Archaeological and Anthropological Sciences (2026) 18:154
https://doi.org/10.1007/s12520-026-02516-3

RESEARCH

Tracing herding strategies in the Samarkand Oasis: isotopic and proteomic insights from Kafir Kala (Samarkand, Uzbekistan)

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Received: 23 May 2025 / Accepted: 28 May 2026

Abstract

The archaeological complex of Kafir Kala is one of the most important sites in the Samarkand oasis, strategically located just a few miles from the main city and along the major junction of the Silk Road. After more than twenty years of systematic archaeological investigation, the importance of Kafir Kala as a nodal point within the broader Eurasian connection network was recognised by its inclusion on the UNESCO World Heritage List in 2023 as part of the Silk Roads. During both the Pre-Islamic (second half of the 7th – early 8th century AD) and the Islamic (early 8th – 12th century AD) phases, ovicaprids were the predominant species in the faunal record. To date, stable isotope analysis from Uzbek archaeological sites is very limited, with no data available for fauna. Similarly, despite the region's historical role in mobility and exchange, $^{87}Sr/^{86}Sr$ analysis has been applied in only a few archaeological contexts. Here, we present the results of a multi-proxy study including proteomic (Zooarchaeology by Mass Spectrometry - ZooMS) and isotope ($^{87}Sr/^{86}Sr$, $\delta^{13}C$, $\delta^{18}O$) analyses on twenty ovicaprid teeth from the Islamic phase of Kafir Kala to gain insights into the management strategies of the most represented species in the local faunal record. The identification of at least two different breeding strategies – marked by clear differences between sheep and goats – together with evidence of contacts with foreign groups, is consistent with enduring local traditions and further highlights the dynamic role of Kafir Kala at the crossroads of the ancient Silk Road trade networks.

Keywords Silk road · Ovicaprids · Mobility · ZooMS · Intra-tooth isotope analysis

Introduction

The city of Samarkand is known worldwide for its role within the ancient Silk Roads route. From the Greek to the Arab conquest (4th century BC – early 8th century AD), Samarkand was the capital of ancient Sogdiana (i.e., southern Uzbekistan and western Tajikistan), the primary center of the spread of Sogdian culture, and one of the agricultural heartlands of Central Asia (Grenet 2004; Mantellini et al. 2017; Rondelli and Tosi 2006; Shirinov and Tosi 2003). Despite its well-known economic role in the commercial trades, the Sogdian economy and society were mainly based on irrigated agriculture (de la Vaissière 2025; Mantellini 2025; Marshak 1996).

The middle Zeravshan Valley is characterised by high environmental and ecological variability – floodplain, steppe, piedmont, and mountain zones – which has historically enabled the diversified exploitation of resources and the coexistence of two socio-economic systems that are

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Published online: 13 June 2026

only seemingly distinct: sedentary farmers and semi-mobile herders (Franceschini 2007; Mantellini et al. 2022; Stride et al. 2009). While the former were able to extend their cultivation across the vast alluvial plain that stretches for about 40 km along both sides of the river, the latter concentrated in the mountains and foothills to the south and north, providing summer pastures for the seasonal transhumance of livestock, as well as stones and timber for construction (Mantellini 2017; Mantellini et al. 2017).

Since 2001, the Uzbek–Italian Archaeological Project (UIAP), based on the collaboration between the Department of History and Cultures of the University of Bologna and the Samarkand Institute of Archaeology of the Cultural Heritage Agency, has aimed to study the diachronic evolution of the city of Samarkand in relation to its surrounding territory and to the social dynamics that have long characterised this region.

Investigations conducted through a multi-temporal and multi-scalar approach have led to the identification of approximately 3,000 archaeological features, attributable both to sedentary settlement in the plains – such as canals and multi-layered anthropogenic mounds locally known as tepa – and to the funerary practices of pastoral communities in the piedmont areas, consisting of underground tombs marked on the surface by low stone mounds barely visible to the naked eye, locally known as kurgan.

While the world associated with mobile pastoralism has left few traces in the archaeological record and is absent from the already scarce written historical sources, the study of agricultural practices that over the centuries have shaped the Samarkand oasis has been far more successful.

