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The rise of urbanism and exchange network: reconstruction of a 4000-year local history of Xinjiang, northwestern China

Yongqiang Wang[1,2], Yi Chen[2], Huihui Cao[3], Ruiliang Liu[4], Richard A. Staff[4,5], Linyao Du[3], Xiao Yuan[1], Shanjia Zhang[3], Jian Ma[1*] and Menghan Qiu[3*]

Abstract

Urbanization is one of the milestones in the development of human society. Many regions in the southern parts of 'the old world' demonstrating an early emergence of agriculture also witnessed the flourishing of some of the earliest cities. Recent, yet still sparse, archaeological evidence appears to indicate a relatively later time for early urbanism in central Eurasia. However, given its vital geographic location and cultural nexus between East and West, more attention should be paid to the sedentary communities and their cities in oases amid the vast droughty desert, particularly in light of the rapidly increasing number of publications on early pastoralism and related communication routes along mountain chains and rivers. This study reveals the trajectory of urbanization and its role in the establishment of an exchange network in Xinjiang's oasis region via reconstruction of the chronological sequence of the local societal history of the Baiyang River Basin along the southern piedmont of the Eastern Tianshan Mountains. A thorough archaeological investigation and refined radiocarbon dating programme was carried out and coupled with information from historical documentation within a Bayesian statistical framework. The results indicate three pulses of local urbanization during: the Early Iron Age, Tang–Yuan period, and Qing Dynasty, respectively. Combining this with evidence from other parts of Xinjiang, we re-evaluate the role of oasis urbanism in the promotion of trans-regional exchange.

Keywords East–West communication, The Silk Road, Field investigation, Landscape archaeology, Radiocarbon dating, Bayesian analysis

Introduction

Humans have a long history of building cities. In Mesopotamia, the fertile land and flourishing of agriculture inspired the process of urbanization and witnessed some of the earliest cities from as early as the late fourth millennium BCE [1, 2]. The building of cities subsequently sprang up in the adjacent zones to where relatively mature agriculture had developed, such as in Ancient Egypt [3, 4] and the Indus Valley [5–7]. Archaeological evidence obtained over recent decades has also shed light on early urbanism in East Asia during the Late Neolithic; the people of the Liangzhu (3300–2300 BCE; specifically, the Middle Liangzhu, 3000–2600 BCE) and Shijiahe (2500–2200 BCE) cultures in the lower and middle

*Correspondence:
Jian Ma
eurasiansteppes@126.com
Menghan Qiu
choumh14@lzu.edu.cn
[1] School of Cultural Heritage, Northwest University, Xi'an 710127, China
[2] Xinjiang Institute of Cultural Relics and Archaeology, Urumqi 830011, China
[3] Key Laboratory of Western China's Environmental Systems (Ministry of Education), College of Earth and Environmental Sciences, Lanzhou University, Lanzhou 730000, China
[4] The Department of Asia, British Museum, London WC1B 3DG, UK
[5] School of Archaeology, University of Oxford, Oxford OX1 3QY, UK

Yangtze River Valley are considered to have experienced urbanization as well [8–14]. Research on the rain-fed agricultural zone of the Yellow River Valley also portrays a picture of early urbanism almost simultaneous with that of the south [15–18]. However, in the middle part of Eurasia, where the history of agriculture is relatively shorter [19], the onset of urbanism has often been overlooked. Since the trajectory and characteristics of urbanization in different zones might be distinctive due to disparate cultural traditions and geographic settings [20], the observation and definition of urbanization also varies based upon different archaeological perspectives [21–27].

The Xinjiang Autonomous Region of China is one of the heartlands in central Eurasia where the Eurasian Steppe and the droughty desert-oasis zones converge. It is also one of the key areas to witness the emergence of prehistoric trans-Eurasian exchange and cultural interaction between the steppes and oases [19, 28]. Within Tongtian Cave in northern Xinjiang both Triticeae crops originating in the west and millet crops from the east have been unearthed, dating to before 2500 BCE [29, 30]. However, so far there is little evidence relating to the establishment of oasis agriculture in Xinjiang before 2000 BCE [19]. The second millennium BCE in Xinjiang's oases witnessed the flourishing of Bronze Age (BA) communities, including Tianshanbeilu and Yanbulake in the east [31–33], Xiaohe and Chawuhu in the centre, and Aketala-Wupaer and Xiabandi in the west [36–38]. Although some BA sites, such as Aketala-Wupaer and North Loulan, have suggested traces of settlement nucleation and clear social complexity [37–39], and recent studies of the Jirentaigoukou site in Ili has shed new light on secondary production and social complexification [40–42], there remains a significant dearth of detailed information relating to early urbanism. After entering the Early Iron Age (EIA) in the first millennium BCE, Xinjiang experienced the establishment of an interconnecting network linking various areas around the Tarim Basin, laying the foundation for the opening of the Silk Road [43]. Synchronously, there was a boom in the development of city-states in Xinjiang and the neighbouring regions, later documented as the "Thirty-Six Kingdoms of the Western Regions", which occurred prior to or during China's Western Han Dynasty (202 BCE to 8 CE) [44]. However, the trajectory of urbanization, and its role in the formation of the exchange network in Xinjiang remains poorly understood.

More recent studies focusing on the antiquity of Xinjiang have had a particular focus on the interaction of its people with those from neighbouring regions, with data from various archaeological sites providing fruitful evidence for its cultural characteristics [45–47], population history [48–51], and subsistence strategy from the perspectives of plant utilization [52–56], animal husbandry [57, 58] and palaeodiet [59–64]. The integration of these results has made a great contribution to unveiling the features and trajectory of Xinjiang's ancient society. Nevertheless, the unique topography of Xinjiang leads to a diversity and discontinuity of habitats which, as a result, has shaped the variety of lifestyle adopted among different areas throughout its history [65–67]. Moreover, the frequent exchange and immigration from multiple directions further complicated the cultural system [51, 68, 69], making it challenging to reconstruct a local societal history through reference to another disparate region. In addition, the limited living space and intensity of human activity at the oases evidently often caused an overlap and/or removal of the previous cultural remains, resulting in the incompleteness of the local archaeological stratigraphies in these arid regions [70]. Such incomplete sequences hence restrict our understanding of the trajectories of both social evolution and urbanization at a local scale, as well as the role of urbanism in broader trans-Eurasian exchanges. Hence, the reconstruction of local societal histories showing observations relating to urbanization processes is necessary to progress our understanding of these issues.

The Baiyang River Basin (BYRB) in the Hami Region of eastern Xinjiang demonstrates rich archaeological remains [71]. Restricted by the supply of water resources, relatively less extensive modern human activities in the BYRB has resulted in a less severe impact on the ancient relics, providing a rare opportunity to explore the history of the local society. Previous archaeological research has been performed in the BYRB to a limited extent, but with preference for the ancient cemeteries and the middle reaches where settlements were concentrated [71]. This present study focuses on the reconstruction of a more comprehensive local societal history from the perspective of landscape and material culture. It employs a thorough archaeological investigation, and fine-grained radiocarbon dating programme, coupled with Bayesian chronological modelling. Through the combination of archaeological evidence, documentary records, refined chronology, and a previous reconstruction of the local palaeoenvironment [72], we aim to unveil the long-term local societal history, and to detect the trajectory of urbanization and its role in the establishment of the trans-regional exchange network.

Study region

The Hami region in eastern Xinjiang

The Hami Region, situated in the eastern margin of Xinjiang, has long been known as "the eastern gate of Xinjiang", connecting the Hexi Corridor to the southeast, the eastern Altai Mountains to the north, the corridor of the

