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Oasis civilization collapse under 3.9 ka climate event in Bactria, Central Asia

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ABSTRACT

Central Asia played a significant role in the early exchange of civilizations across Eurasia. The arid climate, which makes the local ecology sensitive to climate change and the well-preserved archaeological remains, make Central Asia an ideal location for studying the mechanisms of interactions between civilization evolution and environmental change. This research presents archaeobotanical, palynological and stable isotope records from the Djarkutan site in southeastern Uzbekistan, which was occupied between 4100 and 3700 cal yr BP. Our research shows that in the Late Bronze Age, after 4000 yr BP, the local agricultural structure was highly complex. Pollen and stable isotope result indicate a sudden drought event occurred in the local area around 3900 yr BP, which had an impact on the local oasis agricultural system. Subsequently, this event promoted the migration of northern steppe populations into Central Asia, leading to the development of an agro-pastoral economy in the research area.

1. Introduction

Climate change is a crucial factor in the development of early human societies, and research on the interaction between early civilization evolution and environmental change is mainly carried out by integrating archaeological data and paleoclimate records (DeMenocal, 2001; Harvey and Bradley, 2001). Current research indicates that sudden or prolonged cooling, short-term aridification, or persistent multicentury drought caused by climate change are significant factors leading to the social collapses and the demise of cultures in West Asia, North Africa, the Indus Valley, and many other preindustrial civilizations (Büntgen et al., 2011; Hodell et al., 1995; Ljungqvist et al., 2021; Staubwasser et al., 2003; Weiss et al., 1993). However, the specific manifestations and intensities of the same climate event in different regions, as well as the specific ways that different civilizations respond to climate change are varied greatly (Carolin et al., 2019; He et al., 2022). Therefore, Holocene climatic events, including the 4.2 ka event (Ran and Chen, 2019), the Medieval Warm Period (Xoplaki et al., 2016), and the Little Ice Age (Büntgen et al., 2016), significantly impacted communication and interaction patterns in different civilizations, notably affecting agriculture, population, and economies (Li et al., 2021; Liu and Feng, 2012; Yu et al., 2000), and even contributed to wars, riots, and the rise and fall of dynasties (Fang et al., 2015; Wenxiang and Tungsheng, 2004; Zhang et al., 2007).

Exchange was one of the most important driving factors in the development of early civilizations and sociopolitical complexity. Central Asia, which served as a crossroad linking the Eurasian steppe, the Indus valley, and the inner Asia mountain corridor (Dong et al., 2017; Miller,

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1999; Spengler, 2015) experienced high-intensity civilization exchanges that played a crucial role in trans-Eurasian exchange progress during the mid-Holocene. The economics of the oasis agricultural civilizations in this area was highly complex, influenced by the civilizations from the surrounding regions. Barley (*Hordeum vulgare*) and wheat (*Triticum aestivum*), which originated in West Asia, dominated the area (Harris, 2012; Harris et al., 1993b, 1996) while some East Asian elements like common millet (*Panicum miliaceum*), foxtail millet (*Setaria italica*), and local native crops such as Russian olives (*Elaeagnus angustifolia*) and pistachio (*Pistacia vera*) were discovered in the area (Askarov, 1981; Dani and Masson, 1992). Local farmers frequently interacted with nomadic pastoralists in the nearby steppes. During the Chalcolithic and Bronze Age period, a series of early urbanization civilizations, including Anau (Harris et al., 1993a), Namazga (Kohl, 1981), Gonur (Sataev and Sataeva, 2014), and Djarkutan (Askarov, 1981), prospered in the region. Relative sites are also known as the Bactrian-Martiana archaeological complex (BMAC).

As research on early economic and civilization exchanges in Central Asia continues, there is increasing attention paid to the interactions among local environmental changes, early agricultural activities, and civilization exchanges. However, paleoclimate records in Central Asia mainly concentrated on Xinjiang, south Caspian Sea, and Iranian Plateau (Che and Lan, 2021; Chen et al., 2019). Although some scholars have carried out paleoenvironment and paleohydrology reconstruction in the oasis and delta where the archaeological site are concentrated (Dodson et al., 2015; Krivonogov et al., 2014; Lyonnet and Dubova, 2020), high-resolution paleoenvironment records around local archaeological sites in the piedmont oasis are still small in number. In addition, current archaeobotany research in this area mainly focuses on explaining the economic diversity of local civilizations on large spatial and temporal scales (Frachetti, 2009; Frachetti et al., 2010; Spengler, 2015) and the role they played in trans-Eurasian civilization exchanges (Frachetti et al., 2012; Frachetti et al., 2017; Spengler III et al., 2021). Thus, more research is to be done on the evolution history of the local environment around the archaeological sites and the interaction mechanisms between civilization evolution and environmental change.

In this research, we conducted an investigation of cultural remains dating between 4100 and 3700 cal. yr BP in the temple and palace/fortress region of the Djakutan site in southeast Uzbekistan (Fig. 1). The investigation includes an analysis of charred archaeobotanical remains, pollen assemblage, stable isotope evidence, and AMS^{14}C chronological results. We revealed a complex agricultural system dominated by barley and wheat, which also contains East Asian and local elements. Additionally, we found evidence of a rapid drought event at the section which include several cultural layers in the site, that impacted local agricultural activity. By comparing the local paleoclimate record with the northern steppe and Indus Valley, we consider the possible interaction between the steppe population and agricultural civilization in Central and South Asia under the abrupt climatic events and the expansion of steppe population around 3900 yr BP.

2. Research area

The Surkhan Darya is a primary tributary of the Amu Darya (Fig. 2 A) surrounded by the Hindu Kush Mountains, the Western Tianshan Mountains, and the Pamirs in the southeast of Uzbekistan. This region includes lowlands and valleys from Afghanistan, Tajikistan, and Uzbekistan. Historically, these fertile river valleys facilitated the emergence of intensive field agriculture and served as major corridors connecting East, West, and South Asia (Holdich, 1910; Lerner, 2015). The local climate is continental, with rainfall mainly in spring seasons; the average temperature in January is 3 °C, and that in July is 30 °C; the mean annual precipitation in the plain area is 130–360 mm, and that in the piedmont area is 440–620 mm (Fig. 2 B). The local landscape has sparse vegetation cover, and the foothill zone is typically covered with short-growth shrubby fruit and nut forests, along with patches of open grasslands (Fig. 2 C) (Egamberdieva and Öztürk, 2018; Safarov et al., 2014). Soviet archaeologists conducted extensive archaeological excavations in the area during the 1960s and 1970s and discovered a large number of settlements spanning multiple historical periods (Askarov, 1981; Пугаченкова, 1966).

The Djakutan site is located near a dry tributary, 60 km north of the city of Termez on the Bustansai in the Bactrian region. This site exceeds 100 ha, making it the largest known urban settlement and center of the Sapalli-Dashli culture in the Bronze Age Bactrian region (Askarov and Shirinov, 1994). The northern and western boundaries of this site can be distinguished by hills and ravines. A large number of settlements are clearly visible inside the site, which also includes a temple, a fortress or palace (Fig. 2 D). The fortress or palace is situated on the northwest hill and covers about 3 ha. The western part of this complex was destroyed, while the remaining part is surrounded by a wall of 1 m in height and 3.5 m in width, with a palace complex inside (Askarov and Shirinov,

