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Climate of the Past
Discussions

Climate-driven desertification triggered the end of the Ancient Silk Road

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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, in the Ming dynasty. Three causes of the demise of the ancient Silk Road have been suggested: (1) the thriving of the sea trade route after the great geographic discovery in the Ming dynasty; (2) frequent incursions by the Wala and Turpan kingdoms, or fighting in border areas; and (3) climate change. In this study, new evidence from a sedimentary site in Dunhuang oasis together with analysis of historical archives indicate that neither the sea trade route nor the frontier wars were the pivotal reason for the closure of the Jiayuguan Pass. Extreme droughts and desertification events, caused by climate change, occurred in the Dunhuang area, west of the Jiayuguan Pass, during ~1440-1460 AD. After ~1450 AD, desertification rendered the ancient Silk Road impassable in the area, which resulted in a steep fall in the volume of trade as well as political chaos and mass migrations. The final closure of the Jiayuguan Pass in 1539 AD and the abandonment of Dunhuang city further interrupted the operation of the ancient Silk Road.

Keywords: Dunhuang; Ancient Silk Road; climate change; desertification; 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; Afzaal, 2020). As a routeway, the Ancient Silk Road reached a peak in the Tang dynasty (618-907 AD), but this came to an end 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 interruption of cultural exchange and trade between East and West, and the end of the Ancient Silk Road as an historically important routeway.

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 in 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 a critical location on the only 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. The Ming governor established seven garrisons in the Jiayuguan-Dunhuang area and transfer of the leadership to Mongolia in order to consolidate the frontier (Chen, 2000).

Various hypotheses have been proposed to explain the decline and closure 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). In the Middle and Late Ming dynasty, national power declined due to political corruption and financial stresses, but the border nations such as Wala and Turpan continued to expand. 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 administrator weakened and there was a gradual isolation of the governance (Zhang, 1974). As a 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). The thriving of the Maritime Silk Road after the voyages of Zheng He (1405-1431 AD) in the South Seas contributed to the shifting of economic and foreign trade centers from inland in the northwest to the coastal ports in the southeast of the Ming domain. Finally, the role of climate change has been proposed as the principal cause of the abandonment of Dunhuang and the closure of the Ancient Silk Road (Zhang et al., 2018). 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 (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.

In the present study of the recent paleoenvironmental and human history of the region, we focused on 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. In addition, the area has experienced frequent political turmoil and conflicts. First, previous hypotheses are analyzed using newly-discovered historical archives, and then the results of a detailed sedimentary investigation of a newly-discovered site are presented and evaluated. In addition, the relevant available literature is reviewed and a sociopolitical analysis of the historical archives in Duanhuang and the surrounding areas and in Ming China is used to determine the environmental and sociopolitical changes in the area during the study period. Finally, several possible causes of the abandonment of the Dunhuang area and 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 is the zone of climatic interaction between arid Central Asia and monsoon Asia and is climatically characterized by a continental-monsoon climate under the influence of 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 the 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 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 Tulufan, 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 Altun Mountains 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 newly-discovered site reported here (the XSW section) 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). Wind-eroded landforms are common in the region. 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-m 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 process followed the procedures described in Aitken (1998). OSL measurement of coarse-grained (90-125 μm) quartz were performed using an automated Risø TL/OSLDA-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 Corning-759 and BG-39 filters. The purity of the

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quartz extracts was checked by 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}×100%, where m_{105} is the sample weight after oven drying at 105°C, and m_{550} is the sample weight after combustion at 550℃ 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 studied 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

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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. Closure and re-opening of the Jiayuguan Pass and the maritime trading ban

The examination of historical archives demonstrates that the Jiayuguan Pass was first closed in 1524 AD and finally closed in 1539 AD. This was followed by the abandonment of Dunhuang city in 1539 AD, which marked the end of the Ancient Silk Road on land. However, although maritime trade was banned at the beginning of the Ming dynasty (1370 AD), the ban was lifted in 1567 AD, which resulted in the flourishing of the maritime Silk Road in the late Ming dynasty (Zheng, 1985; Liu, 2014). The lifting of the ban on maritime trade in 1567 AD cannot have been the cause of the decline and closure of the land Silk Road in 1539 AD, as the effect could not precede the cause. On the other hand, the only sea trade route was that used during the seven official voyages of Zheng He (1405-1433 AD), during the period of the maritime trading ban (1370-1567 AD), which needs to be investigated.