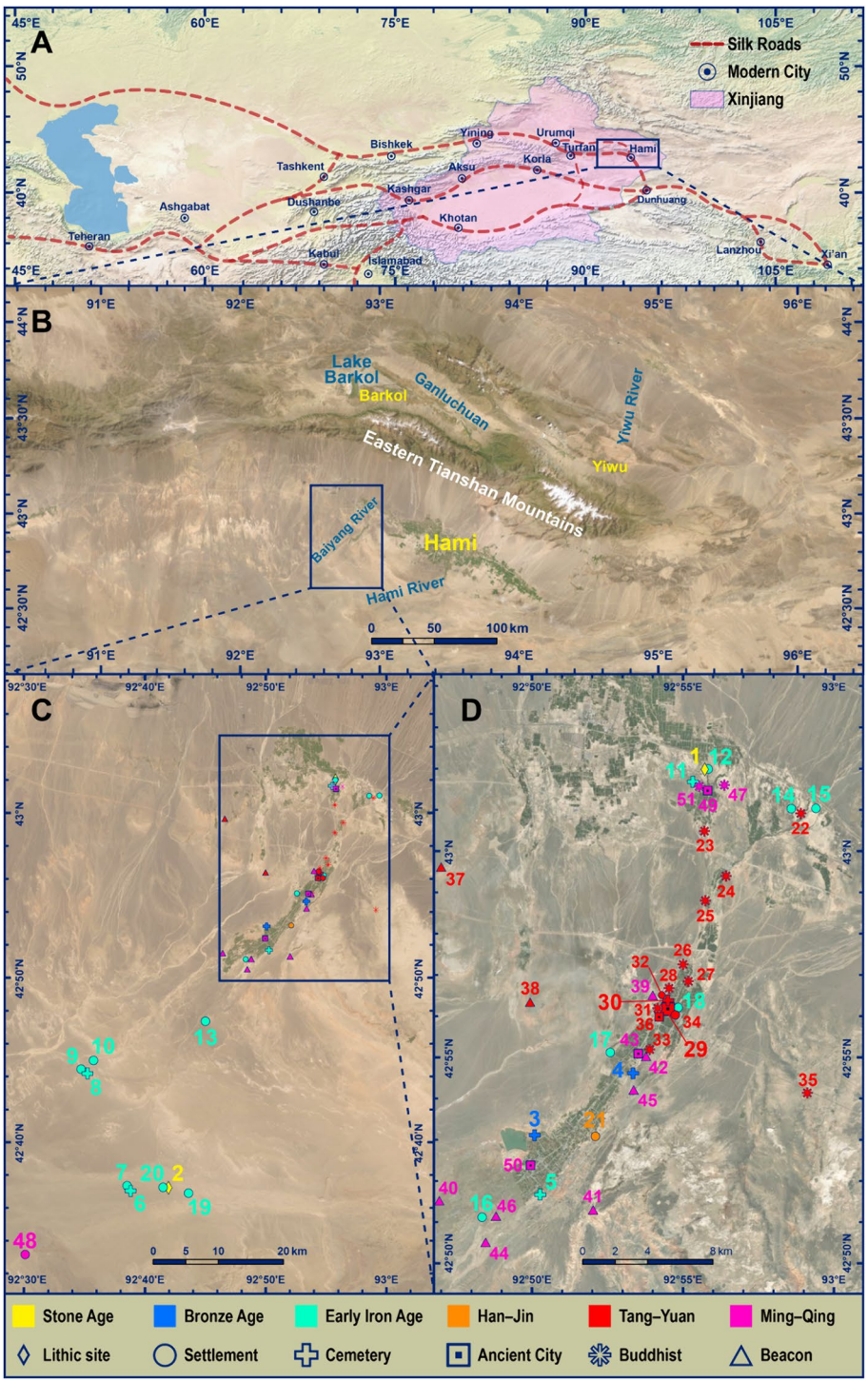

Fig. 1 Maps of the study region at different scales. **A** General map showing the geographic settings of Hami in Xinjiang and the major routes of the Silk Road. (Base map downloaded from http://naturalearthdata.com) **B** Regional map showing the landscape around the Eastern Tianshan Mountains. **C** The entire drainage system of the BYRB, with all relevant archaeological sites marked (with legend at the bottom). Each site is labelled with a distinct identification number in accord with Table S1. **D** Zoomed in map of the upper–middle reaches of the BYRB to better distinguish the clusters of archaeological sites. (Satellite images sourced from: Esri, Maxar, Earthstar Geographics, and the GIS User Community.)

Tianshan Mountains to the west, and the Lop Nor and Tarim Basin to the southwest (Fig. 1a). Modern Hami consists of three major areas: Barkol County in the northwest, Yiwu County in the northeast, and Yizhou District in the south where the city of Hami is sited (Fig. 1b). The Eastern Tianshan Mountains, famous not only for their geographic significance among the seemingly endless Gobi Desert, but also for their prosperous agro-pastoral cultures [31, 32, 47, 73, 74], lie across Hami from west to east, and divide the region into two major zones, the steppe zone and the Gobi Desert–oasis zone (Fig. 1b). The steppe zone is mainly situated around the towering mountains where the relatively higher elevation brings about greater precipitation and lower temperatures. The Gobi Desert–oasis zone occupies most of the lowlands where the climate is ultra arid and the development of oases relies mainly upon the runoff from the mountains, among which two principal oases have developed in the Hami River Basin and the BYRB. The specific geographic settings and the interlaced steppe-oasis ecological systems make this region a 'hotspot' in both the histories of exchange and of conflict [74].

Existing archaeological findings have indicated two distinct cultural traditions rooted in BA communities in Hami. Tianshanbeilu Cemetery in the modern city of Hami shows a strong correlation with both the Late Machang–Siba cultures of the Hexi Corridor to the east, and the Qiemu'erqieke and Andronovo communities to the west in terms of not only material culture, but also biological characteristics [59, 75–80]. Recent research of the Baigetuobie Cemetery on the steppe of Barkol has highlighted its relationship with the Andronovo communities [47], as well as some slab-stone tombs that may belong to the former Qiemu'erqieke Culture. These early exchanges were probably brought by both sedentary agricultural and mobile pastoral lifestyles, which likely profoundly impacted the following eras in Hami [74]. Furthermore, increasing research outputs over ~ the last decade have provided new knowledge in relation to Hami's antiquity, from aspects such as plant utilization [81–85], animal husbandry [57, 58, 86], palaeodiet [87], and palaeodemography and migration [88–90].

The Baiyang River Basin

Situated on the southern piedmont of the Eastern Tianshan Mountains, the BYRB is 60 km west of the Hami River Basin where the modern city of Hami is situated. Formed by several gullies, the water of the BYRB is mainly supplied by mountain precipitation, meltwater runoff, and the emergence of underground springs from the edge of the alluvial fans (Fig. 2a). The entire drainage system assumes an hourglass shape, where several gullies in the upper reaches converge into a narrow single channel in the middle reaches, eventually dispersing into the Nanhu Gobi Desert in the lower reaches (Figs. 1c, 2b–d). Today, the river of the BYRB streams seasonally, maintaining oases in its upper–middle reaches (Fig. 1d). The Chinese name "Bai Yang Gou" is relatively common in arid areas and means "the gully where white poplar grows". Similar to many other oases, the oases of the BYRB experience a warm and arid climate, characterized by abundant sunshine and fertile soil. These conditions make the region an ideal habitat to allow the development of sedentary agriculture from antiquity through to the present. However, the constraint upon water resources has hindered its further development to modern urbanism. As a result, the region nowadays still only supports a town, namely Wupu, and twelve villages, that primarily engage in agricultural production, forming a stark contrast with its apparent greater prosperity in antiquity.

Initial archaeological research of the BYRB traces back to the beginning of the last century and mainly focused on Buddhist relics [91]. More contemporary archaeological research commenced in 1978, with Wupu Cemetery [92], Aisikexia'er Cemetery [93], Ya'er Cemetery [94], South Aisikexia'er Cemetery [95], Lafuqueke Cemetery [96], and Baiyanggou Buddhist Temple [97] being excavated and studied during the following decades. Prior to our investigation starting, a total of 24 ancient ruins in this region had been identified during the third national survey of cultural relics [71].

Materials and methods

Field investigation

Field investigation lays the foundation for further archaeological research and provides the 'key to open the gate' of a region's material history [98, 99]. On the basis of previous investigation [71], a more comprehensive investigation of the BYRB from one end to the other was launched in 2019–2020. As well as reviewing the 24 previously known sites, this investigation also aimed at locating archaeological sites that had previously been missed. By inspecting all sites from both material and landscape perspectives, this investigation was expected to refine the local archaeological sequence and the dynamic distribution of archaeological sites with comprehensive information, as well as providing an observation of the process of urbanization throughout its specific local history. Despite the arid climate, narrow geographic range of habitat, relatively independent oases, and the fragmented nature of relics resulting from natural weathering and disturbance by later anthropogenic activities, this study highlighted several indicators enabling the observation of urbanization with reference to previous approaches: i.e., a population boom, settlement nucleation, massive secondary production, and fortification [100–105].