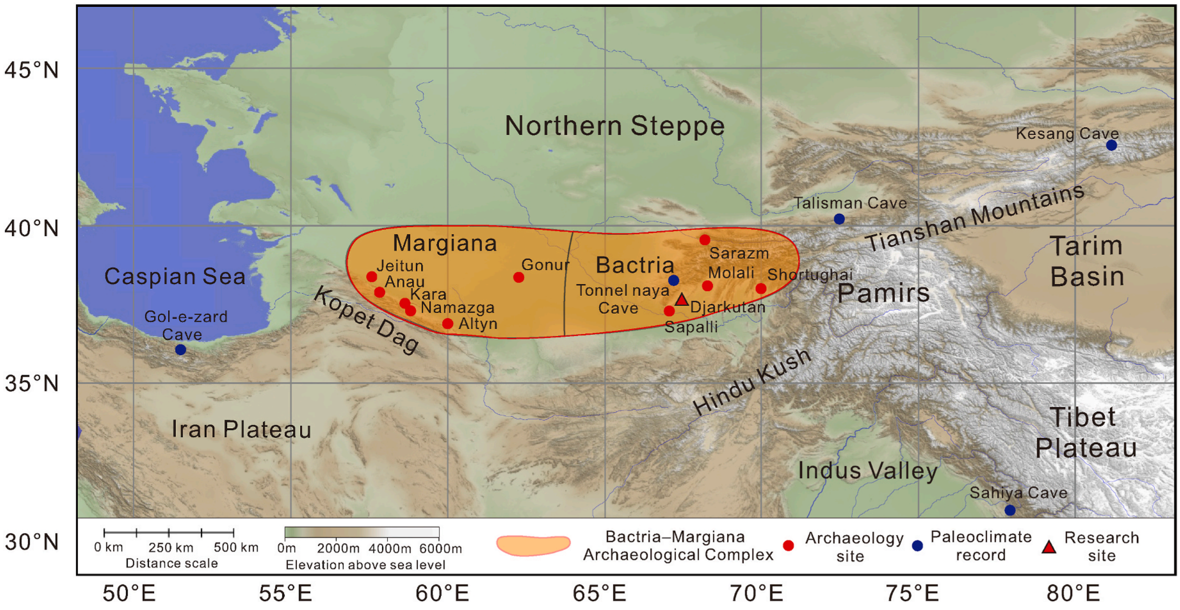

Fig. 1. Location of the research area, the range of BMAC, typical archaeological site distributions.

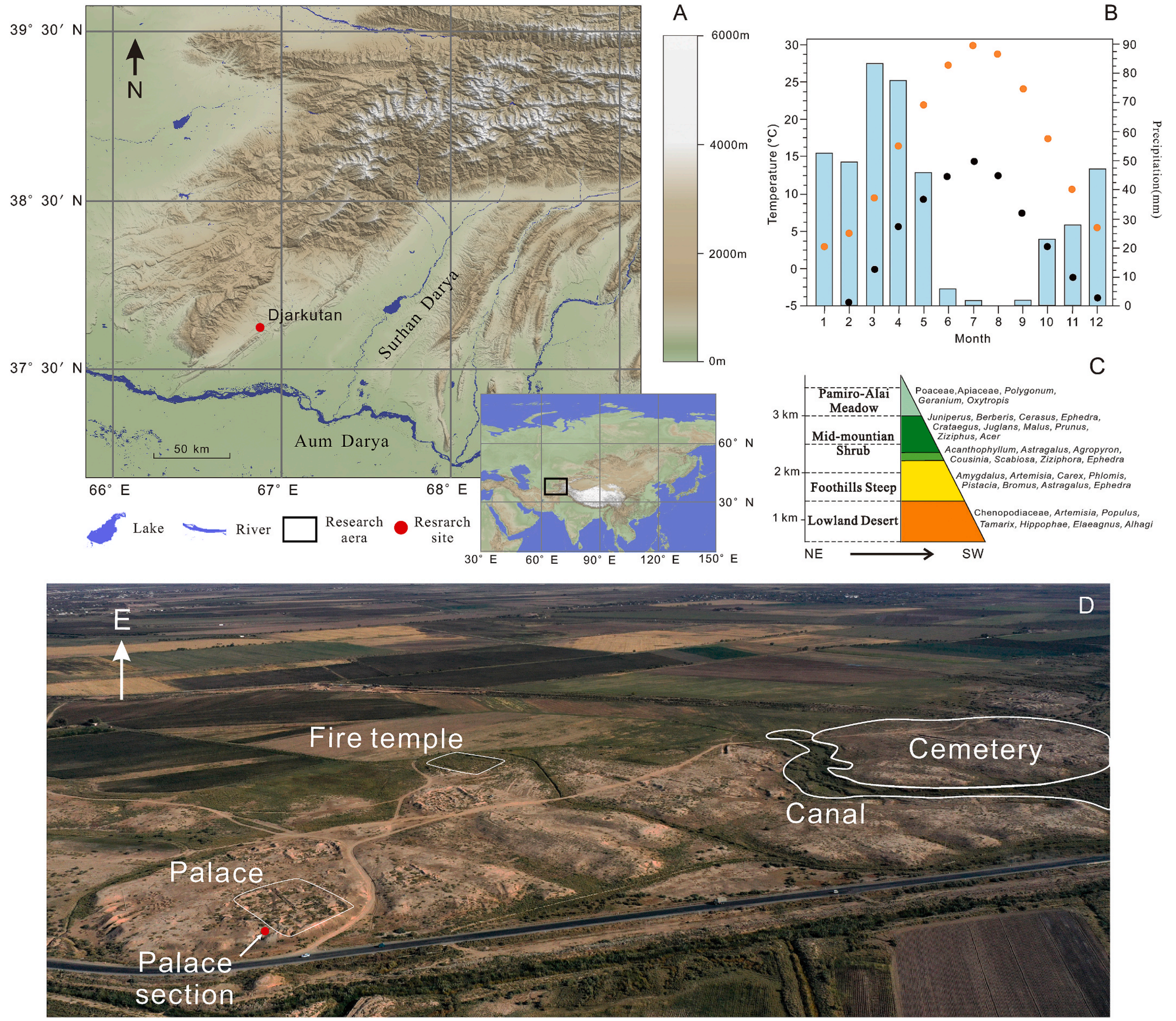

Fig. 2. Research area location, geomorphologic, climate record, archaeology site and vegetation distribution. (A) Research area, geomorphologic and archaeology site distribution. (B) Monthly distribution of average high and low temperature (orange and blue dot) and annual average precipitation (blue bars). (C) Vertical vegetation distribution of typical Pamir-Altai mountains (from Uzbekistan to Tajikistan). (D) Djarkutan Site UAV aerial image, structure and sampling location.

1994).

The temple is situated on the eastern part of the site (Fig. 3 A, B), 300 m south of the palace (Fig. 3 C, D), 50 m from the residential area, and 500 m away from the nearest public cemetery. The surrounding area is uninhabited, making it the center of public religious activities in this urban settlement. The structure of this temple measures 44.5 m in length and 60 m in width, with a wall of 4.5 m in thickness, which is a typical Sapalli cultural architecture, featuring characteristic elements such as surrounding corridors, a monolithic encircling wall, and complexes of outbuildings.

The construction of the temple is roughly divided into three stages, corresponding to the three cultural periods of Djakutan, Kuzali and Molali in Sapalli culture. The main entrance is on the south side, the interior of the temple can be divided into two areas: the religious area in the east and the domestic/industrial area in the west.

The religious area includes a sanctuary and a treasury consisting of a 25-m-long entrance corridor, a sanctuary courtyard with a designated area for sacrifices, and a sacred well located under an eyvan (Askarov and Shirinov, 1994). Additionally, there is a sacral platform featuring the main altar, a repository for sacred ashes (room 5) with two adjoining lateral rooms, and a treasury used for storing temple relics and offerings, such as the holy fire preservation room (room 1). At the center of the platform, there is a large flame altar, and remnants of four post holes suggesting the structure resembling the "Chahai-Taq (Čahārṭāq)" found in the pre-Islamic Iranian region (Askarov and Shirinov, 1994; Djuraeva, 2019). Notably, the main altar is situated at a higher elevation compared to the smaller altars, and all altars are constructed on clay panels.

The western part is dedicated to domestic and manufacturing activities and features separate entrances and exits. Numerous ash pits, as well as metal and ceramic containers, have been discovered in this area, indicating the presence of metallurgical and pottery-making activities, as well as storage facilities. Of particular interest are the storage jars found embedded in the floor of Room 9, which was speculated to be been used for winemaking. Additionally, some small altars were discovered in this area during the later period of the temple's existence (Askarov and Shirinov, 1994).