The evolution of irrigation in the Samarkand oasis has been central to the development of settlement and agriculture in ancient Sogdiana. Supplied by the Zeravshan River and its artificial distributaries, particularly the Dargom – the canal supplying Samarkand still today – and Bulungur canals, the oasis has supported complex agricultural systems from the ancient times to the present (Mantellini 2015, 2018; Mantellini et al. 2017; Stride et al. 2009). Despite the arid climatic conditions, the fertile land of the alluvial plain of Samarkand was extensively exploited for agriculture, being ideal for a wide range of crops, including cereals, cotton, fruit plants and today, tobacco (Shirinov and Tosi 2003). Recent geoarchaeological fieldwork and remote-sensing surveys by the Uzbek–Italian Archaeological Project (UIAP) have mapped extensive canal networks and settlement patterns, demonstrating the enduring relationship between hydraulic engineering, socio-political organization, and environmental sustainability (Mantellini 2017). The origin of the Samarkand irrigation system, and particularly of the Dargom, remains a long-debated and complex issue. Geoarchaeological investigations carried out by the UIAP, supported by radiocarbon dating, indicate that the canal was certainly active by the 2nd century AD (Malatesta et al. 2012; Marconi et al. 2009). However, the existence of numerous sites distributed along the ancient courses of the Dargom and the Eskì Angar, dating to the Greek and Hellenistic periods (4th–1st centuries BC), suggests an earlier origin for these canals (Mantellini 2015, 2018; Mantellini et al. 2020).

The main archaeological site geographically linked to the Dargom river is Kafir Kala. The site is a massive structure of raw clay extending over more than 20 hectares – second in size only to Afrasiab/Samarkand – and dominates the surrounding landscape. Its most prominent feature is the citadel, measuring 70 × 70 m and rising about 25 m above the present ground level, surrounded by a moat with six defensive towers and a residential quarter (*shahristan*) extending on all four sides. To the west, a second moat separates the main complex from the outer settlement (*rabat*), while to the south the necropolis has been largely destroyed by agricultural activity over the past decades. To the east, on the right bank of the Ilonsai stream, lay an important craft area dedicated to ceramic production.

The site is surrounded by both natural and artificial watercourses, which served not only the defensive needs of the settlement but also the long-standing necessity of irrigating fields in a semi-arid environment. Late 19th-century photographs (https://www.loc.gov/resource/ppmsca.14234/), satellite imagery, and mid-20th-century historical maps show that without any human intervention—primarily water management—the area quickly turns into a desolate steppe. The Dargom and, further upstream, the Yanghìaryk channels supplied the water needed for agriculture and for the numerous satellite settlements of Kafir Kala (Mantellini and Berdimuradov 2005). This agricultural pattern still persists today, with the land surrounding the site devoted to fruit growing and seasonal horticultural crops.

The monumentality of the site, its strategic position along the main south–north (to/from Afrasiab) and east–west (to/from Panjikent) routes, its proximity to Afrasiab (12 km), and to the main bridge crossing the Dargom, make Kafir Kala one of the most important settlements for controlling the local routes of the Silk Road. The significance of Kafir Kala as a nodal point within the broader Eurasian connection network was recognised by its inclusion on the UNESCO World Heritage List in 2023 as part of the Silk Roads: Zarafshan-Karakum Corridor serial transnational World Heritage property (https://whc.unesco.org/en/list/1675).