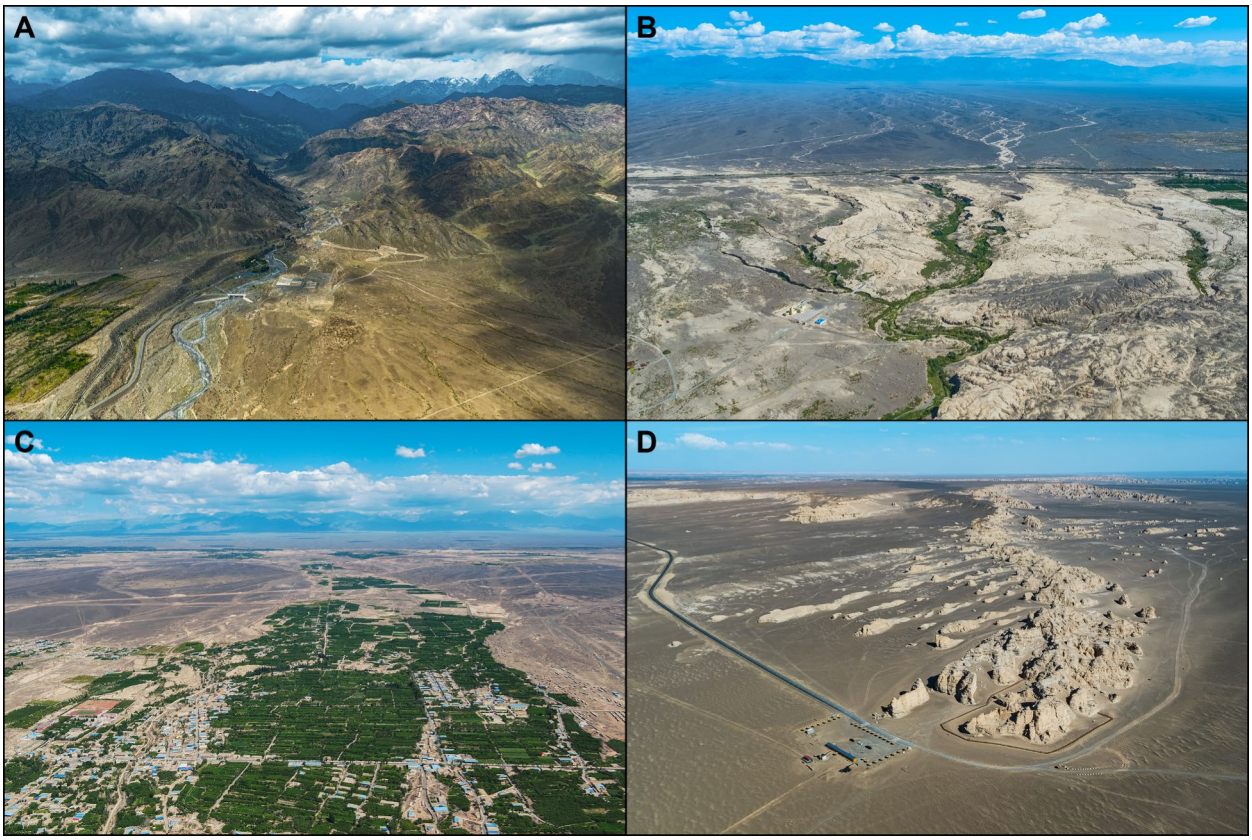

Fig. 2 Aerial photographs of the landscapes in the study region. **A** Landscape of the runoff at the southern margin of the mountains, where the alluvial fan begins. **B** Landscape of the upper reaches of the BYRB, where gullies develop from the margin of the alluvial fan and gradually converge. **C** Landscape of the middle reaches of the BYRB, where oases and settlements develop along the river channel. **D** Landscape of the Aisikexia'er Settlement site in the lower reaches of the BYRB

Radiocarbon dating and Bayesian chronological modelling

In order to provide more precise ages for the individual sites, as well as refined chronology for the relationships between sites, radiocarbon dating and Bayesian chronological modelling was performed [106, 107]. Organic samples chosen from distinct archaeological contexts were collected for radiocarbon dating to, as reliably as possible, represent the age of formation and/or deposition. For cemeteries demonstrating multiple phases, samples for dating were acquired from different burials pre-judged by typology to better span the whole chronology of the cemetery. For sites with complex spatial structure and/or multiple phases of construction, samples were collected from different sections to comprehensively represent the full chronology. Organic inclusions tightly inlaid in the structures were dated to represent the age of construction and/or repair. Human bones, animal bones, and plants with shorter life spans were preferentially selected to reduce the potential influence of 'old carbon' effects, where applicable [108, 109].

Radiocarbon dating was mainly carried out at the Key Laboratory of Western China's Environmental Systems (Ministry of Education) in Lanzhou University (Lanzhou), following a standard protocol that was previously reported [110], although some dates were also acquired from Beta Analytic Inc. (Miami, FL) and Peking University (Beijing) for comparison purposes. All radiocarbon dates were produced by accelerator mass spectrometry (AMS), and the calibration of radiocarbon data was carried out using the online OxCal program (version 4.4.4) with the IntCal20 calibration curve [106, 111, 112].

A radiocarbon dataset from the BYRB was established through combination of the newly produced dates and previously published data to construct a summed probability distribution (SPD) curve using the 'Sum' function and to apply Kernel density estimation (KDE) modeling using the 'KDE_Model' function in the OxCal program [111, 113]. The SPD approach has been previously applied elsewhere to approximate population density during prehistory [114–117], while the KDE method is suggested as a better approach in

summarizing radiocarbon datasets (i.e., produces less 'noisy' datasets, and is less biased by structural features in the radiocarbon calibration curve such as plateaux) [113]. To reduce the influence of archaeological bias [114], a binning process using 'undated events within phases' to summarize the similar radiocarbon dates was employed before applying the KDE modeling [113]. Bayesian Phase modelling was also applied on various clusters of archaeological sites to provide robust estimates for the start and end of use of each grouping (applying the 'Boundary' function in OxCal) [118, 119]. For simplicity, the median values of each start or end Boundary are quoted in the Discussion below [120].

Results

Radiocarbon dating and chronology

This study covered a total of 51 archaeological sites in the BYRB, the geographic and archaeological details of which are reported in Table S1; 82 radiocarbon dates were newly acquired from 33 of these sites, among which 21 dates were reported in previous publications [121–123], and 17 dates were previously mentioned without quoting the raw measurements [72]. The combination of 44 brand new dates with this raw information from the 17 previously mentioned dates [72] is introduced in Table 1. All of the 82 data points generated from our present study, plus another 44 dates that have been previously reported by other studies [55, 82, 84, 86, 89] constitute the full AMS radiocarbon dataset of the BYRB, and this is presented in Table S2, along with comprehensive accompanying information.

Spanning from 2000 BCE to 1950 CE, these 126 calibrated radiocarbon dates represent the chronology of human settlement within the BYRB, and may be of further use in future analyses such as those pertaining to archaeological networks [124–126] and reconstructing palaeodemography on a broader geographic scale [115]. The KDE curves for the BYRB were produced to account for both high frequency noise and archaeological bias, and as well as the original SPD curve [113, 114], are used to represent population history in Sect. 5.1 of this paper.

The application of Bayesian chronological modelling generated more credible ages of several clusters of sites in the BYRB, which are further discussed below. The absolute ages of several well-dated prehistoric archaeological settlements in other parts of Xinjiang, including North Loulan [39], Xintala [127, 128], Aketala and Wupaer [37, 38, 128], Jirentaigoukou [40, 42, 129], Loulan [130], Niya [131], Yuansha [132, 133], and Kuiyukexiehai'er [134] are also used for comparison purposes in order to better understand the trajectory of urbanization in Xinjiang.

Observation of the archaeological complex in BYRB

The 51 archaeological sites investigated in this study span in age from the Stone Age to the Qing Dynasty (1644–1912 CE), among which 24 had been previously reported [71], with the remaining 27 sites newly reported herein. Based upon both the material typology of relics and radiocarbon data, each site was affiliated to a specific period; among these, there were 2 sites assigned to the Stone Age (i.e., before 2000 BCE in lowland Xinjiang), 2 sites to the BA (ca. 2000–1000 BCE in lowland Xinjiang), 16 sites to the EIA (1000–221 BCE in lowland Xinjiang), 1 site to the Han–Jin period (221 BCE–580 CE, covering the time from the establishment of Qin to the eve of Sui), 17 sites to the Tang–Yuan period (581–1368 CE, covering the time from Sui to Yuan), and 13 sites to the Ming–Qing period (1368–1912 CE). Each site was given an independent identification (ID) number (Table S1). Some important illustrative examples of the material relics discovered or unearthed from the BYRB from different periods are exhibited in Fig. 3.

The Stone Age

Two lithic sites were identified during the investigation, namely Tuohuqi (ID 1) and Nanhu (ID 2) (Fig. 1 and Table S1). Located in the upper reaches of the BYRB, the Tuohuqi lithic site sits on an area of undulating wasteland eroded by wind and surface runoff. One piece of a core, 3 pieces of flakes, and 2 pieces of microblades were collected from the ground surface. Made of silicite or shale, the microblades are the discarded proximal and/or distal parts, indicating that the site was probably temporarily occupied for lithic tool processing. Further downstream, towards the furthest extremity of the drainage basin, the Nanhu lithic site lies in the Nanhu Gobi Desert, where the tail-ends of the Baiyang River and Kurukeguole River meet. A set of 211 lithic artefacts, comprising 32 cores (26 discoid, 2 conical, and 1 irregular), 130 ordinary flakes, 28 tools (17 scrapers, 3 awls, 4 choppers, and 4 balls), and 21 processed fragments, were collected on a Yardang table (Fig. 3a). The assemblage and form of these collected artefacts probably indicate Nanhu as a site for elementary production. Unfortunately, preserved stratigraphy of both sites is absent.