At the beginning of the Ming Dynasty (Hongwu year), new diplomatic and security risks in the southeast coastal region threatened the emperor's dominance (Gu, 1977). In 1371 AD, the founder of the Ming dynasty, Zhu Yuanzhang, assembled 111, 730 soldiers to establish commanderies which were designed to prevent any private maritime trading (Research Institute of History and Language of the Central Academy in Taiwan, 1962). This policy was intended to counter incursions by Japanese pirates, to promote tribute trade, and to stabilize the social conditions on the southeast coast and maintain the autocratic governance of China. In addition, “Huairou's cultural policy” was implemented by the ruling regime. This policy involved the Ming government providing goods in return which were of much greater value than those supplied by the tribute trade. The aim of Zheng He’s voyages (1405-1433 AD) in the Yongle year was to establish diplomatic relations with foreign countries and to promote the image of a powerful Ming government overseas (Gu, 1977). Although this policy helped boost the international reputation of the Ming government, it resulted in a substantial fiscal deficit. Therefore, the voyages of Zheng He were conducted for reasons of national prestige and they did represent genuine profit-driven trading activity along the maritime Silk Road.

The ban on maritime trade not only resulted in dire poverty among the inhabitants of the southeast coast, but it also caused the Ming government to lose a huge amount of income from maritime trade. The maritime trade restriction lasted for about two hundred

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years until it was lifted by the Longqing emperor in 1567 AD (the first year of the reign of Longqing) at the port of Yue in Zhangzhou, Fujian Province (Chen, 1962). From then onwards, the maritime trading activity of the Ming dynasty developed rapidly and private foreign trade was revived and began to flourish. Furthermore, it helped develop connect domestic and international markets for the Ming dynasty (Liang, 1989).

In summary, the previous assumption that the maritime trade policy of the Ming dynasty was responsible for the demise of the Ancient Silk Road on land is untrue. Before 1567 AD，the Ming continued the ban on maritime trade which impoverished both the government and the common people. The voyages of Zheng He represented the desire of the rulers of China to establish political connections with foreign countries and not to promote trade and economic development. After the lifting of the ban in 1567 AD, private citizens in the southeast coast started to carry out maritime trade, with the result that the economy began to revive. However, the abandonment of Dunhuang and the interruption of the Ancient Silk road occurred in 1539 AD, decades before the cancellation of the maritime trade ban. In addition, Zheng He's voyages ended more than a century before the official closure of the Jiayuguan Pass.

4.2. Effects of warfare on the Ancient Silk Road

Frequent warfare in the northwestern part of the Ming domain was suggested to be another reason 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 Guanxi to reduce pressure on the border (Zhang, 1974). The Jiayuguan Pass was not only a military fastness, but also the only 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. 2). The classification of agri-nomadic conflict was adopted because it directly reflects the conflict between the central government and nomadic peoples (Fig. 2a). The frequency of tribute trade and the number of tribute states in the Western Regions are illustrated in Fig. 2b and 2c. 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 demise 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 almost no 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 only 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 not the primary of the collapse of trade along the Ancient Silk Road trade. 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 frequently occurred during periods in which 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 was not responsible neither for the decline of the Ancient Silk Road, nor for the final closure of the Jiayuguan Pass.

4.3. Influence of climate change on the Ancient Silk Road

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Climate change has been an important and sometimes critical influence on the rise and fall of ancient civilizations (Wang et al., 2018), 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 on the demise of the Roman empire and large-scale human migration in Europe during the historical period (Büntgen et al., 2011). Another example is the decline of the Loulan Kingdom on the Ancient Silk Road (Fontana et al., 2019; Fig. 1). Although a climatic hypothesis has been proposed for the abandonment of Dunhuang (Zhang et al., 2018), the relationship between climate change and the decline of Dunhuang city during the later Ming dynasty has not been adequately examined. In addition, it is highly debated whether climatic deterioration was responsible for local desertification and the cessation of trading along the Ancient Silk Road.

4.3.1 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 demise 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. 2), 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 (corresponding to the Spring and Autumn Period) and after ~1450 AD (the Ming dynasty). These conditions would have been very unfavorable for human habitation of the area.