Since the early 20th century, Kafir Kala has been the subject of sporadic research, mostly focused on its topographical and architectural aspects (Berdimuradov and Mukhammadiev 2016; Grigorev 1946; Masson 1928; Nilsen 1966; Shishkina 1961). The first systematic stratigraphic investigations were carried out by the Samarkand Institute of Archaeology in the early 1990s, followed by those conducted by the UIAP from 2001 onward (Mantellini and Berdimuradov 2005) and later by the Uzbek-Japanese Expedition (Begmatov et al. 2016, 2020). Joint excavations carried out over the past two decades on the upper citadel and in several areas of the southern and northern *shahristan* have revealed continuous occupation between the 4th/5th and 15th centuries, with three major phases: (1) pre-Islamic, (2) Islamic, and (3) Timurid. The pre-Islamic phase (second half of the 7th – beginning of the 8th century AD) yielded the exceptional discovery of more than 700 clay *cretulae* – seal impressions used for administrative purposes – suggesting that Kafir Kala held a prominent political, economic, and social role during this period. Some scholars argue that it may be identified with the locality of Rewwdad, mentioned by the Arab geographer Istakhri in the 10th century as one of the rural residences of the governor (*ikhshid*) of Samarkand (Grenet 2020; Grenet and de la Vaissière 2002). This phase ended with a major fire caused by the Arab invasion in 712, which led to the temporary abandonment of the site. During the Islamic phase (first half of the 8th – 12th century AD) Kafir Kala lost its political and administrative status and shifted into a residential settlement. During this period the citadel changed function and became a residential area (Mantellini et al. 2016). This is evidenced by the reuse of earlier structures and the construction of new rooms, as well as by the presence of hearths, structured fireplaces (*achak*), domed-oven (*tandir*), cooking installations, and pottery. The occupation from this period has yielded abundant archaeobotanical remains of herbaceous species – barley, vetch, chickpea, pea, and fava bean – as well as fruit species such as peach, apricot, and plum (Bonvicini 2009). The Timurid phase (14th – 15th centuries) is attested only in the residential quarter (*shahristan*) and in the necropolis, confirming the site's residential function during this period as well. Numerous traces of domestic activities, similar to those found in the citadel, were identified, along with refuse pits containing heterogeneous material (Mantellini et al., 2025).

The long-term occupation of Kafir Kala is clearly evidenced by the 6009 faunal remains that were recovered exclusively during the UIAP excavations on the citadel (code KK-1), and belonging to the pre-Islamic phase (2030 remains) and Islamic phase (3979 remains). The present study focuses on samples from animal bones recovered from the central part of the citadel, specifically from layers excavated during the 2013 and 2014 campaigns, which are associated with the abandonment of the site following the Arab conquest of 712 and with the first Islamic occupation of the 8th century.

Overall, domestic animals are the most numerous, with ovicaprids accounting for almost 80% of the remains, followed by cattle (12%), horses (2%), and pigs (0.7%). A small number of galliforms and wild animals have also been identified, including foxes, which are the most numerous, as well as some remains of wild boar, deer and other wild ungulates (unidentified, but morphometrically compatible with gazelles, roe deer and saigas). Substantial continuity is evident between the two occupation phases, with sheep and goats being the most prevalent species. The minimum number of sheep and goats was 460 for the Islamic period, and 1,151 for the Islamic period (Online resource 1). In some cases, it was possible to distinguish between sheep and goats based on morphology, which revealed a higher proportion of sheep than goats (Boessneck 1969; Halstead et al. 2002; Zeder and Pilaar 2010). However, age-mortality curves revealed differences in economic strategies. During the pre-Islamic phase, animals were mainly killed as adults (aged 2–4 years), indicating a particular focus on producing high-quality meat and milk. With the transition to the Islamic phase, the slaughter of many young individuals (up to 1 year of age) and some older individuals (6–8 and 8–10 years of age) demonstrates a greater emphasis on by-products (milk and wool). This shift, coupled with the broader increase in meat consumption and the introduction of domestic animals like dogs and cats, is consistent with the evolving function of the site (Serrone et al. 2021). The Samarkand oasis is thus a region of great archaeological, historical, and cultural significance. However, despite many years of international research involving scholars from various fields (e.g., historians, art historians, archaeologists, geographers), many aspects of the past societies inhabiting this area remain understudied. To date, economic, husbandry and agricultural practices, as well as sedentary–semi-nomadic interactions, have been investigated primarily through ethnographical, (geo)archaeological fieldwork, archaeobotanical and zooarchaeological analysis (Berdimuradov et al. 2007; Maini and Serrone 2021; Malatesta et al. 2012; Mantellini et al. 2017; Serrone et al. 2021; Spengler et al. 2021). This also applies to other important areas near Samarkand and more broadly across Uzbekistan (Decruyenaere et al. 2024; Mir-Makhamad et al. 2021, 2023, 2024). To our knowledge, only one study has analysed dietary practices and social interactions through stable isotope analysis on human remains from Uzbek sites ($\delta^{13}C$, $\delta^{15}N$) (Hermes et al. 2018), while nothing is available on faunal remains. Furthermore, despite being an area where mobility of people and exchange of goods were central to the economy and cultural traditions, strontium ($^{87}Sr/^{86}Sr$) isotope analysis in Uzbekistan has been conducted in a few archaeological contexts, and only one publication is available to date (Kroll et al. 2022).