The Bronze Age

Two BA cemeteries in the BYRB, namely Wupu (ID 3) and Kalaya (ID 4) had been previously identified, but were further reviewed during this investigation (Fig. 1 and Table S1). Having originally been excavated in 1978 and 1986 [92], the Wupu Cemetery was revealed to have a close relationship with the Yanbulake Culture, and provided the initial BA research impetus within the BYRB.

Table 1 New radiocarbon dates reported in this study, given in years before present (a BP)

Site name	Site type	Site ID	Material dated	Lab code	^{14}C date (a BP)	Uncertainty (a)	Calibrated age (95.4% ranges)
Wupu	Cemetery	3	Plant	Beta-501060	2700	30	910–800 BCE
Wupu	Cemetery	3	Plant	Beta-501061	2450	30	760–410 BCE
Wupu	Cemetery	3	Plant	Beta-501062	2450	30	760–410 BCE
Kalaya	Cemetery	4	Human bone	Beta-483693	3170	30	1510–1390 BCE
Kalaya	Cemetery	4	Human bone	LZU20562*	2930	20	1220–1040 BCE
Kalaya	Cemetery	4	Human bone	Beta-524405	2980	30	1380–1050 BCE
Kalaya	Cemetery	4	Human bone	Beta-535070	3520	30	1940–1740 BCE
Kalaya	Cemetery	4	Human bone	LZU20564*	3540	20	1950–1770 BCE
Kalaya	Cemetery	4	Plant	LZU20183*	2450	20	750–410 BCE
Ya'er	Cemetery	5	Bone	BA	2405	20	660–400 BCE
Ya'er	Cemetery	5	Bone	BA	2325	35	520–220 BCE
Ya'er	Cemetery	5	Bone	BA	2685	20	900–800 BCE
Ya'er	Cemetery	5	Bone	BA	2880	20	1190–980 BCE
S. Aisikexia'er	Cemetery	6	Human bone	BA110455	2480	35	780–420 BCE
S. Aisikexia'er	Cemetery	6	Bone	BA110456	2345	30	520–370 BCE
S. Aisikexia'er	Settlement	7	Reed	LZU20170	2310	20	410–260 BCE
S. Aisikexia'er	Settlement	7	Reed	LZU20171	2440	20	750–410 BCE
Aisikexia'er	Settlement	9	Reed	LZU20168	2480	20	770–510 BCE
Aisikexia'er	Settlement	9	Straw	LZU20169	2420	20	730–400 BCE
Aisikexia'er	Kiln	10	Charcoal	LZU20187	2570	30	810–560 BCE
Tuxike	Settlement	21	Straw	LZU20057	1840	20	120–250 CE
Baiyanggou	Buddhist	22	Straw	Beta-524400	780	30	1210–1280 CE
Baiyanggou	Buddhist	22	Straw	Beta-524401	920	30	1030–1210 CE
Baiyanggou	Buddhist	22	Straw	LZU19303*	1040	20	980–1040 CE
Baiyanggou	Buddhist	22	Wood	LZU19304*	1050	20	900–1030 CE
Baiyanggou	Buddhist	22	Straw	LZU19305*	850	20	1160–1260 CE
Baiyanggou	Buddhist	22	Straw	LZU19308*	1080	20	890–1030 CE
Baiyanggou	Buddhist	22	Straw	LZU20172*	900	20	1040–1220 CE
Baiyanggou	Buddhist	22	Reed	LZU19309*	950	20	1030–1160 CE
Baiyanggou	Buddhist	22	Charcoal	BA141923	900	25	1040–1220 CE
Baiyanggou	Buddhist	22	Charcoal	BA141924	865	20	1150–1230 CE
Tuohuqi	Buddhist	23	Straw	LZU20179*	950	20	1030–1160 CE
Tuoma	Buddhist	24	Reed	LZU20173*	990	20	990–1160 CE
Tuoma	Buddhist	24	Straw	LZU22006	880	30	1040–1230 CE
Tuoma	Buddhist	24	Branch	LZU22005	870	30	1040–1270 CE
Qiapu	Buddhist	25	Branch	LZU22004	360	30	1450–1640 CE
Qiapu	Buddhist	25	Branch	LZU20180*	940	20	1030–1160 CE
Lafuqueke	City	29	Straw	LZU19-3*	140	20	1670–1950 CE
Lafuqueke	Buddhist	31	Cloth	LZU19301	80	20	1690–1920 CE
Lafuqueke	Buddhist	31	Human bone	Beta-483690	180	30	1650–… CE
Lafuqueke	Storage	32	Straw	LZU20165	450	30	1410–1480 CE
Lafuqueke	Storage	32	Animal bone	LZU20554	280	20	1520–1670 CE
Lafuqueke	Storage	32	Charcoal	LZU20053	330	20	1490–1640 CE
Kazima	Grotto	33	Straw	LZU20178*	1090	20	890–1020 CE
Nuogayibulake	Buddhist	35	Tamarisk	LZU20164	1020	20	990–1040 CE
Nuogayibulake	Buddhist	35	Tamarisk	LZU21356	1090	20	890–1020 CE
Xiaoquanzi	Beacom	38	Wood	LZU21079	1420	20	600–660 CE
Xiaoquanzi	Beacom	38	Reed	LZU21084	960	20	1020–1160 CE
Xiaoquanzi	Beacom	38	Straw	LZU23622	710	20	1270–1380 CE

Table 1 (continued)

Site name	Site type	Site ID	Material dated	Lab code	^{14}C date (a BP)	Uncertainty (a)	Calibrated age (95.4% ranges)
Xiaoquanzi	Beacom	38	Reed	LZU23623	1080	20	890–1030 CE
Kazima	City	43	Wood	LZU20054*	120	20	1680–1930 CE
Kazima	City	43	Wood	LZU21074	70	20	1690–1920 CE
Kazima	City	43	Wood	LZU21358	180	20	1660–… CE
Kaga	Beacon	44	Tamarisk	LZU21320	330	20	1490–1640 CE
Talike	Beacon	46	Straw root	LZU21334	300	20	1500–1650 CE
Tuohuqi	Buddhist	47	Straw	LZU20186*	320	20	1490–1650 CE
Tuohuqi	Buddhist	47	Straw	LZU21339*	340	20	1470–1640 CE
Sanpu	City	49	Straw root	LZU21311	70	20	1690–1920 CE
Wupu	City	50	Straw	LZU21299	140	20	1670–1950 CE
Wupu	City	50	Straw	LZU21078	120	20	1680–1930 CE
Wupu	City	50	Wood chuck	LZU21343	150	20	1660–… CE

Dates previously mentioned in [72] were labelled with an asterisk after each relevant lab code

Typologically and absolutely dated to the Late BA (up to 1200 BCE) and EIA, the chronology, biological anthropology, and subsistence of the Wupu people have been previously reported in detail [84, 86, 90] (Table S2).

Situated in the middle reaches of the BYRB, the Kalaya Cemetery preserved more than 1000 tombs. Pottery, bronze, iron, wood, textile, and stone artefacts were discovered in the cemetery during the investigation, among which the double-eared canister-shaped pottery jar decorated with alternated vertical straight and wavy lines (Fig. 3b) was recognized as one of the typical types of vessels that were popular in the early phase of the BA Tianshanbeilu Culture [33]. The characteristics of other relics were indicative of a strong relationship with the Wupu, Ya'er (ID 5) and Yanbulake Cemeteries during the EIA. Spanning the period from 2000 to 400 BCE, radiocarbon dates of the Kalaya Cemetery also indicate the continuous utilization of this grand cemetery during the BYRB's BA and EIA (Table 1 and Table S2).

The Early Iron Age

The BYRB witnessed a flourishing of archaeological sites during the EIA. In addition to the tombs spanning from the BA into the EIA at two cemeteries, 16 sites were assigned to this period (Fig. 1 and Table S1), including excavated cemeteries such as Tuohuqi (ID 11) in the upper reaches, Ya'er [94] in the middle reaches, and Aisikexia'er (ID 8) [93] and South Aisikexia'er (ID 6) [95] in the lower reaches. These cemeteries strongly indicate the complexity of the local society through their well-organized layout and evident funeral and ritual processes, as well as the transition from single burials of individuals to multiple-burials of families/groups over time. Tuohuqi (ID 12), Baiyanggou (14), and Qiaxi (ID 15) settlements in the upper reaches, Akedun (ID 17) and Gaotai (ID 18) settlements in the middle reaches, and Aisikexiaer Pottery Kiln (ID 10), Tuokelong Smelting (ID 13), Kurukeguole (ID 19) and Nanhu (ID 20) settlements in the lower reaches are all newly identified EIA sites (Fig. 1 and Table S1).

