiang, L. X.: The impact of climate change and human activity on the ecological status of Bosten Lake, NW China, revealed by a diatom record for the last 2000 years, Holocene, 29, 1871-1884, 2019.

Frankopan, P.: The silk roads: A new history of the world. Bloomsbury Publishing, 2015.

Gallet, S., Jahn, B.M., and Torii, M.: Geochemical characterization of the Luochuan loess-paleosol sequence, China, and paleoclimatic implications, Chem. Geol., 133, 67-88, 1996.

Gao, F. S., and Zhang, J. W.: Jiayuguan Pass and the Great Wall of Ming dynasty, Heritage Press, 1989 (in Chinese).

Ge, Q. S., Zheng, J. Y., Fang, X. Q., Man, Z. M., Zhang, X. Q., Zhang, P. Y., and Wang, W. C.: Winter half-year temperature reconstruction for the middle and lower reaches of the Yellow River and Yangtze River, China, during the past 2000 years. Holocene, 13, 933-940, 2003.

Gou, X. H., Gao, L. L., Deng, Y., Chen, F. H., Yang, M. X., and Still, C.: An 850-year tree-ring-based reconstruction of drought history in the western Qilian Mountains of northwestern China. Int. J. Climatol., 35, 3308-3319, 2015a.

Gou, X. H., Deng, Y., Gao, L. L., Chen, F. H., Cook, E., Yang, M. X., and Zhang, F.: Millennium tree-ring reconstruction of drought variability in the eastern Qilian Mountains, northwest China. Clim. Dyn., 45, 1761-1770, 2015b.

Gu, Y.T.: The major events of Ming history, China publishing House, 1977.

Hao, Z.X., Zheng, J.Y., Yu, Y.Z., Xiong, D.Y., Liu, Y., Ge, Q.S.: Climatic changes during the past two millennia along the Ancient Silk Road. Progress in Physical Geography: Earth and Environment. 44(5), 605-623, 2020,

Herzschuh, U., Tarasov, P., Wünnemann, B., and Hartmann, K.: Holocene vegetation and climate of the Alashan Plateau, NW China, reconstructed from pollen data. Palaeogeogr. Palaeoclimatol. Palaeoecol., 211, 1-17, 2004.

Huang, S., Feng, Q., Lu, Z.X., Wen, X.H., and Deo, R.C.: Trend Analysis of Water Poverty Index for Assessment of Water Stress and Water Management Polices: A Case Study in the Hexi Corridor, China. Sustainability, 9, 756, 2017.

Huang, W. W., and Wu, S. G.: New Local Records of Suzhou. China Publishing House, Beijing, 2008.

James, A. M.: Eurasian Crossroads: A history of Xinjiang. Columbia University Press, New York, 2007.

Jones, M.K., Hunt, H., Lightfoot, E., Lister, D., Liu, X.Y., and Matuzeviciute, G.M.: Food globalization in prehistory, World Archaeol., 43, 665-675, 2011.

Kataria, N., Kataria, A. K., Agarwal, V.K., Garg, S.L., and Sahani, M.S.: Filtered and excreted loads of urea in different climatic conditions and hydration states in dromedary camel. J. Camel. Pract. Res., 8, 203-207, 2001.

Lecavalier, B. S., Fisher, D. A., Milne, G. A., Vinther, B. M., Tarasov, L., Huybrechts, P., Lacelle, D., Main, B., Zheng, J., Bourgeois, J., and Dyke, A. S.: High Arctic Holocene temperature record from the Agassiz ice cap and Greenland ice sheet evolution, Proc. Natl. Acad. Sci., 114, 5952-5957, 2017.

Li, B.C.: Study on Desertification of Hexi Corridor in historical period, China. Beijing: Science Press, 2003. (in Chinese),

Li. B.C.: Investigation on the Ancient Ruins in the Western Sandy land of Minqin County. J. Desert Res., 1990 (in Chinese with the English abstract).

Li, H.M., Liu, F.W., Cui, Y.F., Ren, L.L., Storozum, M.J., Qin, Z., Wang, J., Dong, G.H.: Human settlement and its influencing factors during the historical period in an oasis-desert transition zone of Dunhuang, Hexi Corridor, northwest China. Quatern. Int., 113-122, 2017.

Li, J., and Zheng, B. L.: Historical geography of Dunhuang. Gansu Education Press, Lanzhou, 2013 (In Chinese).