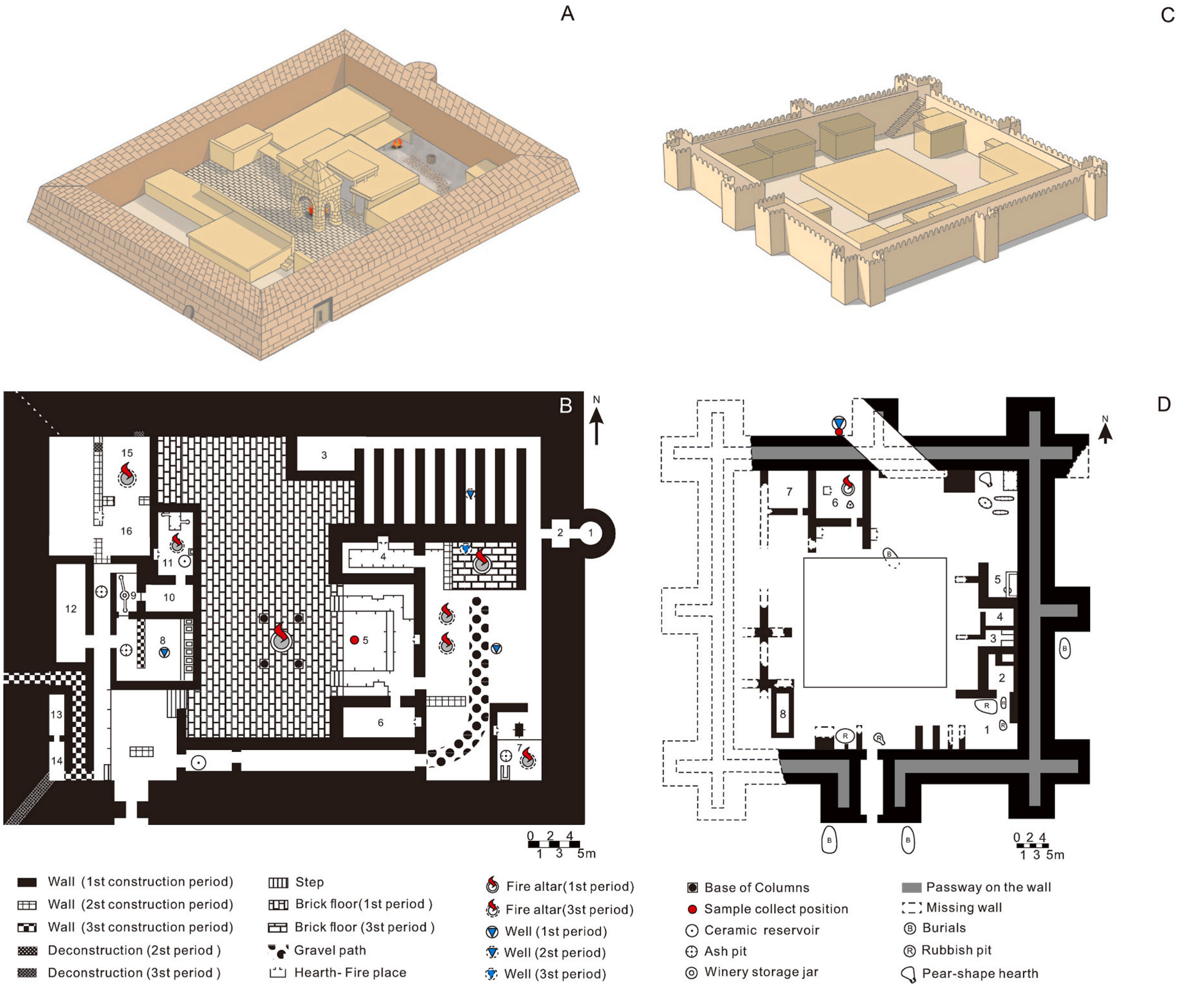

Fig. 3. Structure and restoration image of temple and palace in Djakutan site. (A) Restoration of the temple; (B) Structure of the temple; (C) Restoration of the palace/fortress; (D) Structure of the palace/dortress.

Although the temple exhibits several characteristics of Zoroastrianism, such as a significant number of flame altars, an ash storage room, and potential remains resembling the “chahār-tāq" structure prevalent in Central Asia, it possesses certain elements that do not align with the typical features of Zoroastrianism during the Achaemenid period, which include the presence of a large domestic and manufacturing area, the absence of pure ashes and the sacrificial pits used for purification (Boyce, 1996; Stausberg, 2008). Consequently, it would be inaccurate to classify the temple in Djarkutan solely as a Zoroastrian fire temple. Instead, it serves as a valuable testament to the early local practices of flame worship and provides insights into the customs preceding the emergence of Zoroastrianism in Central Asia.

The public necropolis area is situated in the southern part of the site, separated from the northern settlement by a canal. Prior to the establishment of the public necropolis in Djarkutan, early burials were dispersed throughout the residential area, often found beneath the floors or within the walls of houses. The burials in the public necropolis area span the entire chronological period of the site’s existence (Askarov and Shirinov, 1994).

Based on current excavations of burials near the palace and within the public necropolis, the predominant burial practice involved placing the deceased in a fetal position on one side, accompanied by a significant assortment of ceramic, stone, and bronze artifacts. Male individuals were positioned on their right sides with their backs toward the entrance of the grave, while females were positioned on their left sides facing the entrance. The direction of the burials varied across different periods, and the funerary assemblages also exhibited variations among individual burials. Notably, some burials contained lavish funerary offerings, including relics symbolizing power in a complex and stratified society, such as scepter heads.

3. Materials and methods

3.1. Radiocarbon dating

Samples for radiocarbon dating were selected from different layers of the section in the palace and the ash pit in the temple. Nine dates were obtained from charred plant remains, including three grapes and six charcoal samples. The pretreatment protocol followed by acid-base-acid (ABA) method. First, the samples were cleaned of any adhering sediment and other materials, and then they were crushed. The process involved washing them in hot HCl (5%), rinsing, treating them with 1% NaOH, rinsing again, followed by treatment with hot HCl (5%), rinsing, and drying. After the pretreatment, the samples were combusted to CO_2 by oxidation at 800 °C using CuO. The CO_2 was purified in the presence of silver wire to absorb any SO_x and NO_x produced, and then it was reduced to graphite with H_2 at 550 °C using an iron catalyst. The pressed graphite targets were sent to the Radiocarbon Dating Laboratory of Beta Analytic for accelerator mass spectrometry measurements. The radiocarbon ages were subsequently calibrated using OxCal v4.4 software with the $IntCal_{20}$ database (Ramsey, 2009; Reimer et al., 2020).

3.2. Archaeobotanical analysis

Archaeobotanical samples were collected in Room 5 of the temple and the section near the northern part of the palace wall. We conducted column sampling in the section for environmental and archaeobotanical studies. Sediment samples were collected below the ground surface in the palace section, at 5 cm intervals. Flotation samples were floated using a 0.3-mm mesh screen at a workstation near the site. All the light materials obtained were transported to the archaeobotany laboratory of the IVPP. The archaeobotanical samples were initially sorted, with wood charcoal and other macrobotanical remains systematically removed, and then further identified using a Leica M205 C stereomicroscope.

3.3. Pollen analysis

The pollen was extracted and analyzed at the pollen laboratory in IVPP using the heavy liquid flotation method (Moore et al., 1991). Approximately 100 g of the bulk sample was treated with a heated 10% aqueous HCl solution for 2 h, followed by rinsing and drying of the sample. The pretreated samples underwent heavy liquid separation, first with $ZnCl_2$ (density 2.0 g ml^{-1}), and then with a potassium iodide/ZnI_2 mixture (density 2.0 g ml^{-1}). The upper suspension was subsequently rinsed, dried, and treated with a 1:10 vol mixture of concentrated sulfuric acid and acetic anhydride. The pollen concentrate was then dried and mounted in glycerine for microscopic identification. Pollen grains and spores were identified and counted using a Zeiss MA1 microscope at a magnification of × 400.

3.4. Stable isotope analysis

The pre-treatment experiment and data analysis of $\delta^{13}C$ and $\delta^{18}O$ in this study were carried out in IVPP. A total of 80 bulk sediment samples were used for stable isotope analysis. The samples were oven-dried at 40 °C, ground to pass a 0.15 μm mesh screen, and 2 g of the sieved sample was taken for further analysis.

For $\delta^{13}C/^{18}O_{VPDB}$, Gasbench II (Thermo Scientific) was used as the front end of the reaction. Solid phosphoric acid (103%) was used, and the samples were reacted at 25 °C for 12 h. This converted the sample into CO_2 gas, which was then tested using a 253 Plus continuous flow isotope ratio mass spectrometer (IRMS). The standard reference materials IAEA-603 ($\delta^{13}C = 2.46‰VPDB$, $\delta^{18}O = -2.37‰VPDB$) and IAEA–CO–8 ($\delta^{13}C = -5.764‰VPDB$, $\delta^{18}O = -22.7‰VPDB$) were used. The relative deviation of repeated samples for carbon stable isotope values in sediment samples was $<\pm 0.2‰$, and the relative deviation for oxygen stable isotope values was $<\pm 0.4‰$.