Carpentry flourished in Xinjiang during the EIA, leaving an abundance of wooden artefacts in the ruins and tombs, such as bows and arrows [56], farm implements, vehicles, and musical instruments. The wooden farm implements and baked cereal foodstuffs that were frequently found in the burials strongly indicate the strengthening of agriculture. Tens of wooden-cart wheels, usually with traces of use on their edges, were discovered from Kalaya, Wupu, and Ya'er Cemeteries during the present investigation and previous excavations (Fig. 3c), strongly suggesting the popularity of such vehicles in the EIA of the BYRB's. Furthermore, eleven well decorated musical instruments, namely Konghou (Chinese harps), were unearthed from South Aisikexia'er Cemetery during the excavation, which are regarded as a symbol of exchange around the Tarim Basin, and the rise of ritual ceremony and spiritual life [135, 136].

A cluster of archaeological sites in the lower reaches of the BYRB, including Aisikexia'er (settlement (ID 9), pottery kiln, and cemetery), South Aisikexia'er (settlement (ID 7) and cemetery), and the satellite sites (Tuokelong smelting site, and Kurukeguole and Nanhu settlements), is evidence of settlement nucleation, well-developed multiple production, and fortification (Figs. 1c, 2, and 4). Among these sites, the castle-shaped Aisikexiaer settlement constructed on a Yardang table (Fig. 4a) is probably the most impressive, acting as a centre within the lower reaches. Though having suffered from a serious collapse

Fig. 3 typical material relics from the BYRB spanning different periods. **A** Stone artefacts collected from the Nanhu lithic site (ID 2). **B** A double-eared canister-shaped pottery jar decorated with alternated vertical straight and wavy lines unearthed from the Kalaya Cemetery (ID 4). **C** A typical piece of wooden-cart wheel collected from Ya'er Cemetery (ID 5) during the EIA. **D** A bronze mirror with inscriptions relating to the Eastern Han Dynasty (25–220 CE) unearthed from tomb M476 of the Han–Jin period at Ya'er Cemetery. **E** A set of metalworks unearthed from Lafuqueke Cemetery (ID 30) from the Tang–Yuan period. **F** Broomcorn millet grains unearthed from the Lafuqueke Storage site (ID 32), dated to the Ming–Qing period (Table S1)

due to erosion by wind and water, the site still retains several houses and a 50 m long, 8 m tall wall, with gateways and lookout windows. The investigation also indicates a vast surrounding region covered by drift sands of archaeological interest. The pottery kiln site is 1.7 km northeast of the settlement site and collapsed some time during its long history. Within an area of 400 m^2, three locations were identified due to the dense debris of kiln walls and potteries, as well as a 20 cm thick layer of plant ash and charred woods at each location (Fig. 4b). Four similar pottery kilns were also discovered in the Nanhu site which is 4 km east of the South Aisikexia'er. The

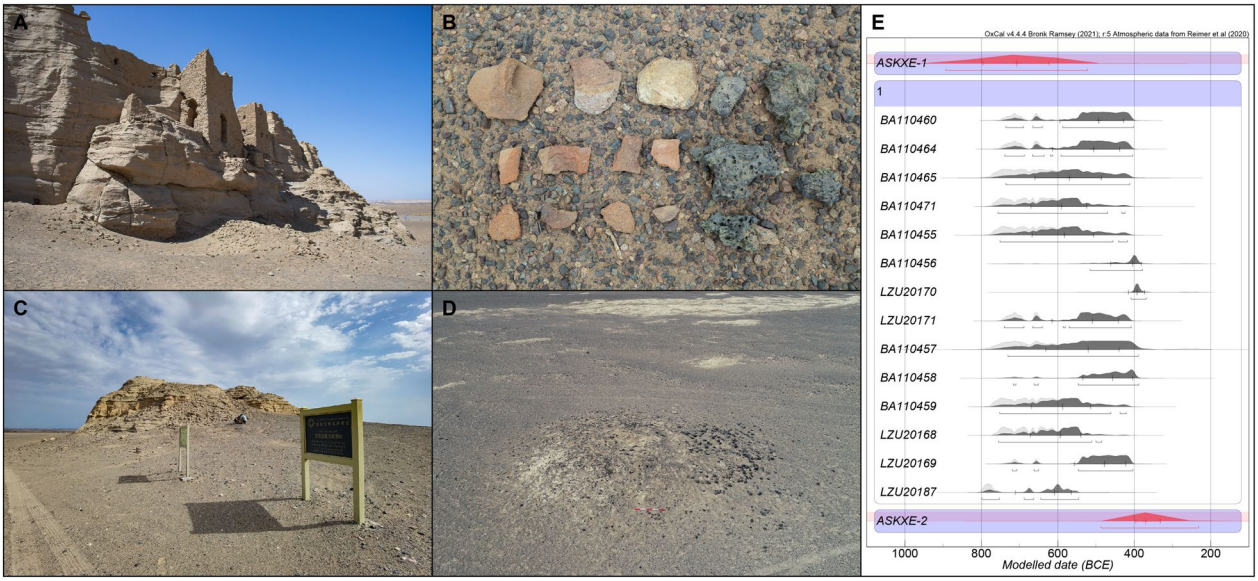

Fig. 4 Landscape, cultural remains, and chronology of the Aisikexia'er cluster in the lower BYRB. **A** The castle-shaped Aisikexia'er settlement. **B** Pottery shards and slag at the site of Aisikexia'er Pottery Kiln. **C** South Aisikexia'er, with the settlement situated on the tableland of a Yardang and the cemetery in the neighbouring Gobi Desert. **D** Tuokelong smelting site in the Nanhu Gobi Desert. **E** Plot of the calibrated radiocarbon dates in black and the modeled start and end boundaries in red (Table S2)

Tuokelong smelting site was identified by an oval mound densely covered by smelting slag, debris of flue piles, and a little iron slag, which seems to represent a collapsed smelting furnace. The typology of the pottery shards near the furnace indicates the site as coetaneous with the other Aisikexia'er sites. To date, this cluster of sites has yielded 14 radiocarbon dates and was subject to Bayesian chronological modelling to further refine the span of use (Table 1 and S2; Fig. 4e). The output provides an approximate span of 708 to 372 BCE for the chronology of the cluster.

The Han–Jin period

There are very few remains in the BYRB dating to the Han–Jin period, with only the Tuxike site (ID 21) and one tomb, namely M476, in Ya'er Cemetery, having been identified. The Tuxike site in the middle BYRB is a collapsed building constructed with adobe, and yielded the sole radiocarbon date from this period. Tomb M476 in Ya'er Cemetery is a double burial, with accompanying pottery jar and a bronze mirror. The mirror exhibits some typical characteristics of the Eastern Han Dynasty of China and has an eight-character inscription that roughly translates as, "Since long missed, beg not so soon for oblivion" (Fig. 3d). According to the textual records relating to the histories of the competing Eastern Han and Xiongnu regimes, the possible location of the old Yiwu City, and the history of garrison farming (Tuntian) [137], the identity of the tomb owner could likely relate to such an agrarian garrison.