Li, Y.P., Ge, Q. S., Wang, H. J., Liu, H. L., and Tao, Z. X.: The relationships between climate change, agricultural development and social stabilities in Hexi Corridor over the last 2000 years. Sci. China Earth Sci., 62, 1453-1460, 2019.

Li, S.C., The Report of Prehistoric Archaeology Survey in The Hexi Corridor, Cultural Relics Press, Beijing, 2011 (in Chinese).

Li, X., Yang, K., Zhou, Y.: Progress in the study of oasis-desert interactions. Agr. Forest Meteorol., 230-231, 1-7, 2016.

Liang, F.Z.: International trade and silver import and export of Ming Dynasty, China Publishing House, Beijing, 1989.

Liu, Y., Sun, J., Song, H., Cai, Q., Bao, G., and Li, X.: Tree-ring hydrologic reconstructions for the Heihe River watershed, western China since AD 1430. Water Res., 44, 2781-2792, 2010.

Liu, Y.S.: The Silk Road, Jiangsu People's Publishing House, 2014.

Mann, M. E., Zhang, Z. H., Rutherford, S., Bradley, R. S., Hughes, M. K., Shindell, D., Ammann, C., Faluvegi, G., and Ni, F.B.: Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly, Science, 326, 1256-1260, 2009.

Qiang, M.R., Chen, F.H., Zhang, J.W., Gao, S.Y., and Zhou, A.F.: Climatic changes documented by stable isotopes of sedimentary carbonate in Lake Sugan, northeastern Tibetan Plateau of China, since 2 ka BP. Chinese Sci. Bull., 50, 1930-1939, 2005.

Qian, Y., and Jin, H. L.: Study on Oasis along the Silk Road, Xinjiang people's publishing house, 2010 (in Chinese).

Reimer, P. J., Bard, E., Bayliss, A., Beck. J. W., Blackwell, P. G., Ramsey, C. B., Buck, C. E., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P., Haflidason, H., Hajdas, I., Hatte, C., Heaton, T. J., Hoffmann, D. L., Hogg, A. G., Hughen, K. A., Kaiser, K. F., Kromer, B., Manning, S. W., Niu, M., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Staff, R. A., Turney, C. S., and Plicht, J. V. D.: IntCal13 and Marine13 radiocarbon age calibration curves 0-50,000 years cal BP. Radiocarbon, 55, 1869-1887, 2013.

Research Institute of History and Language of the Central Academy in Taiwan: Ming Taizu Shilu. Taiwan, 1962b.

Research Institute of History and Language of the Central Academy in Taiwan: Ming Yingzong Shilu. Taiwan, 1962a.

Sakai, A., Inoue, M., Fujita, K., Narama, C., Kubota, J., Nakawo, M., and Yao, T.: Variations in discharge from the Qilian mountains, northwest China, and its effect on the agricultural communities of the Heihe basin, over the last two millennia. Water Ecol., 4, 177-196, 2012.

Schmid, B.V., Büntgen, U., Easterday, W.R., Ginzler, C., Walløe, L., Bramanti, B., and Stenseth, N.C.: Climate-driven introduction of the Black Death and successive plague reintroductions into Europe. Proc. Natl. Acad. Sci., 112, 3020-3025, 2015.

Shui, S.: A discussion on the thirst-resisting ability of camel. J. Inner Mongolian College of Agriculture and Animal Husbandry, 11, 55-59, 1990 (In Chinese).

Stamp, L.D.: A history of land use in arid regions. Literary Licensing, LLC. 1961.

Tan, L.C., Dong, G.H., An, Z.S., Edwards, R.L., Li, H.M., Li, D., Spengler, R., Cai, Y.J., Cheng, H., Lan, J,H., Orozbaev, R., Liu, R.L., Chen, J.H., Xu, H., Chen, F.H., Megadrought and cultural exchange along the proto-Silk Road. Science Bulletin, 2021. 66(6): 603-611. Doi:10.1016/j.scib.2020.10.011.

Thompson, L.O., Yao, T., Davis, M.E., Henderson, K.A., Mosley-Thompson, E., Lin, P. N., Beer, J., Synal, H.A., Cole-Dai, J., and Bolzan, J.F.: Tropical climate instability: The last glacial cycle from a Qinghai-Tibetan ice core. Science, 276, 1821-1825, 1997.

Wang, S.C.: The chronology of humanistic and environmental change during historical period in Hexi Corridor and neighbouring areas, China. In “Environment change and the rise and fall of human civilization in arid areas of northwest China”, Yin, Z. S., eds. Geological Publishing House, Beijing, 1992 (In Chinese).