When Sr-C-O isotope analyses are combined, they represent a powerful tool for studying animal feeding habits and (vertical) mobility, providing new insights into animal management strategies in relation to the surrounding environment (Armaroli et al. 2024; Makarewicz et al. 2017; Trentacoste et al. 2020). Here we present the results of a multi-proxy study including both isotope ($^{87}Sr/^{86}Sr$, $\delta^{13}C$, $\delta^{18}O$) and ZooMS analyses on ovicaprid teeth from the citadel of Kafir Kala, with the aim of getting insights into the management strategies of the most represented species in the faunal record and their implications within a broader economic and cultural framework.

Discriminating between sheep and goats in the zooarchaeological record is not always straightforward due to the similarity between their skeletal remains (Buckley et al. 2010; Gillis et al. 2011; Wolfhagen and Price 2017; Zeder and Pilaar 2010) (cf. Online Resource 3). To distinguish between sheep and goats in the dataset, ZooMS analysis was applied on collagen for species determination (Buckley et al. 2010). Tooth enamel was sampled sequentially along the crown length to detect isotopic changes during the formation time (i.e., ~1 year) (Lazzerini et al. 2021), thus providing seasonal resolution (Balasse 2002; Zazzo et al. 2012, 2012). The local bioavailable (i.e., water soluble and available to organisms) Sr (Holt et al. 2021) was determined using plant samples collected both from around the site and from surrounding areas, primarily following past transhumance routes along the Karatyube piedmont. Overall, this study not only enhances our understanding of husbandry strategies at the site of Kafir Kala during the Early Medieval period, but also lays the groundwork for future isotopic and proteomic studies in ancient Sogdiana.

Geology of Uzbekistan

Uzbekistan occupies the transition between the western Tien Shan orogen to the east and the relatively stable Turan Platform to the west (Brunet et al. 2017; Moores and Fairbridge 1997). The Turan Platform is underlain by a multiply folded basement of Late Proterozoic–Early Triassic sedimentary, metamorphic and igneous rocks, which belongs to the Ural–Mongolian Late Palaeozoic belt. This basement is overlain by weakly deformed Jurassic–Quaternary cover (Brunet et al. 2017; Moores and Fairbridge 1997). In the southeast, Phanerozoic tectonics created the western Tien Shan ranges, where uplift has exhumed the platform basement and the Paleozoic accretionary systems of the Central Asian Orogenic Belt (Brunet et al. 2017). These mountain belts are built largely of Devonian–Carboniferous volcanic and sedimentary successions, intruded by voluminous granitoids related to long-lived subduction, accretion and final closure of the Turkestan (South Tien Shan) Ocean (Brunet et al. 2017; Choulet et al. 2022).

Within the South Tien Shan, two major segments crop out in Uzbekistan: Kyzylkum–Nurata and Gissar (Brunet et al. 2017). Both developed along the southern margin of the Turkestan Ocean during Late Silurian–Early Carboniferous passive-margin stages and were later affected by rifting of the underlying Precambrian Karakum continent (Brunet et al. 2017). In the Gissar Segment this rifting opened the short-lived Gissar Basin, accompanied by thick Carboniferous volcanic piles and construction of the large Gissar batholith, with subduction to the north indicated by suprasubduction magmatic signatures and remnants of oceanic crust in the Gissar suture (Brunet et al. 2017; Choulet et al. 2022). Late Carboniferous collision and closure of both the Turkestan and Gissar basins were followed in the Early Permian by widespread post-collisional magmatism: granitoid and alkaline intrusions across Kyzylkum–Nurata, Gissar, Sultan-Uvais and Chatkal–Kurama, many of which are important hosts to gold and other ore deposits (Choulet et al. 2022).

Further west, these orogenic blocks pass into the gently deformed Turan foreland, where the basement is buried beneath thick Mesozoic–Cenozoic basins such as Amu Darya and Fergana (Brunet et al. 2017), filled with Jurassic–Paleogene marine and continental sediments and very thick Neogene–Quaternary continental deposits that now underlie the Kyzylkum desert and much of the lowland (Brunet et al. 2017; Moores and Fairbridge 1997). Cenozoic convergence between India–Eurasia and Arabia–Eurasia reactivated many Paleozoic structures, renewed uplift in the Tien Shan, and helped generate intramontane depressions while leaving the western platform as a broad lowland (Brunet et al. 2017; Ismailov et al. 2023).