The Tang–Yuan period

Another abundance of archaeological remains in the BYRB dates to the Tang–Yuan period, including settlements, Buddhist constructions, and the beacon tower system (Figs. 1 and 5; Table S1). Identified as the seat of the Nazhi County in the Tang Dynasty [96, 137], Lafuqueke City (ID 29) (Fig. 5c), along with its public cemetery (ID 30) (Fig. 5d), Buddhist temple (ID 31), and storage site (ID 32) in the middle reaches undoubtedly provided the central node of the BYRB at that time (Fig. 5b–d). Investigations at the ancient city, as well as the Buddhist temple, have been carefully reported previously [121, 122]. An excavation of the public cemetery was carried out synchronously with the investigation and have provided some evidence for trans-regional migration and communication [88, 89, 138] (Fig. 3e). The storage site is on the same elevation as the Yardang tableland where the city and the cemetery, as well as the Mamiqi settlement (ID 34) and Sipu City (ID 36), are seated. It is likely that the terrain of these sites used to be continuous at that time, and was cut off due to the later formation of gullies (Fig. 5b). Thus, the storage site is judged as contemporaneous with the other sites, and was utilized until later times, as evidenced by the radiocarbon dates of the remains of the grains left in situ (Table 1). The radiocarbon dates obtained from

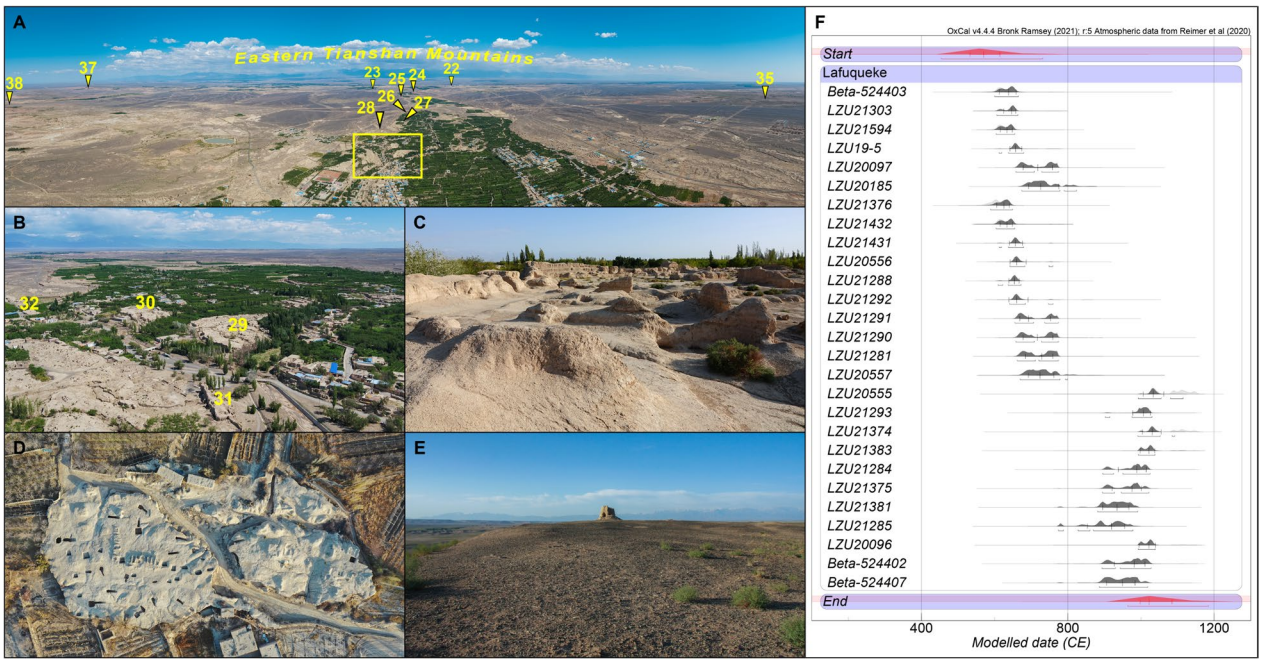

Fig. 5 Landscape, cultural remains, and chronology relating to the Lafuqueke cluster around the middle BYRB. **A** The panorama of the upper–middle BYRB with relevant sites labelled. **B** A local landscape of the Lafuqueke cluster with relevant sites labelled. **C** Internal view of the Lafuqueke City. **D** Orthophoto of the Lafuqueke Cemetery. **E** Landscape at the Xiaoquanzi Beacon. **F** Plot of the calibrated radiocarbon dates in black and the modeled boundaries in red (Table S2)

the city, cemetery, and Buddhist temple (n = 30) were included within the Bayesian modelling, with the elimination of the obvious younger outliers that potentially represent later repairs (n = 3) (Fig. 5f). The chronology of the Lafuqueke cluster spans from 569 to 1022 CE. As revealed by previous research, a warning system of beacon towers and other facilities was erected during the Tang Dynasty [123], among which, the Daquanzi (ID 37) and Xiaoquanzi (ID 38) (Fig. 5e) beacon towers adjacent to the BYRB were also involved in the investigation as the observation of fortification.

In addition, this period also witnessed the boom and bust of Buddhism, which has left the BYRB with a unique treasure of cultural heritage (Fig. 6). A cluster of Buddhist constructions was established along the Baiyang River (Figs. 1 and 5a), including the temples of Baiyanggou (ID 22) (Fig. 6a), Tuohuqi (ID 23) (Fig. 6b), Tuoma (ID 24) (Fig. 6c), Qiapu (ID 25), Kumutulu (ID 26), Yangdake (ID 27), Jialangjulong (ID 28) (Fig. 6d), and Lafuqueke (Fig. 6e), as well as the Kazima Grotto (ID 33) (Fig. 6f) and two groups of buildings inside the Lafuqueke City. The chronology of the Buddhist remains is represented by 27 radiocarbon dates and spans from 940 to 1254 CE, as produced by the Bayesian chronological modelling (Fig. 6g), which is consistent with existing historical evidence [139]. Nuogayibulake (ID 35) was previously identified as a beacon tower, although it is currently suspected as representing another Buddhist Room considering its lowland location and coeval chronology.

The Ming–Qing period

The Ming–Qing period witnessed the further expansion of living space within the BYRB, and essentially provides the pattern of modern settlements (Fig. 1). As indicated by documentary records from the Qing Dynasty, the city of Lafuqueke (Nazhi) was probably abandoned, though retaining some limited human activities (Fig. 3f and Table S2). Instead, three smaller cities emerged to replace Lafuqueke, as identified within this investigation, namely Sanpu (ID49), Kazima (ID 43; probably the Sipu City named in documents), and Wupu (ID 50). Beacon towers at Youkuribage (ID 39), Zhibiannongchang (ID 40), Maoliuquan (ID 41), Kazima (ID 42), Kaga (ID 44), Kalaya (ID 45), and Talike (ID 46) constitute a warning system in the BYRB from the Qing Dynasty. Two pagodas in the upper reaches, namely Tuohuqi (ID 47) and Baigu (ID 51), were built as monuments by the Qing Government for the slain soldiers in the resistance of rebellion. The Huyangwo (or Danqiaoka, ID 48) settlement was identified deep into the Gobi Desert with two defensive houses, which is speculated to have been a facility, namely Xun, of the Qing Government.

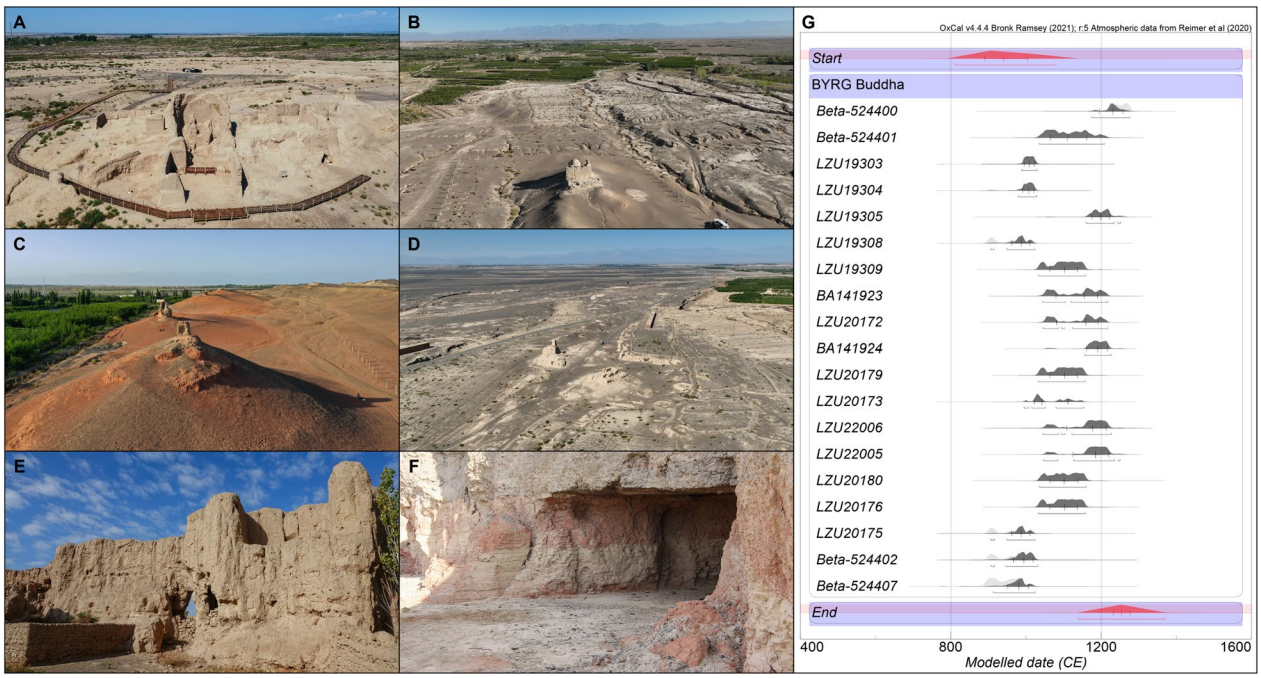

Fig. 6 Images and chronology of the Buddhist remains. **A** The Great Buddha Hall at Baiyanggou Temple. **B** Landscape at the Tuohuqi Temple. **C** Landscape at the Tuoma Temple. **D** Landscape at the Jialangjulong Temple. **E** Main building of the Lafuqueke Temple. **F** Entrance of the Kazima Grotto. **G** Plot of the calibrated radiocarbon dates in black and the modeled boundaries in red (Table S2)

Discussion

The trajectory of urbanization and the possible driving forces

In this section, we highlight the major steps towards urbanization, as evidenced through observations pertaining to landscape, subsistence, settlement pattern, and ritual practices, as well as seeking to address some possible driving forces for the variation seen.