Wang, Y., Li, L. J., and Zhang, W.G.: Exchange history of Eurasia. Lanzhou University Press, Lanzhou, 1-17, 2000 (In Chinese).

White, S., Pei, Q.: Attribution of historical societal impacts and adaptations to climate and extreme events: integrating quantitative and qualitative perspectives. Climate reconstruction and impacts from the archives of societies, 2, 44-45, 2020.

Wilson, R., Anchukaitis, K., Briffa, K. R., Büntgen, U., Cook, E., D'Arrigo, R., Davi, N., Esper, J., Frank, D., Gunnarson, B., Hegerl, G., Helama, S., Klesse, S., Krusic, P. J., Linderholm, H. W., Myglan, V., Osborn, T. J., Rydval, M., Schneider, L., Schurer, A., Wiles, G., Zhang, P., and Zorita, E.: Last millennium northern hemisphere summer temperatures from tree rings: Part I: The long term context. Quat. Sci. Rev., 134, 1-18, 2016.

Xie, Y., Ward, R., Fang, C., and Qiao, B.: The urban system in West China: A case study along the midsection of the ancient Silk Road - He-Xi Corridor. Cities, 24, 60-73, 2007.

Yang, B., Qin, C., Bräuning, A., Burchardt, I., and Liu, J. J.: Rainfall history for the Hexi Corridor in the arid northwest China during the past 620 years derived from tree rings. Int. J. Climatol., 31, 1166-1176, 2011.

Yang, B., Qin, C., Shi, F., and Sonechkin, D.M.: Tree ring-based annual streamflow reconstruction for the Heihe River in arid northwestern China from AD 575 and its implications for water resource management. Holocene, 22, 773-784, 2012.

Yang, B., Qin, C., Wang, J., He, M., Melvin, T.M., Osborn, T.J., and Briffa, K.R.: A 3,500-year tree-ring record of annual precipitation on the northeastern Tibetan Plateau. Proceedings of the National Academy of Sciences, 111, 2903-2908, 2014.

Yang, Y.S., Zhang, S.J., Oldknow, C., Qiu, M.H., Chen, T.T., Li, H.M., Cui, Y.F., Ren, L.L., Chen, G.K., Wang, H., and Dong, G.H.: Refined chronology of prehistoric cultures and its implication for re-evaluating human-environment relations in the Hexi Corridor, northwest China. Science China Earth Sciences, 62, 2019. https://doi 10.1007/s11430-018-9375-4.

Yu, T.: A Complete History of the Western Regions. Zhongzhou Ancient Books Publishing House Co., Ltd., Zhengzhou, 2003 (in Chinese).

Yuan, G.Y., and Zhao, Z.Y.: Relationship between the rise and decline of ancient Loulan town and environmental changes, Chinese Geogr. Sci., 9, 78-82, 1999.

Zhang, J., Huang, X., Wang, Z., Yan, T., and Zhang, E.: A late-Holocene pollen record from the western Qilian Mountains and its implications for climate change and human activity along the Silk Road, Northwestern China. Holocene, 28, 1141-1150, 2018.

Zhang, Q., Hu, Y.Q.: The geographical features and climatic effects of oasis. Adv. Earth Sci., 17(4), 2002.

Zhang, T.Y.: History of Ming dynasty. China Publishing House, Beijing, 1974 (in Chinese).

Zhai, S.D.: The changes of the beacon flint and the land Silk Road in Dunhuang. Gansu Social Sci., 05, 135-140, 2017 (In Chinese).

Zheng, Y.J.: On Zheng He’s voyage. Ocean Press, China, 1985 (In Chinese).

Zhou, X.Y., Li, X.Q., Dodson, J., and Zhao, K.L.: Rapid agricultural transformation in the prehistoric Hexi corridor, China. Quatern. Int., 426, 33-41, 2016.

Zhou, W.Z., and Ding, J.T.: Dictionary for the ancient Silk Road. People's publishing house in Shaanxi Province, Xi’an, 2016 (In Chinese).