For $\delta^{13}C_{TOC}$, the sieved sample was treated with 2 mol/L HCl for 24 h to remove carbonates, then rinsed with deionized water to neutral PH and dried. $\delta^{13}C_{TOC}$ values were measured using a Flash2000 elemental analyzer interfaced with a 253 Plus continuous flow isotope ratio mass spectrometer (IRMS). Standard reference materials IAEA-CH3 ($\delta^{13}C = -24.7‰VPDB$), U1 ($\delta^{13}C = -34.1‰VPDB$), U2 ($\delta^{13}C = -8.0‰VPDB$), and U3 ($\delta^{13}C = 11.7‰VPDB$) were used to assess the analytical accuracy. The standard deviation for repeated measurements of $\delta^{13}C_{SOM}$ was $<\pm 0.2‰$.

4. Result

4.1. Chronological results

The Djarkutan site was first excavated in the 1960s. Due to the archaeological theories and technical limitations at the time, no systematic archaeobotany and chronological research were carried out. Currently, many problems still exist about absolute dating of culture sequences, cultivated crops composition in different periods and the influence on local economic development after different exotic crops appear.

Total 8 carbonized plant remains were selected for AMS^{14}C dating in the palace section and the temple (Supplementary Table S1 and S2). Among them, 3 samples from the temple are all carbonized grape seeds, 5 charcoal were selected from the palace section. Radiocarbon dating results show that in Djakutan site, the temple age was 3702–3976 cal. yr BP (Fig. 4, Supplementary Fig S1), and the palace section dated to 3855–4100 cal. yr BP, the ages of those two units are overlap in the time.

4.2. Productive agriculture system in the Bronze Age Central Asia

The identification of carbonized plant remains in the Djakutan site include 727 charred seeds, with 18 genera and 21 species identified, and 903 charred seed fragments lacking enough identified detail (Fig. 5, Supplementary Fig S2 and Table S3). Most of the carbonized plant remains were discovered in Room 5 of the temple. Compared with the palace section, the crop diversity in the temple was significantly increased. The food crops mainly included six-row barley (*Hordeum vulgare* var. *hexastichum*), naked barley (*Hordeum vulgare* var. *coeleste*) and common wheat (*Triticum aestivum*). Legumet included peas (*Pisum sativum*), chickpeas (*Cicer arietinum*), and lentils (*Vicia lens*), all of which had the West Asian origin. East Asia elements such as common were foxtail millets are also present.

A large diversity of economic crops were present in the temple, including fruits such as Russian olives, apricots (*Prunus* sp.), apples/pears (*Malus/Pyrus* sp), grapes (*Vitis vinifera*), and flax (*Linum usitatissimum*). Among these, grapes were the most abundant, with 163 complete seeds and 561 grape fragments present. Morphological analysis illustrates a considerable range were under cultivation, which were divided into four distinct morphotypes, most showed some domestication characteristics (Chen et al., 2022). Meanwhile, the pottery jars found in temple Room 9 (Askarov and Shirinov, 1994), which are suspected to be a “winery”, providing evidence on the religious meaning and important ritual role about grapes in the Bronze Age Central Asia.

Rosaceae fruit remains include a large number of apricots and some apple/pear fragments. Due to the morphological similarities among the seeds of many horticultural plants in the Rosaceae family, the reliability of identifying charred remains based on their morphological characteristics is relatively low. In Djarkutan, most of the Rosaceae seeds are deeply charred, making it impossible to accurately determine whether the charred seeds are apples or pears.

Compared to grapes and other Rosaceae fruit remains found in the temple, the number of Russian olive remains is relatively rear. At present, many scholars believe that exotic crops were mostly used as status symbols of high-level people or used in religious and sacrificial activities (Spengler, 2019), so local fruit like Russian olives might not represent in ritual activities.

The remains of desert shrub and weeds also appear at Djarkutan, and mainly include Syrian mustard (*Euclidium syriacum*) and cleaver (*Galium spurium*). Current research on early agricultural activities in the Iranian Plateau suggests that weeds like Syrian mustard served as fuel (Whitlam et al., 2020). Considering the presence of large flame altars, the domestic and manufacturing area in the temples, this is likely true.

4.3. Pollen analysis result

An analysis was conducted on a total of 54 pollen and 80 stable isotope samples from the palace section at Djarkutan. Within these samples, a total of 32,668 pollen and spore grains were identified, representing 28 different taxonomic categories (Fig. 6, Supplementary Fig. S3, S4). Arbor pollen, including *Pinus*, *Betula*, *Quercus, Alnus, Ulmus, Corylus, Moraceae*, *Tamarix*, were rare across all samples. This indicates that trees were not extensively grow in the valley where the site is located.

The analysis of herbaceous pollen in the samples revealed Chenopodiaceae, *Ephedra*, *Artemisia*, Asteraceae (include *Aster* and *Taraxacum*), Poaceae, Fabaceae, Rosaceae, Caryophyllaceae, Lamiaceae,

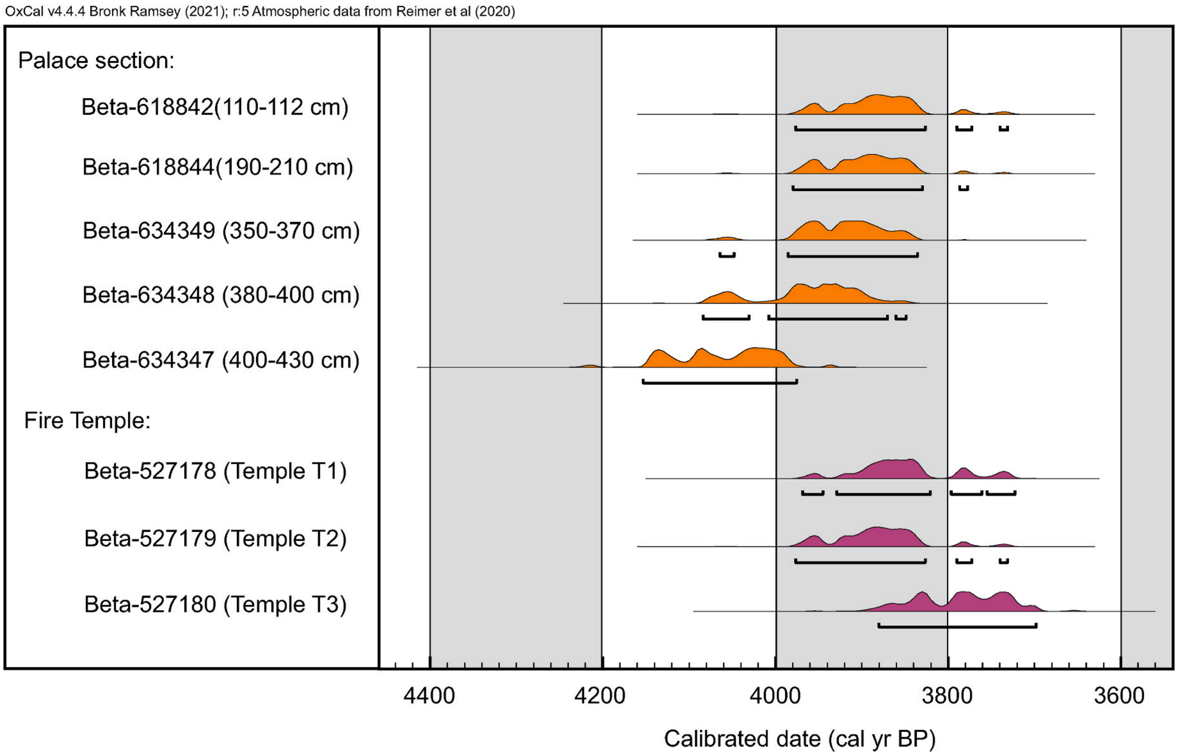

Fig. 4. AMS ^{14}C dating results of Djakutan site.

Ranunculaceae, Malvaceae, Zygophyllaceae, Geraniaceae, Rubiaceae. Aquatic plants include Typhaceae and Cyperaceae were present. Among these, Chenopodiaceae accounted for the majority of the pollen percentage, up to 95.34% of the identified pollen.

In certain areas where the presence of Chenopodiaceae is relatively reduced, there is a relatively high abundance of Asteraceae and Poaceae pollen. Notably, most of the Poaceae pollen grains identified had diameters larger than 30 μm, suggesting the influence of cropping. Utilizing Tilia 2.0 software (http://www.tiliait.com/), a Pollen diagram was generated, and CONISS analysis was conducted to further analyze the pollen spectrum. Integrating the lithology, chronological sequence, and pollen data, the pollen spectrum was divided into 4 distinct assemblage zones.