As with hundreds of other lithic sites distributed across the Gobi Desert that have been identified in recent years, the lack of preserved stratigraphy presents a major issue in establishing the chronology of the Stone Age remains in Hami. To date, only at the Qijiaojing microlithic site, 130 km to the west, have researchers discovered such a stratigraphy, with ages of ca. 9000 BCE obtained via optically stimulated luminescence [140]. The warming climate from the beginning of the Holocene (ca. 9700 BCE) could have been a positive factor for the survival of hunters-gatherers [141]. However, some points such as the judgment of cultural layers remain debatable for the site. Estimated through typological analysis, the two lithic sites are possibly from the Late Palaeolithic [142, 143]. However, despite lacking in absolute chronology, the discovery of Stone Age remains in the BYRB, including the presently arid Hami Basin, provides evidence of hunting-gathering, and thereby is likely indicative of a more habitable environmental situation in the lower reaches compared to the present day.

The local BA in Hami witnessed the onset of agriculture and a sedentary lifestyle, as well as communication between East Asia and the Eurasian Steppe as evidenced by human migration, the spread of technology, and material exchange [74]. Our investigation at Kalaya Cemetery strongly indicates a synchronous development of sedentism and the interconnection between the oases of the BYRB and Hami City across the entire BA. As revealed by the SPD and KDE plots, the intensity of human activity in the BYRB generally remained stable (Fig. 7a). The overall cooling and wetter climate during the Late Holocene (since ca. 2200 BCE) in arid central Asia [141, 144] may have been beneficial to the development of oasis civilizations. Relatively stable hydrological conditions are also considered to be an advantage for the growth of the early sedentary society in the BYRB [72] (Fig. 7a). However, further research on these early remains is still needed to better understand the evolution of the local society during the BA. Although there is a lack of quantification regarding the palaeodemography, the scale of the Kalaya and Tianshanbeilu Cemeteries, each containing over a thousand burials, may suggest the considerable size of the population to some extent [59, 80]. Relevant research has also revealed an assemblage of millet farming and herbivore pastoralism, supplemented by hunting, in human

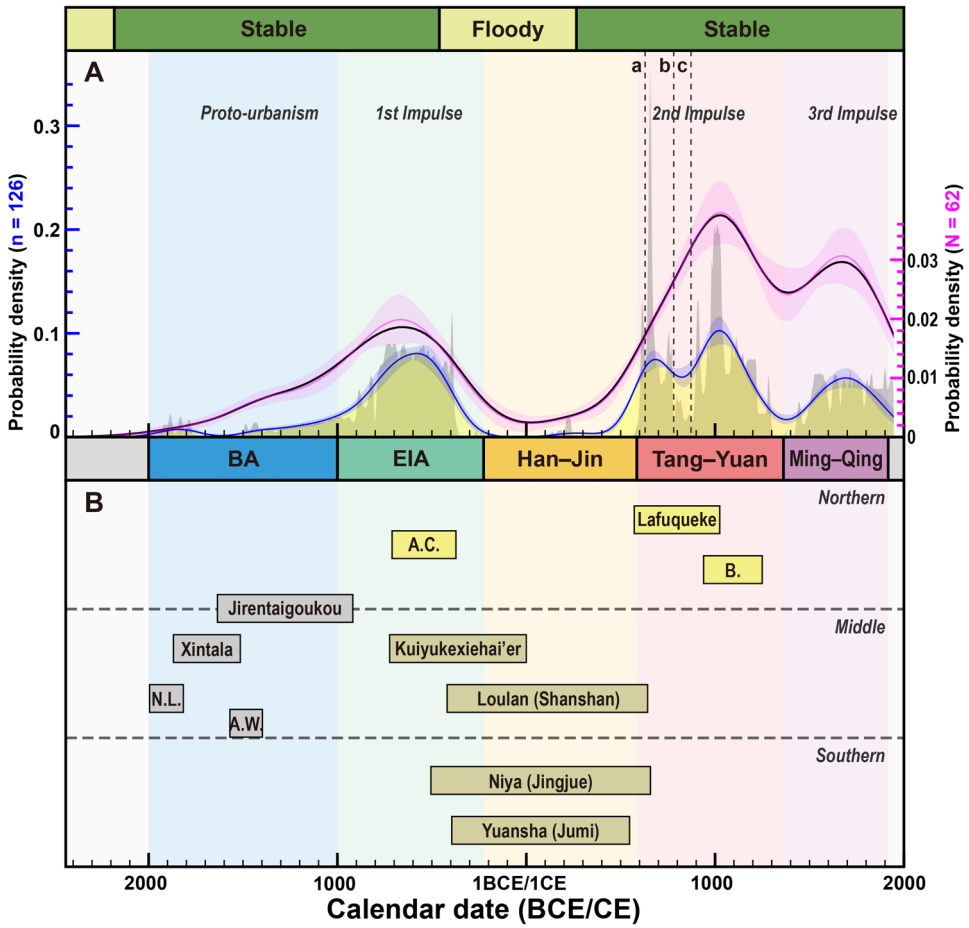

Fig. 7 The trajectory of societal evolution and urbanization through time. **A** Variations evident in the SPD (grey shadow), KDE modelling (yellow shadow with its mean ± 1σ in blue), and summarized KDE modelling (purple line with its mean ± 1σ in pink) of the local society (Table S2) and environmental conditions [72] in the BYRB. Three labelled events are: a) Tang Government established Yizhou Prefecture and Nazhi County in 630 CE; b) Tubo, the Tibetan regime, captured the Protectorate of Beiting in 780 CE; c) Gaochang Uighur Kingdom re-took the Hami Region in 876 CE [122]. **B** Trajectory of urbanization in different regions among the Silk Road network of Xinjiang. A.C. stands for the Aisikexia'er cluster, B. for Buddhist remains in the BYRB, N.L. for North Loulan, and A.W. for the Aketala-Wupaer cluster

subsistence [59, 87], a well-developed pottery production, and a gradually developing bronze metallurgy [75, 76, 145]. Though the settlement of these communities hasn't yet been identified, it appears that the continuous development of sedentism, packaged with agro-pastoralism and pottery-bronze production, had formed a sizeable local society, which firmly laid the foundation for further urbanization.

As reported above, the EIA in the BYRB witnessed the flourishing of culture and society, among which, several specific issues are worth highlighting: (1) the boom of settlements and, probably, population, as reflected by the expansion of archaeological sites from the middle reaches to the entire basin and the increase of cemeteries (Figs. 1c and 7a); (2) settlement nucleation and fortification as observed at the Aisikexia'er cluster in the lower reaches (Fig. 4); (3) the prosperous secondary production of metallurgy, pottery-making, textile manufacture, and carpentry, as indicated by the remains of production sites (Fig. 4) and the implements contained within burials [93, 95, 136]; (4) the development of regional and trans-regional transportation, as indicated by the rise of horse riding in the northern steppes [57], the widespread presence of wooden vehicles (Fig. 3c), and the trans-regional interconnection with the Tarim Basin [43, 134]; and (5) the enrichment of spiritual and ritual activities as indicated by the funereal customs and the Konghou musical instrument [95, 135, 136]. Based on this evidence, we estimate that the BYRB experienced an impulse of urbanization during the EIA. As well as these internal factors, threats brought by the rise of the mounted pastoralists in the northern steppes [57, 58] could possibly have provided an external driver in forcing the formation of the

fortified cities. Since then, the interaction between the farmers and the nomads has become a recurrent theme in Xinjiang's history.

The Han–Jin period in the BYRB appears to be dominated by the theme of decline (Figs. 1c and 7a). Possible contributory factors include: (1) the unstable local hydrological condition [72]; (2) the geopolitical competition between sedentism and nomadic regimes, especially between the Han and Xiongnu [74, 123]; (3) the shift of sedentary population to the neighbouring Hami Oasis, which could also be a result of the former factors; 4) that the population retreated to the upper–middle reaches during this period and their archaeological remains might potentially have been erased by subsequent human activities in the area.