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[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 mountain 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 (Fig. 2), 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 1447-1567 AD (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 paleoclimate records from various locations (Thompson et al., 1997; Wilson et al., 2016; Lecavalier et al., 2017), and is recorded in historical documentary records from China (Ge et al., 2003). This evidence indicates that 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 limit factor being water availability (Qian and Jin, 2010). At the present time vegetation survival in the oasis of the Hexi Corridor is mainly dependent on runoff from the Qilian Mountains, which is derived first from precipitation in the highlands and second from glacier meltwater (Liu et al., 2010; Yang et al., 2011; Sakai et al., 2012). The striking 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 resulted in its abandonment.

4.3.2 Documentary 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 (Bureau of National Cultural Relics, 2011) as well as the habitability of the surrounding environment (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). Agricultural technological innovations 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. S1), 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. S1), which suggests that human occupation of the Hexi Corridor was primarily determined by the environmental conditions.

The second desertification event occurred at ~1450 AD. It 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, sang folk songs about the migrations through the Jiayuguan Pass during the Ming dynasty. An epic of the migration of the Yugur minority history contains the following: "Violent winds swept livestock away, sand dunes submerged tents and houses, rivers dried up, grassland was desolated" (Wang, 1992; Editing Group of Brief History for Yugur minority, 2008). From these descriptions it can be deduced that the prolonged drought at around 1450 AD may have led to the disappearance of the oasis. Hence, the altered eco-environment reduced the productivity of agriculture and animal husbandry, which resulted in 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), 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).

4.3.3 Desertification events in the ancient Silk Road area

Various indicators of climatic variations, wars and the tribute trade are plotted in Fig. 2 against the chronologic 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 strong possibility that climate change was the primary cause of the demise 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 likely that environmental deterioration was the cause of the decline of the tribute trade and the cessation of hostilities. On the other hand, climatic perturbations and environmental degradation may not necessarily be a direct trigger of a societal crisis, and would instead result in an institutional failure caused by the lack of a centralized response to the environmental crisis in the area (Feng et al., 2019). The social disturbance associated with migrations and chaos in the Ming dynasty (Fig. 2d) was most likely to be an indirect consequence of environmental changes.

We now address the issue of how desertification during ~1450-1530 AD in the Dunhuang oasis and adjacent regions led to the closure of the 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 adjacent regions indicate that Dunhuang oasis and Guazhou oasis were not functioning during ~1450-1530 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 were 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 =

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450 km. The distances of Hami, Ruojiang and Jiayuguan to Dunhuang are already close to or above this limit, which is barely sufficient for camel travel (shown by the dots in Fig. 1, near Dunhuang and Shazhou oasis). On the other hand, the distances between other oases along the routes on the piedmonts of the high mountain ranges (Qilian, Kunlun and Tianshan) are generally less than 200 km. 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 much greater than the maximum distance that a camel caravan can achieve (450 km) without a water supply. This was likely to be the physical cause of the demise of the Ancient Silk road during the periods of desertification.

5. Conclusion

We have systematically investigated the possible reasons for the interruption of the operation of the Ancient Silk Road during the Ming Dynasty. The results suggest that neither the rise of the maritime Silk Road nor the effects of warfare were major causes of the severance of exchanges between Western countries and the Ming government. 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 caused the destruction of 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. As a consequence, chaos and mass migrations occurred between Dunhuang oasis and Jiayuguan oasis during 1495-1528 AD in the Ming Dynasty. The Jiayuguan Pass was finally closed in 1539 AD and Dunhuang city was abandoned. However, the immediate fall in tribute trade occurred in ~1450 AD, long before the chaos and migrations but consistent with the beginning of the desertification event. Therefore, the fundamental cause of the demise of the Ancient Silk Road trade was almost certainly climate-driven desertification.