Pollen Zone I (430-300 cm; Chenopodiaceae-*Artemisia*-Asteraceae-Poaceae) indicates an arid steppe environment dominated by Chenopodiaceae. However, in certain areas, the percentage of Asteraceae and Poaceae could reach up to 60%. Other taxa such as Cyperaceae, Typhaceae, *Tamarix*, *Ephedra*, Fabaceae, Rosaceae, Moraceae, Lamiaceae, *Salix*, *Corylus* were present in small quantities.

Pollen Zone II (300-230 cm; Chenopodiaceae-Asteraceae-Poaceae-Typhaceae) has a similar composition to Pollen Zone I. Chenopodiaceae still dominates, but there is relatively more variation. There are noticeable changes in the herbaceous taxa abundances, with a significant decrease in *Artemisia* and Asteraceae, and an increase in Typhaceae. The areas where Poaceae and Typhaceae increased correspond to the decrease in Chenopodiaceae. other taxa such as *Quercus*, Fabaceae, Geraniaceae, Polygonaceae, Lamiaceae, and Cyperaceae are present in small quantities.

Pollen Zone III (230-120 cm; Chenopodiaceae) indicates an extreme arid condition. During this period, Chenopodiaceae dominates the pollen spectra. Other herbaceous taxa such as *Artemisia*, Asteraceae, and Poaceae are greatly reduced. Asteraceae and Poaceae taxa are essentially absent during this stage, suggesting the impact of drought conditions on local agricultural activity. Other taxa such as *Alnus*, *Ephedra*, *Tamarix*, *Artemisia*, Fabaceae, Rosaceae, Moraceae, Caryophyllaceae, Lamiaceae appear in low quantities.

Pollen Zone IV (120-0 cm; Chenopodiaceae-Asteraceae-Poaceae) is similar to Pollen Zone I, where Chenopodiaceae remains dominant but in reduced proportions then Zone III. *Artemisia*, Asteraceae, and Poaceae reappear and increase. This shift in the herbaceous pollen proportions indicates an expansion of mountain meadows and woodlands, accompanied by a decrease in the dry desert vegetation. There is a low presence of tree pollen, including *Pinus, Betula, Quercus*, and *Ulmus*. Other taxa such as Fabaceae, Lamiaceae, Malvaceae, Zygophyllaceae, Rubiaceae, Cyperaceae occur sporadically.

The climate in Central Asia is generally arid, with a local landscape characterized by sparse vegetation cover and comprised of saline, alkali and drought resistant plants such as Chenopodiaceae, *Ephedra*, and *Artemisia*, which is consistent with our pollen results. We also observed most of the Poaceae pollen grains diameters larger than 30 μm in the section. Early agricultural activities in Central Asia centered around the oases, reliant on irrigation (Zhou et al., 2016) and thus vulnerable to climatic conditions (An et al., 2005). Considering the abundance of barley, wheat and millet discovered in the site, the Poaceae pollen change may reflect the Poaceae cropping intensity in the Djakutan aera at different periods.

4.4. Stable isotope analysis result

In the Djakutan site, 80 stable isotope samples were analyzed, including $\delta^{18}O_{vPDB}$, $\delta^{13}C_{vPDB}$ and $\delta^{13}C_{TOC}$, in comparison with the pollen records. The results are as follows:

The $\delta^{13}C_{vPDB}$ and $\delta^{13}C_{TOC}$ result showed fluctuations, which associated with changes in vegetation types and carbon sources and reflected shifts in the composition of plant communities and potential changes in local agricultural practices. The $\delta^{13}C_{TOC}$ is generally negative, with 5 positive shifts occurring during the Pollen zone I and II, but these do not correspond well with the other records. Notably, in some positions where positive shifts occur, the pollen assemblages show a higher content of Poaceae and relatively lower content of Chenopodiaceae. This observation suggests a possible relationship between agricultural activities and the concentration of $\delta^{13}C_{TOC}$ in the cultural layers.

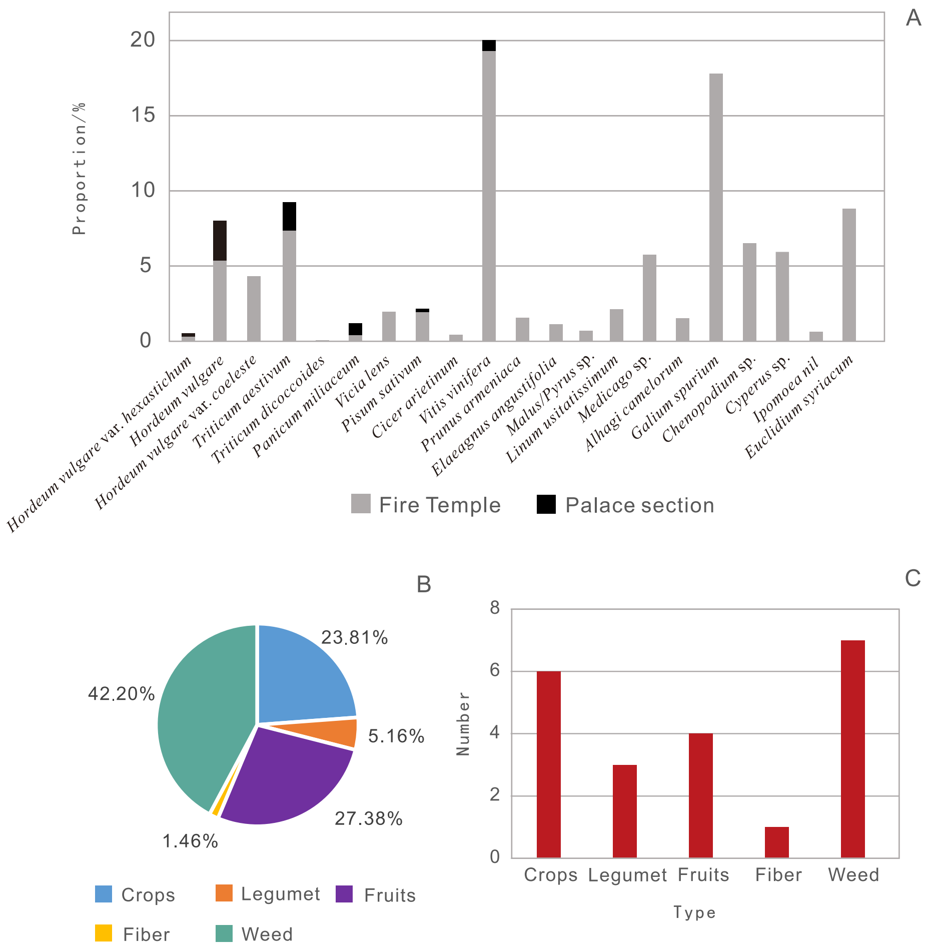

Fig. 5. Archaeobotanical results from the Djakutan site. (A) Proportion of different charred seeds remains; (B) Proportion of seed groups and (C) species numbers of different groups.

In pollen zone III, $\delta^{13}C_{TOC}$ has relatively positive shifts compared with Pollen zones I and II. This observation aligns with the abundant presence of Chenopodiaceae recorded during this stage. Additionally, the discovery of carbonized millet in the section further supports the idea that local farmers may have increased the cultivation of C_4 crops during the drought period. However, in Pollen zone IV, the $\delta^{13}C_{TOC}$ values did not decrease despite the reduction in Chenopodiaceae pollen and the increase in Poaceae. Instead, they remained positive, which fails to establish a significant correspondence with the pollen records.

The $\delta^{13}C_{vPDB}$ result had no consistent trend between pollen and $\delta^{18}O_{vPDB}$ results. In pollen zone I, the $\delta^{13}C_{vPDB}$ values remain relatively stable. However, in pollen zone II, two noticeable negative shift peaks emerge at the top and bottom, which do not correspond to other records. The $\delta^{13}C_{vPDB}$ record in pollen zones III and IV exhibits slight fluctuations but remains relatively stable. The difference from other records might be related to the more intense human activities near the section.