The BYRB then welcomed a 'Golden Age' of local society during the Tang–Yuan period marked by the replenishment of settlements, extensive settlement nucleation and urbanization in the upper–middle reaches, the establishment of warning systems, the peak of garrison farming and agriculture, as well as the prosperity of Buddhism (Figs. 1, 5–7). In contrast to the abandoned lower reaches, settlements drastically developed and nucleated around two sites, respectively in the upper and middle reaches, those of the Baiyanggou Temple as the centre of Buddhism of the entire Hami Region and the Lafuqueke City as the seat of Nazhi County (Fig. 1d). Unlike many other coeval cities in Xinjiang that were primarily built in support of Tang's military aims, the urbanism at Lafuqueke City developed more spontaneously, which was mainly driven by the local society [122]. Of note, a short interval of development has been detected in the SPD and KDE curves, which is consistent with the local history of social unrest [122] (Fig. 7a). Such unrest was recently suggested to be the result of geopolitical conflicts induced by the favourable warm and wet climatic conditions [146]. After the period of unrest, the flourishing of Buddhism symbolized both a well-developed economy [147] and a distinctive aspect of the local society [148]. We argue that the rise of Buddhist settlements and temples can be considered to represent a unique form of the local urbanism.

After experiencing another decline during the transition from Tang–Yuan to Ming–Qing, a renaissance of settlement occurred from the sixteenth century CE onwards in the BYRB, as revealed by archaeological evidence (Figs. 1 and 7a). However, Lafuqueke City was almost abandoned and no longer the centre of the BYRB, along with the shift of official transportation routes to the upper reaches [122] (Table S2). The rise of three towns surrounded by a warning system reveals a decentralized urbanism during the Qing Dynasty [123] (Fig. 1d), which also shapes the contemporary pattern of settlements in the BYRB.

Re-evaluating the role of urbanism in establishing an exchange network in Xinjiang

Lowland sedentary agriculture and highland nomadic pastoralism are 'two sides of a coin' in the subsistence practices employed during Xinjiang's antiquity [19, 74, 129]. Researchers have highlighted the role of nomadic ecology traversing the mountain zones in promoting trans-regional exchanges [149, 150]. However, the contribution of oasis sedentism to the establishment of the trans-regional network has not been well illustrated. Heavily reliant upon the water runoff from the neighbouring high mountains and deeply involved in the interaction between the civilizations of the steppes and the oases, the ancient settlement of the BYRB acted as an epitome of Xinjiang's broader lowland civilization, and is likely representative of arid central Eurasia more generally. Here, the reconstruction of a 4000 year local societal history of the BYRB (Fig. 7a) and the combination of archaeological evidence from other regions (Fig. 7b) enables us to re-consider the role of urbanism in the establishment of the broader exchange network in Xinjiang.

One of the perennial issues with Xinjiang's prehistoric archaeology is the lack of settlement remains associated with the prosperous cultures buried in the tombs. As indicated by the burials, Xinjiang's lowlands experienced the establishment of oasis ecology during the BA, which enabled people to subsist and develop in the arid zones [59, 151, 152]. As more and more settlements have been identified and excavated over the recent decade, the features of sedentism in prehistoric Xinjiang are becoming clearer. Investigations of the Loulan region in eastern Tarim produced evidence of sedentism in North Loulan for the mysterious Xiaohe Culture [39]. Almost synchronously, the on-going excavation at Aketala-Wupaer, a cluster of at least 38 archaeological sites distributed on the oasis of Kashgar in western Tarim, has raised some indications for nucleation and the hierarchy of settlements, well-developed agriculture, and bronze production [37, 38]. The successive occupation of this region from the second to the first millennium BCE suggests a great potential to further detect the trajectory of the evolution and urbanism of Xinjiang's sedentary society in the future [37]. Excavations at Adunqiaolu and Husita sites at Bortala in northwestern Xinjiang have shed light on the seasonal dwellings of the Andronovo Cultural Complex during the steppes' Middle–Late Bronze Age (ca. 1800–1000 BCE) [45, 54, 153], while the neighbouring Ili region witnessed the development of a large, year-round settlement at Jirentaigoukou [40]. Based upon the foundation of agro-pastoral production, massive secondary production started to develop along with the remarkable growth of population, which further resulted in the complexification of the local society in the Ili River Valley [41,

42]. Though many traces have been detected in various archaeological sites, it is still too early to declare 'urbanism' in Xinjiang's BA, as yet. Future excavations and research on these sites should contribute to our increased understanding. Here, we suggest the description of this period as 'proto-urbanism', with reference to previous concepts [154], in which the growth of a sedentary population and economy laid the foundation for the cities and states to take off (Fig. 7).

The first impulse for true urbanization in Xinjiang emerged during the EIA. Similar to the pattern of the Aisikexia'er cluster in the BYRB (Fig. 4), the seed of the city and state also germinated in the fertile soil of the northern Tarim Basin, such as at the Kuiyukexiehai'er Ancient City in Luntai County [134, 155], followed by some well-known cities around the broader basin, such as Loulan, Niya (Jingjue), and Yuansha (Jumi) [130–133]. These early city-states soon interconnected the lowland Xinjiang as a whole [43] and evolved into the Thirty-Six Kingdoms joined by the early Silk Road network [44], and became involved in the competition between the Han and Xiongnu Empires [156]. Similar to the Mediterranean world and Mesopotamia [103, 157], one of the crucial driving forces underlying the evolution of city-states–kingdoms–Empire in Xinjiang was the unceasing growth of urban population and production economy, which was also the key for promoting trans-regional communications and exchange. The rise of mounted pastoralists or nomads, not only boosted the communications between different regions [149, 150], but might also have triggered the evolution of the sedentary society in Xinjiang. In contrast with the prosperous Tarim Basin, the decline of urbanism in the BYRB during the Han–Jin period (Fig. 7) also hindered transportation and trade, which therefore prevented the Eastern Tianshan Mountains from being connected to the early Silk Road networks. It seems that during the seventh century CE a second impulse of local urbanization was accompanied by a Golden Age in the BYRB (Fig. 7), together with the competition between Tang and Tubo, that promoted trans-regional exchange and consequently triggered the opening of the New North Route and the northward shift of Xinjiang's Silk Road [146, 156, 158, 159]. Although less intensive, the third impulse of urbanization in the BYRB during the Qing Dynasty prominently shaped the region's modern form and, importantly, maintained the region's position within the trans-regional network through to the modern day.

Conclusion

Three impulses of urbanization detected in the BYRB took place respectively during the EIA, the Tang–Yuan period, and the Qing Dynasty. The first impulse of urbanization in the BYRB occurred synchronously with that in the adjacent Tarim Basin, which established early states and promoted the trans-regional network in the oases of Xinjiang. The declining local trajectory of urbanization during the subsequent Han–Jin period, on the contrary, likely impeded the region's interconnection with the early Silk Road network. The second impulse of urbanization witnessed the 'Golden Age' of the local society and played a profound role in shaping the Silk Road during the Tang Dynasty. Among which, the flourishing of Buddhist settlements could also be regarded as a specialized outcome of urbanism. The final impulse of urbanization since the Ming–Qing period acts as a bridge between the region's antiquity and modern times in shaping the layout of contemporary local society.

This study has laid a solid archaeological foundation for future research on the local society of the BYRB and should be instructive for the further exploration of Xinjiang's antiquity. Future exploration of BA settlements in Xinjiang are suggested to allow the potential for the detection of the onset of urbanism. The sequence of urbanism detected in the BYRB is iconic and of reference value for the broader oasis zone in central Eurasia. Moreover, the role of urbanism in the formation of the trans-regional exchange network has been highlighted. Further validation of the role of urbanism in the trans-regional exchange network from various regions in central Eurasia will be helpful to improve our understanding of the topic.

Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

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Author contributions

Yongqiang Wang: conceptualization, Investigation, Resources, Funding acquisition, Writing–Original draft. Yi Chen: Investigation, Writing–Original draft. Huihui Cao: formal analysis, Investigation, Data curation. Ruiliang Liu: writing–Original draft. Richard A. Staff: writing–Review & editing, Formal analysis. Linyao Du: writing–Original draft, Visualization. Xiao Yuan: formal analysis, Investigation. Shanjia Zhang: investigation, Funding acquisition. Jian Ma: resources, Supervision, Funding acquisition. Menghan Qiu: conceptualization, Formal analysis, Investigation, Writing–Original draft, Writing–Review & editing, Visualization.

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Data availability
All data reported in this study are available in supplementary information.

Declarations

Competing interests
The authors declare no competing interests.

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