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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 Duanghuang 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; the purple triangle indicates the lifting of the trading ban during the Ming dynasty). (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

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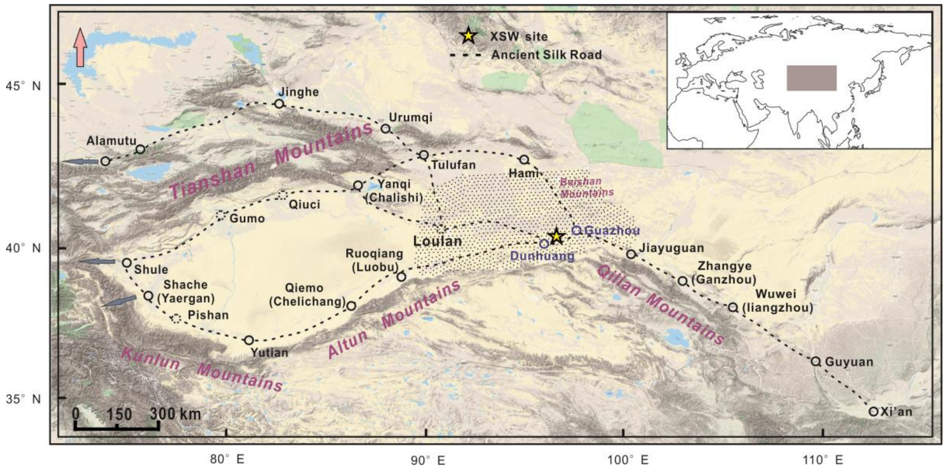

Figure 1.

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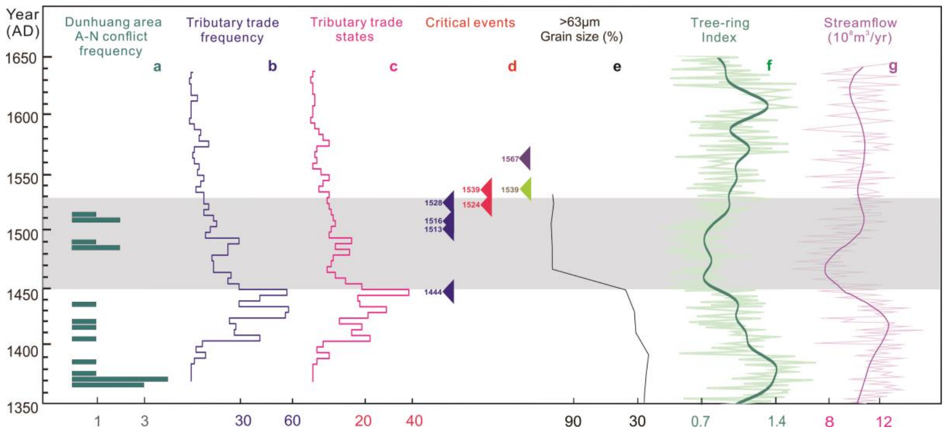

Figure 2.

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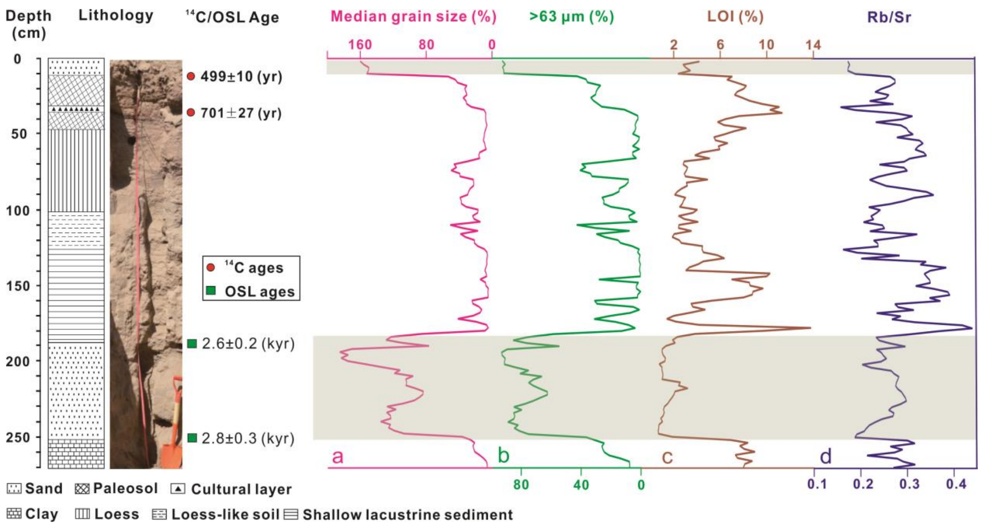

Figure 3.

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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

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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