Figure captions

Figure 1. Location of the study area and cities along the Ancient Silk Road (dotted circles are oasis cities which were already abandoned before the Ming dynasty; solid circles are oasis cities which still existed during the Ming dynasty; the cities in parentheses were under Ming governorship; the dotted area is Gobi Desert near Dunhuang and Guazhou) (The base map was captured from ©Google Maps)

Figure 2. Comparison of records of wars, climate change and cultural events in the Dunhuang area during the Ming-Qing dynasties. (a) Frequency of agri-nomadic wars in the Dunhuang area. (b) Tribute trade through the Jiayuguan Pass between the Ming government and Western countries. (c) Number of tribute states of Western countries. (d) Major events in the Ming dynasty (blue triangles are mass migrations; red triangles indicate the closure of the Jiayuguan Pass; the green triangle indicates the abandonment of Dunhuang city). (e) Grain size (>63-μm fraction) of the XSW section (this study). (f) Tree-ring based precipitation record from the western Qilian Mountains (after smoothing) (Gou et al., 2015a). (g) Tree-ring based streamflow record from the upper reaches of the Heihe River (after smoothing) (Yang et al., 2012).

Figure 3. Lithology, ^{14}C and OSL ages, and climatic proxies for the XSW section. (a) Median grain size (Md). (b) >63-μm fraction. (c) Loss on ignition (LOI). (d) Rb/Sr ratio.

Table captions

Table 1. Radiocarbon dating results for the Xishawo (XSW) section

Table 2. OSL dating results for the Xishawo (XSW) section

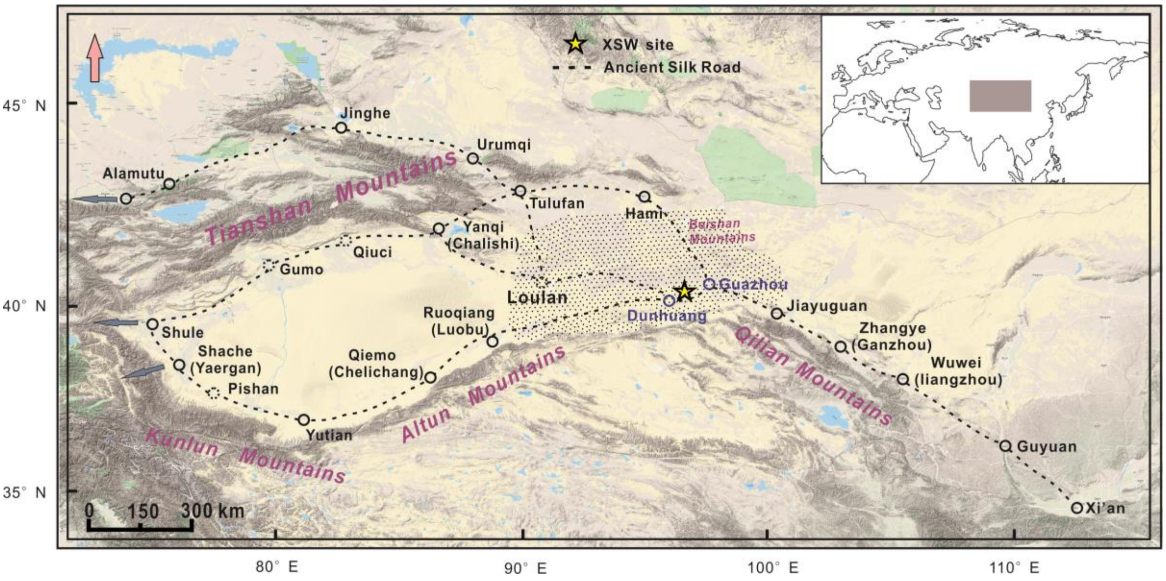
XSW site
Ancient Silk Road
45° N
40° N
35° N
80° E
90° E
100° E
110° E
0 150 300 km
Alamutu
Jinghe
Urumqi
Tulufan
Hami
Tianshan Mountains
Beishan Mountains
Yanqi (Chalishi)
Qiuci
Gumo
Loulan
Guazhou
Dunhuang
Jiayuguan
Zhangye (Ganzhou)
Wuwei (liangzhou)
Guyuan
Xi'an
Shule
Shache (Yaergan)
Pishan
Yutian
Qiemo (Chelichang)
Ruoqiang (Luobu)
Altun Mountains
Qilian Mountains
Kunlun Mountains

Figure 1.