The $\delta^{18}O_{vPDB}$ record exhibits changes corresponding to different stages of the pollen spectrum. In pollen zones I, II, and IV, significant changes occur mainly at the transition points between zones, while the $\delta^{18}O_{vPDB}$ record remains relatively stable within each zone. Notably, the $\delta^{18}O_{vPDB}$ record in zone II shows a relatively positive trend. In pollen zone III, a rapid positive shift in the $\delta^{18}O_{vPDB}$ record aligns well with the rapid increase in Chenopodiaceae in the pollen spectrum.

Current research suggests that $\delta^{18}O_{vPDB}$ records from closed water bodies can effectively reflect ambient temperature and evaporation (Alonso-Zarza and Tanner, 2009; Talbot, 1990). However, considering that the record is derived from the cultural layer in archaeological sites, it is challenging to distinguish the contribution of human activities from the natural environment changes in the section. In comparison to $\delta^{13}C$, which has multiple sources and is susceptible to human activities and biomass changes, $\delta^{18}O$ is primarily influenced by the local hydrological balance (Leng and Marshall, 2004; Li and Ku, 1997; Talbot, 1990), making it more valuable for analysis.

The change trends of different isotopic records at Djakutan generally do not exhibit consistent patterns. According to recent studies, synchronous changes in $\delta^{13}C_{vPDB}$ and $\delta^{18}O_{vPDB}$ usually indicate increased evaporation, reflecting a trend of aridification in the climate (Leng and Marshall, 2004). However, in the palace section of the Djakutan site, there is no obvious correlation between the change trends of $\delta^{13}C_{vPDB}$ and $\delta^{18}O_{vPDB}$ values (R Pearson $= -0.303$; p value < 0.01; Supplementary Table S4 and S5). This lack of correlation could be influenced by intense human activities, which impact the dissolved inorganic carbon in the water body and the composition of both native and introduced plant species in the surrounding areas. These factors make it challenging to provide an explanation for the asynchronous signals observed in the records.

By comparing the stable isotope records of the sediments with the pollen spectrum and cluster analysis, it is evident that different isotopic records exhibit varying degrees of response at the interfaces of different pollen zones. Furthermore, when comparing the Poaceae pollen data with the stable isotopes in the Djakutan profile, an observation that the $\delta^{18}O_{vPDB}$ record shows an opposite trend to the concentration of Poaceae. Specifically, when the proportion of Poaceae decreases in the profile, the $\delta^{18}O_{vPDB}$ shifts towards a positive value.

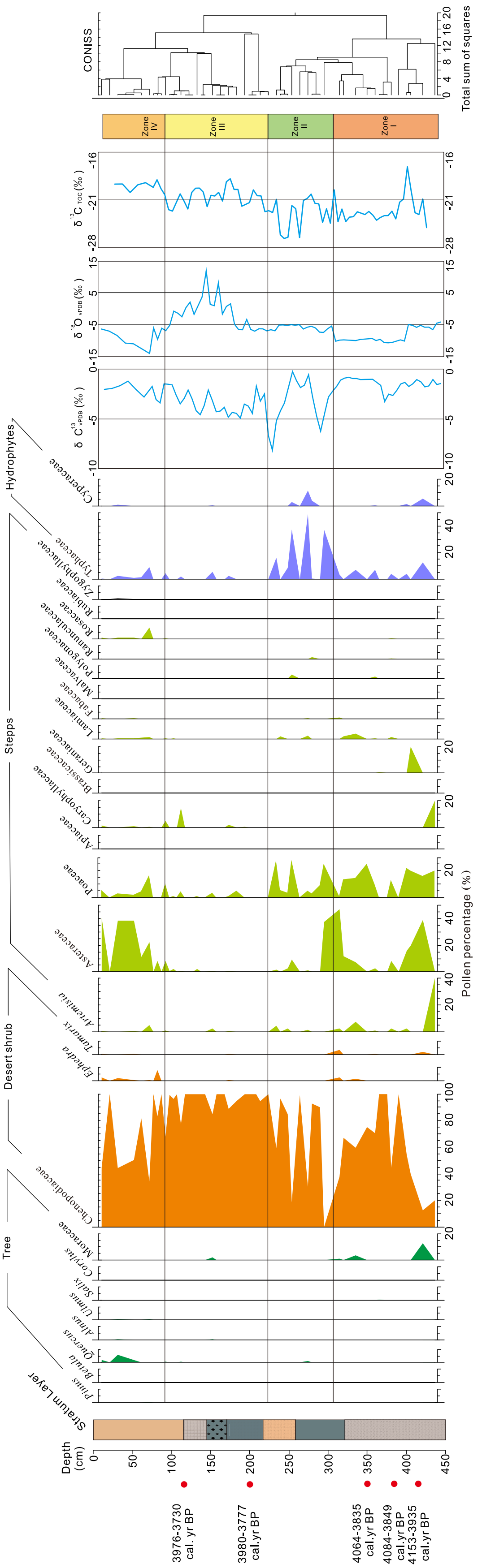

Fig. 6. Stratigraphic chart, Pollen diagram, stable isotope record and the results of CONISS analysis of the transit time distribution palace section from Djarkutan.

5. Discussion

5.1. *Climatic, environmental and agricultural history in Bronze Age bactria region*

Given that the sediment samples were collected from the cultural layer within the archaeological site, it is crucial to consider the influence of human activities when interpreting the various proxies. Based on the pollen, $\delta^{18}O_{vPDB}$ and $\delta^{13}C_{vPDB}$ data, as well as the chronological results from the section, we can reconstruct the agricultural history at the Djarkutan site. During the 4200-4000 yr BP, the agricultural activities were relatively intensive. But a drought took place between 3900 and 3800 yr BP. During this period, the proportion of desert shrub pollen rapidly increased, while the count of Poaceae pollen decreased to almost negligible levels, the $\delta 18O_{vPDB}$ record in this period also shows a relatively positive trend and synchronized with the increased of desert shrub component in pollen records.

Although it is difficult to distinguish the contributions of different factors between natural signals and human activity influence on the isotope changes in Djarkutan cultural layer; however, if the trend of pollen and isotope changes in the cultural layer is consistent with the surrounding paleoclimate record, it does not preclude using the cultural layer isotopic signal to compare the relative trends and interpret the environment change process in the surrounding area. To provide a climate background for comparison, higher resolution stable isotope records from stalagmites in Kesang Cave in China (Cai et al., 2017), Tonnel naya cave in Uzbekistan (Cheng et al., 2016), Talisman cave in Kyrgyzstan (Tan et al., 2021), Sahiya cave in northwestern India (Kathayat et al., 2017; Sinha et al., 2015) and Gol-e Zard cave in northeastern Iran (Carolin et al., 2019) were selected. These records were compared with the $\delta^{13}C_{vPDB}$ and $\delta^{18}O_{vPDB}$ records in the Djarkutan site, which serve as the regional environmental background of the archaeological culture record (Fig. 7).

The results show that during 3900–3800 yr BP, there was a major positive shift in the high-resolution $\delta^{18}O$ records in Sahiya Cave, northwest India, which is consistent with the record in the Djarkutan site. In Tonnel naya Cave, southeast Uzbekistan, the resolution is relatively low during this period, but the trend is consistent with the record in Djakutan site, with the positive shift peak in $\delta^{18}O$ record. Similarly, records from Talisman Cave in Kyrgyzstan and Gol-e Zard Cave in Iran exhibit a positive shift, although the fluctuations are relatively subdued, particularly the record in Iran. But considering that both of the cave are located in the mountains, the elevation differences between these cave records and sites make the climate proxy records in the mountains imprecise in reflecting the magnitude of environmental changes in the valleys. Also, Gol-e Zard Cave is located near the southern coast of the Caspian Sea, with its relatively abundant precipitation and the presence of large water bodies, possibly dampening local temperature changes in $\delta^{18}O$ values. However, the relatively consistent fluctuations and trends of these records still prove the possibility of rapid drought events occurring in the Central Asia valley.

However, the $\delta^{18}O$ record from Kesang Cave, situated at the southern edge of the northern steppe, exhibits a slightly negative shift during the period of 3900–3800 yr BP, contrary to other records in Central Asia and the Indus Valley. Despite the low resolution of stable isotope records in Kesang Cave during this particular period, corroborative evidence can be found in the pollen deposits of nearby lakes located in the northern steppe (Beer et al., 2007; Leroy and Giralt, 2020), these pollen records indicate a relatively humid environment with the increase in the A/C ratio and *Picea* peaks during the 3900-3800 yr BP, providing validation for the reliability of the $\delta^{18}O$ record.

5.2. *Environmental change and the civilization exchange in Bronze Age bactria region*

The archaeobotany results from Djatkutan reveal a highly complex

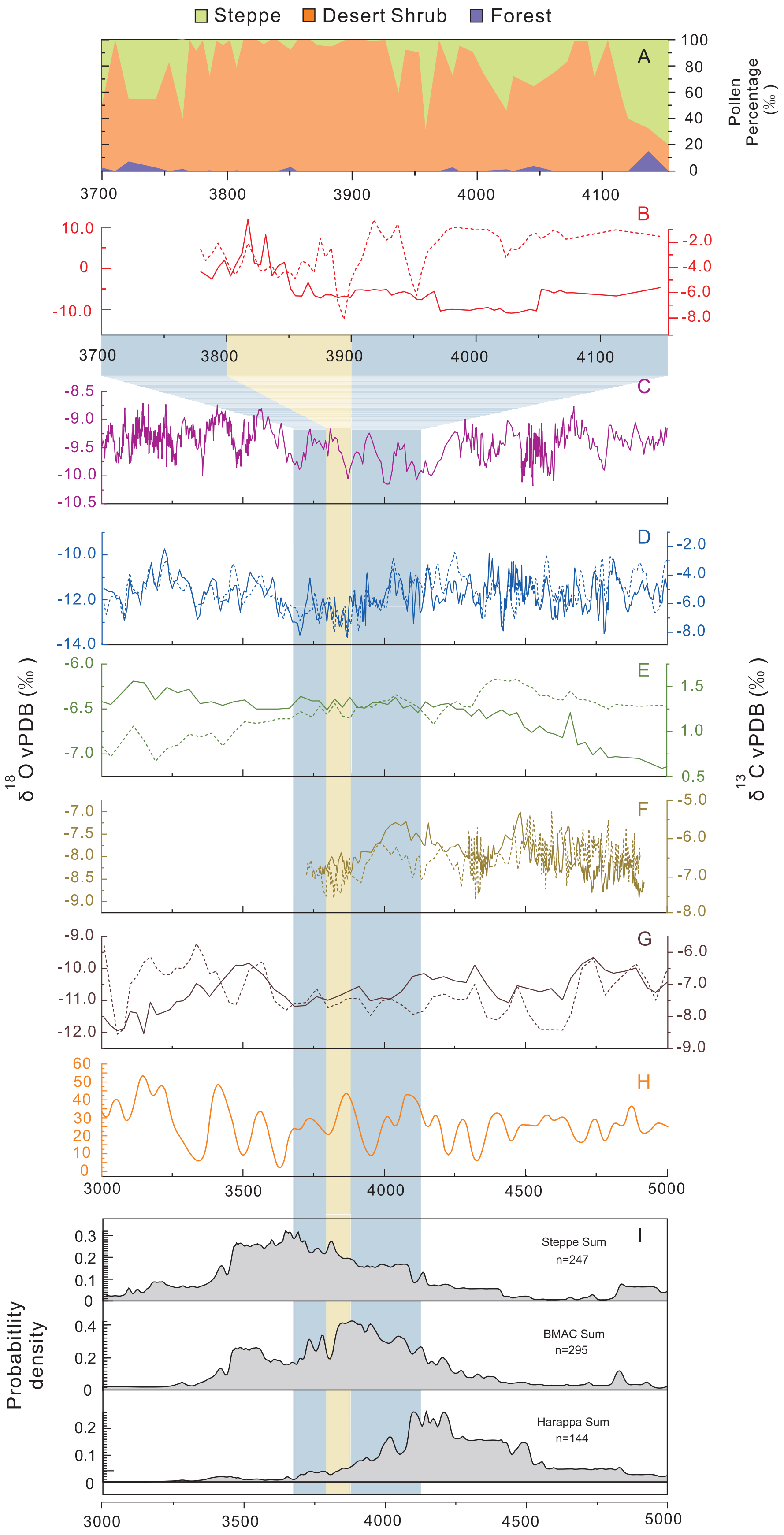

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Fig. 7. Stable isotope records comparison of between the Djakutan profile record and surrounding areas, the dashed line is the $\delta^{13}C$ record, and the solid line is the $\delta^{18}O$ record. (A) Djarkutan pollen fraction; (B) Djarkutan $\delta^{13}C$, $\delta^{18}O$ record; (C) Sahiya cave in northwest India (Kathayat et al., 2017); (D) Talisman cave in Kyrgyzstan (Tan et al., 2021); (E) Tonnel naya Cave, Uzbekistan (Cheng et al., 2016); (F) Gol-e Zard cave in northeastern Iran (Carolin et al., 2019); (G) Kesang Cave in Xinjiang, China (Cheng et al., 2016); (H) Holocene solar activity records (Usoskin et al., 2007); (I) Radiocarbon summed probability density in northen steppes, BMAC and Indus valley around 4000 yr BP.

oasis agricultural system during the Bronze Age in Central Asia. Radiocarbon dating result indicates that the temple in Djatkutan existed at least from 3976 to 3720 cal yr BP. Numerous fruits, such as grapes, were discovered, providing new evidence for the spread of horticultural along the Silk Road and the utilization and preferences among different social levels in the Bronze Age Central Asia. This diverse, adaptable, and productive oasis agricultural system significantly contributed to the prosperity of early civilizations in Central Asia and facilitated exchanges among civilizations across Eurasia.

Most of the charred plant remains found in the Djarkuta site originated from the fire temple. Chronological results show that the construction of the temple was not earlier than 4000 yr BP, and it was expanded 3 times in the subsequent period and ceased to function as a center of fire worship in the Molali period (Askarov and Shirinov, 1994). The above results indicate that the large number of crop and fruits found at the site belong to the first phase of the temple is existence. But the pollen and stable isotope results in Djarkutan palace section indicate a drought event occurring around 3900-3800 yr BP, which coincides with the appearance and rapid development of the fire temple (Askarov and Shirinov, 1994; Lyonnet and Dubova, 2020).

Early urbanization was an important feature at the archaeological site from BMAC during the Bronze Age. The emergence and development of ceremonial places represented by temples in archaeological sites is important evidence of the development of human social complexity and the emergence of nobility in the Bronze Age Central Asia, reflecting the increased of the productivity of local oasis agricultural civilization (Askarov, 1981). However, during 3900–3800 yr BP, the aridification, resulted in environmental pressure striking local agricultural production. The prosperity of sacrificial activities in the temple during this period was in sharp contrast with the challenging environment. According to modern anthropological research, the faith of religious believers may be strengthened due to natural disasters (Sinding Bentzen, 2019). Therefore, rapid development of the temples under harsh environments may have resulted from the environmental pressure, and as one of the important factors affecting the early civilization, and may be one of the driving forces for the emergence and development of early human worship behavior in Central Asia.

Although the environmental background and paleoclimate record at the Djarkutan show similarities with the early climate records in the surrounding areas, the altitude, resolution and time span differences between different records limit our discussion about environmental changes over the 500 years covered by the Djarkutan palace section, especially drought during 3900–3800 yr BP. On a millennium scale, the arid record in Central Asia around 3900 yr BP is not the most severe stage in the record. After 4000 yr BP, the overall trend of paleoclimate records in Central Asia gradually became more humid. But by comparing the different isotope records in research and surrounding area, we noticed that although the amplitude varies change is great in different regions during the 3900-3800 yr BP., all records showed multiple peaks in this period. That indicates the drought event in Djarkutan at 3900 yr BP is more likely to be a rapid and sudden drought caused by unstable climate fluctuations within a short period, which impacted local oasis based agricultural production.

The drought records in the Indus Valley are consistent with the records in the BMAC, while the records in the northern steppes did not show the same trend during 3900–3800 yr BP. Ancient DNA research indicates that steppe pastoralists appeared in Central and South Asia after 4000 yr BP. In the BMAC region, relics related to the pastoralist population, such as handmade pottery and metalwork with Andronovo characteristics, generally increased in the late Bronze Age and early Iron Age cultural layer (Dani and Masson, 1992). In the Indus Valley, the mature Harappa period (4600-3900 yr BP) declined rapidly after 3900 yr BP and entered the Late Harappa period (3900-3600 yr BP). The number of sites decreased rapidly, and their distribution region split into several parts, showing a trend of fragmentation and de-urbanization (Fig. 8) (Dutt et al., 2019; Madella and Fuller, 2006; Pokharia et al., 2014). Ancient DNA records from the Indus civilization during 4000–3000 yr BP also show some nomadic population records from the north (Narasimhan et al., 2019), which might indicate population interaction between the northern steppe and the agricultural civilization in Central Asia and the Indus Valley during this period.