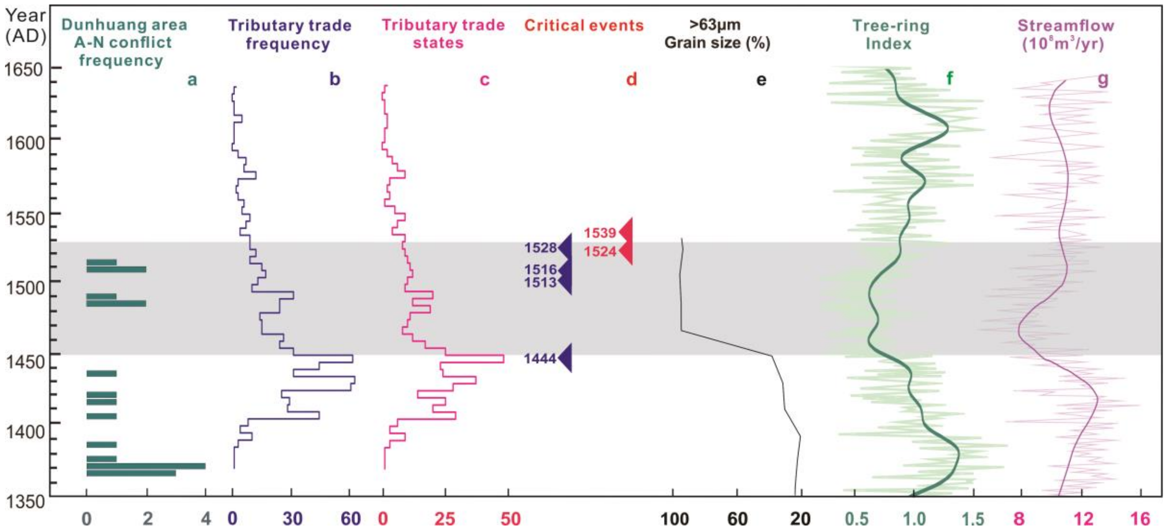
Year (AD)
Dunhuang area A-N conflict frequency
Tributary trade frequency
Tributary trade states
Critical events
>63μm Grain size (%)
Tree-ring Index
Streamflow (10^8m^3/yr)
a
b
c
d
e
f
g
1650
1600
1550
1500
1450
1400
1350
1539
1528
1524
1516
1513
1444
0
2
4
0
30
60
0
25
50
100
60
20
0.5
1.0
1.5
8
12
16

Figure 2.

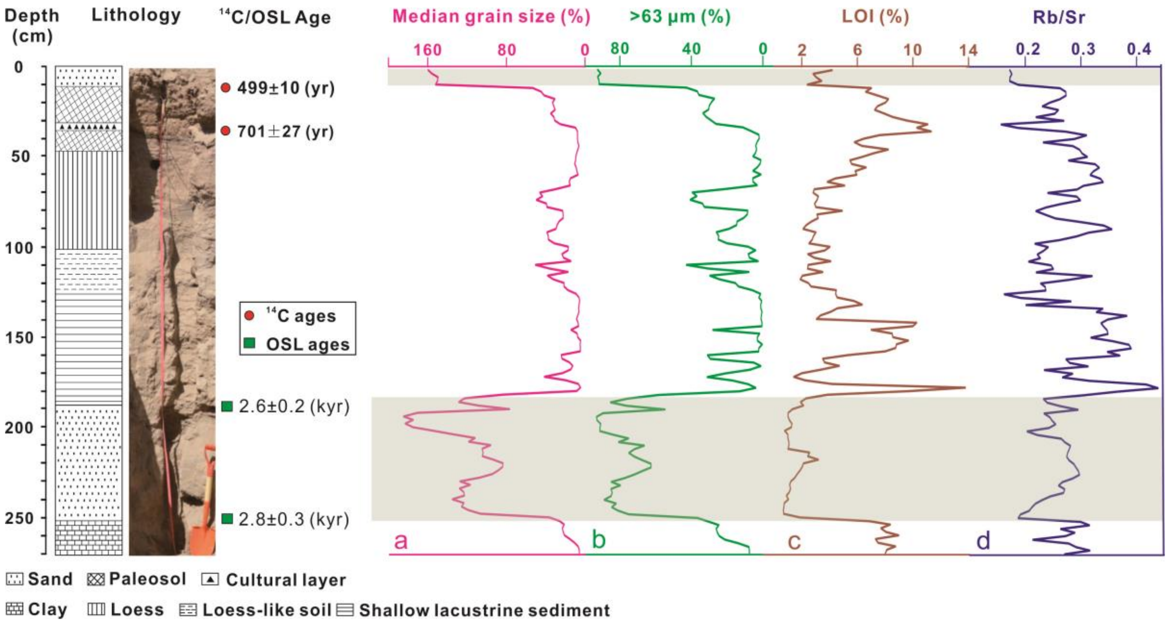
Depth (cm)
Lithology
14C/OSL Age
0
50
100
150
200
250
499±10 (yr)
701±27 (yr)
14C ages
OSL ages
2.6±0.2 (kyr)
2.8±0.3 (kyr)
Median grain size (%)
160
80
0
>63 μm (%)
80
40
0
LOI (%)
2
6
10
14
Rb/Sr
0.2
0.3
0.4
a
b
c
d
Sand
Paleosol
Cultural layer
Clay
Loess
Loess-like soil
Shallow lacustrine sediment