By collating nearly 700 archaeological radiocarbon dating results and comparing the ^{14}C summed probability distribution from the northern steppes, the Oxus civilization, and the Harappan civilization during the Bronze Age (Fig. 7 I), the results reveal that the late Harappan civilization experienced a significant decline after 4000 yr BP compared to the mature Harappan period. In BMAC, 4000 yr BP are relatively stable, but a rapid decline occurs after 3850 yr BP, and the decline continued with fluctuations. This is consistent with the aridification record found in the cultural layer from Djakutan. In contrast, cultures in the northern steppe gradually flourished after 3850 yr BP, corresponding to the urban decline observed in the BMAC during the same period.

Currently, there are still uncertainties regarding the reasons for the decline of the Harappan civilization. Early research on the Indus civilization generally suggested a connection between the decline of the Harappan civilization and the migration of Indo-Aryans (Dani and Masson, 1992), However, aDNA studies in South Asia populations have shown that the genetic signal of northern steppe immigrants appeared in South Asia during 4000–3000 yr BP and subsequently mixed with the local population (Narasimhan et al., 2019). Paleoclimate records also indicate that the fall of the Indus civilization corresponds to aridification, a decline in the Indian monsoon, and a reduction in temperatures in the northern hemisphere around 4000 yr BP (Kathayat et al., 2017)。

Regarding the emergence of the northern steppe relic and population in Central Asia, current research suggests that the invasion of the northern steppe population into the Central Asia oasis after 4000 yr BP is a complex issue linked to many factors, include the increase in the population leading to conflict between human community and natural resources on the Eurasian steppes, the emergence and development of mobile pastoralists and nomadic economy, the domesticate of horses and the use of wheeled chariots (Dani and Masson, 1992; Kuzmina, 2008; Spengler III et al., 2021). In addition to the above factors, the collapse of agricultural production in oasis also potentially facilitated the path for the northern invaders. Although this explanation lacks conclusive evidence, but the drought events we discovered at the Djarkutan provides new evidence for this hypothesis, which coincides with the steppe population expansion and the collapse of local agriculture production the in southern Central Asia during 3900–3800 yr BP.

Therefore, the agricultural decline and the local civilizations collapse caused by sudden aridification and climate fluctuation in Central Asia may be one of the important factors contributing to the appearance of the northern steppe population in the southern Central Asia after 4000 yr BP.

6. Conclusions

Archaeobotanical, palynological and stable isotope analysis from Djarkutan sites in southeastern Uzbekistan, and the results were

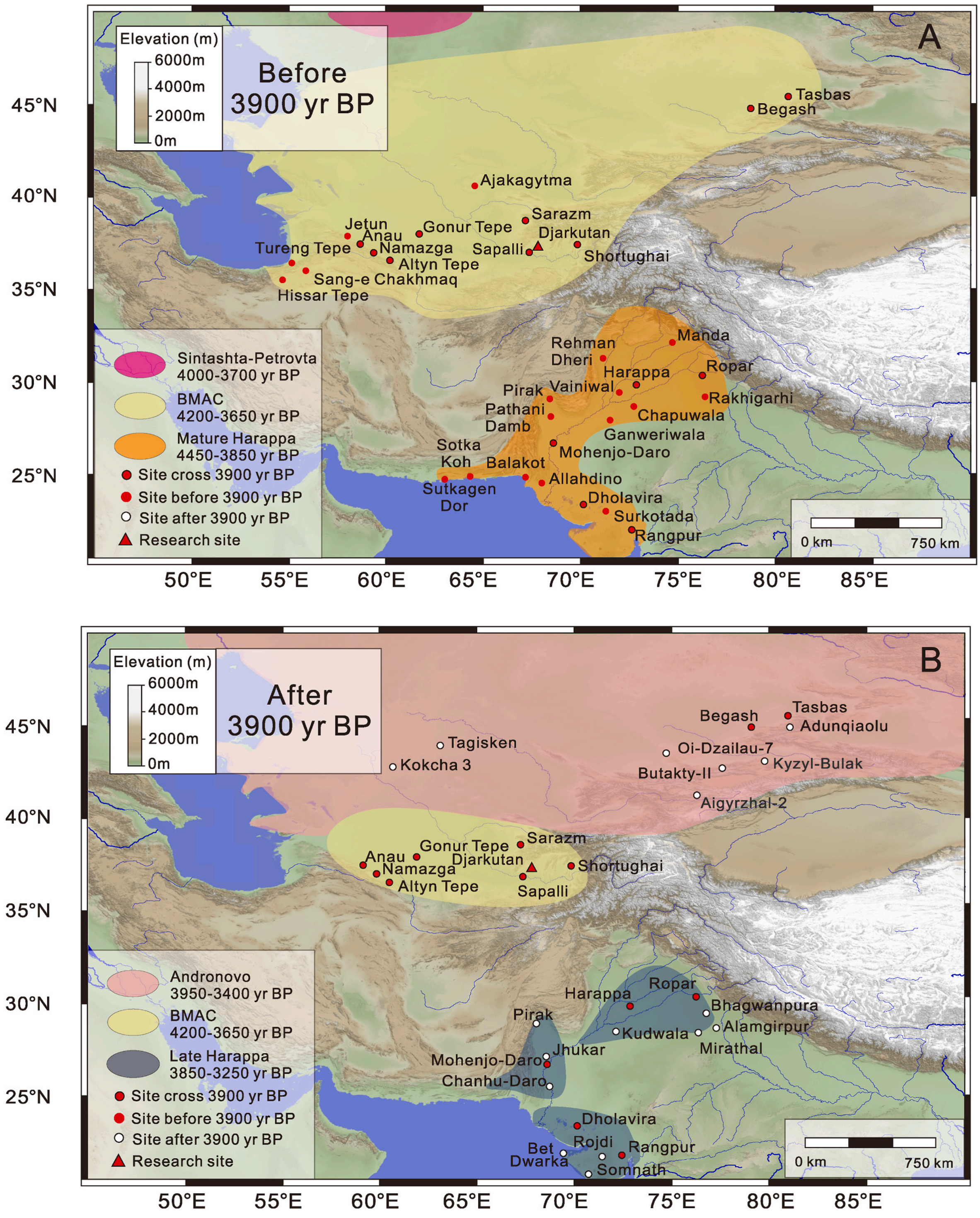

Fig. 8. Distributional change of different cultures between Sintashta-Petrovka, Andronovo from northern steppe, the Oxus civilization from BMAC and the Harappan civilization in Indus Valley before and after 3900 yr BP. (A) Before 3900 yr BP; (B) After 3900 yr BP.

compared with the Holocene paleoclimate records and early civilization activities in the research area, leading to the following conclusions.

1. In the Late Bronze Age, after 4000 yr BP, local agricultural structures were highly complex, containing different types of cereals and fruits originated from Eastern and Western Civilizations. The complex oasis agricultural systems provided a foundation for the prosperity and development of early civilizations in Central Asia and the exchanges of early civilizations on the Eurasian continent.
2. Pollen and stable isotope data indicate a century drought occurred in the research area around 3900 yr BP, which had an impact on the local oasis agricultural system, corresponding to the age of the temple. The Intensification of religious activities during the drought period may indicate the role of increased external environmental pressure in promoting the worship behavior of the local people.
3. Comparing the environmental background of the Djarkutan site with paleoclimate records in the surrounding areas, during 3900 yr BP, the nomadic civilization in the northern steppe began to expand

rapidly, in contrast with the decline of the Oxus civilization in Central Asia and the Harappan civilization in the Indus Valley, which may indicate that deterioration climate around 3900 yr BP promoted the migration of northern steppe populations into Central Asia, leading to the development of an agro-pastoral economy in research area.

Author contributions

Guanhan Chen, Xinying Zhou, and Xiaoqiang Li designed the study. Guanhan Chen and Junchi Liu carried out a major part of the laboratory analyses. Guanhan Chen, Xinying Zhou, Junchi Liu contributed to data interpretation. Guanhan Chen drafted the manuscript. Mutalibjon Khasanov and Nasibillo Kambarov Participated in field work and sample collection. Akhmadali Askarov provided the archaeological background. Hui Shen, Keliang Zhao, Jiacheng Ma, Jian Ma and Jianxin Wang offered constructive suggestions.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2024.108793.

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