Figure 3.

Table 1.

Lab No.	**materials**	**Conventional ^{14}C age (yrs BP)**	**Calibrated ages (yrs BP)/AD**	
			2σ (95.4%)	
LZU127	Tree bark	425±15	499±10 （478-514）	1440-1460 AD
LZU1417	charcoal	765±40	701±27 （659-760）	1190-1291AD

Table 2.

Lab No.	Depth (cm)	Grain size (μm)	De (Gy)	OD (%)	U (ppm)	Th (ppm)	K (%)	Cosmic dose rate (Gy/ka)	Dose rate (Gy/ka)	Age (ka)
XSW-170	170	90-125	4.4±0.2	3.9	1.43±0.06	4.72±0.17	0.98±0.04	0.20	1.7±0.1	2.6±0.2
XSW-235	235	90-125	5.1±0.4	16.9	1.46±0.06	5.03±0.18	1.10±0.04	0.18	1.8±0.1	2.8±0.3

Appendix A

Fig. A1. Comparison of the longitude and median dates of Bronze Age cultural sites in the western Hexi corridor and eastern Xinjiang Province. The purple rectangle corresponds to an absence of dates in the western Hexi Corridor and Xinjiang province. The purple line shows the longitude of the XSW section.

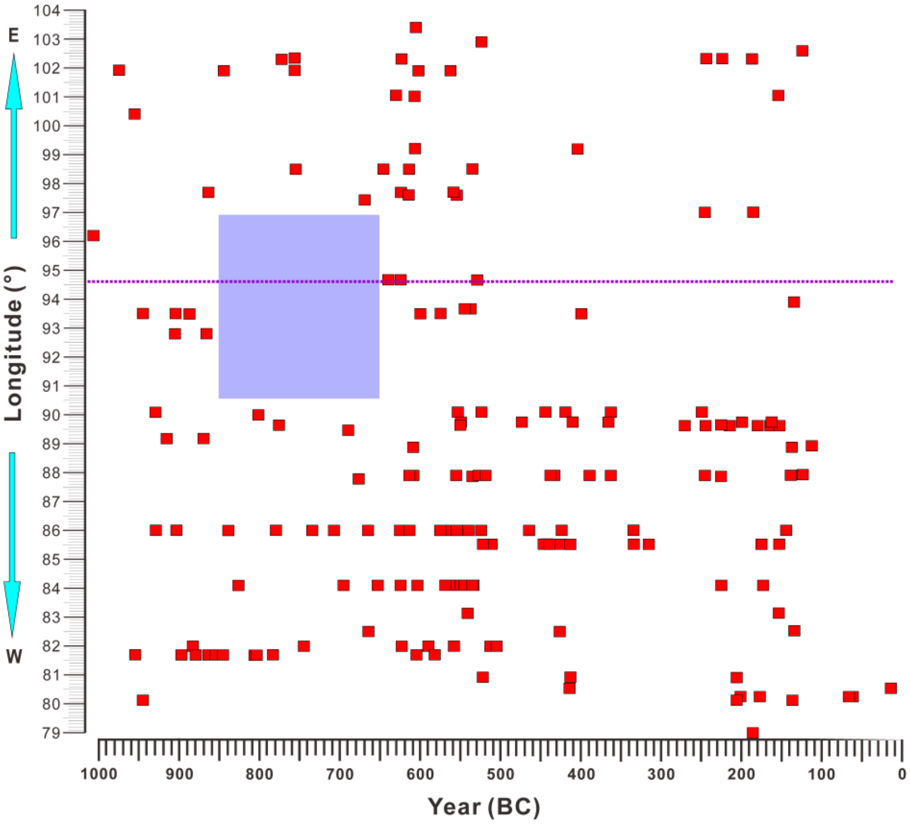

Fig. A1.