Samarkand is located in the central Zeravshan depression, an east–west valley between the Turkestan and Zeravshan ranges, where the Zeravshan River has built a wide piedmont and floodplain system (Dolgopolova et al. 2017; Konopelko et al. 2017). Within roughly 50 km, the southern skyline is formed by the granitic and metamorphic ranges of the Gissar system, strongly dissected by valleys that feed coarse alluvial fans at the mountain front (Konopelko et al. 2017). These fans, derived largely from the Gissar–Karatyube granitoid massif, bring to the piedmont a bedrock signal characterised today by moderately radiogenic Sr isotope ratios typical of evolved continental crust (with present-day $^{87}Sr/^{86}Sr$ values clearly higher than mantle-like rocks and broadly in the range expected for upper-crustal granites, around and above ~0.706; Choulet et al. 2022; Konopelko et al. 2017). Downslope, the fans grade into finer-grained fan and floodplain deposits that support the Samarkand oasis, while younger Zeravshan floodplain and terrace sediments form a broad belt farther north. Much of this surface is mantled by loess and loess-like silts, which smooth the relief and provide fertile but mechanically soft soils (Dolgopolova et al. 2017).

The long-lived irrigation network, including the Dargom canal system, cuts across these fans and palaeochannels, re-using and modifying earlier river courses as it distributes Zeravshan water and sediments across the southern piedmont (Malatesta et al. 2012; Mantellini et al. 2011), mixing the radiogenic foothill Sr with more heterogeneous riverine and loess-derived inputs (combining relatively low $^{87}Sr/^{86}Sr$ contributions from more mantle-influenced rocks with higher $^{87}Sr/^{86}Sr$ from carbonates and fine loess or alluvial deposits). Geoarchaeological sections show how this alluvial–colluvial framework, combined with canal construction and maintenance, has repeatedly created stable, well-watered surfaces ideal for settlement, making the Samarkand area a prime node for agriculture, routes and urban development over millennia (Malatesta et al. 2012; Mantellini et al. 2011).

Materials and methods

A total of $n=20$ ovicaprid teeth were selected for combined proteomic and isotopic analysis. All samples were recovered from the citadel of Kafir Kala and were chosen to represent the full stratigraphic sequence of the Islamic phase of occupation (Online Resource 3). Due to their easier identification and clear association with adult individuals, third permanent molars were preferentially selected ($n=7$). However, because of the overall poor preservation of the assemblage and the high proportion of younger individuals, fully mineralised and well-preserved third molars suitable for analysis were limited. As a result, we also included fully mineralised second molars ($n=3$), which similarly reflect dietary intake during adult life, and other molars with uncertain identification (M1/M2, $n=10$) due to morphological similarity. We acknowledge that isotope signals from first molars (Britton et al. 2015; Kohn et al. 1998; Wright and Schwarcz 1999) may be affected by the suckling effect. However, this interpretation is still debated. For instance, high-spatial resolution studies on humans and non-human primates have questioned the universality of this pattern (Smith et al. 2025). In our case, no clear isotopic outliers or patterns consistent with early-life feeding signals were observed among the M1/M2 category. Given this, and in light of the general isotopic homogeneity across the sample set, we consider the results to provide a reliable proxy for ovicaprid diet and mobility at Kafir Kala.

Proteomics (ZooMS)

ZooMS analysis was conducted sampling ~ 50 mg of dentine or bone (i.e., maxillary or mandibular). This technique involves the application of mass spectrometry MALDI-TOF (Matrix Assisted Laser Desorption Ionization – Time of Flight) for the identification of peptide profiles, particularly of type I collagen extracted from archaeological/paleontological bones and teeth (Buckley 2018; Buckley et al. 2009). Collagen was extracted and prepared according to Buckley et al. (2009). In brief, samples were demineralised using 500 µl 0.6 M HCl to recover the Acid Soluble (ASM) and the Acid Insoluble Matrix (AIM). Then, 500 µl ammonium bicarbonate (50 mM, pH 7.8) was added to the AIM prior to gelatinization in a thermoblock (65 C° for 60 min). Both ASM and AIM fractions were ultrafiltered (Nanopall filters 3k Da MWCO), pooled, and resuspended in a final volume of 500 µl 50mM ammonium bicarbonate, before digestion. All samples were digested using proteomics-grade trypsin, performing digestion at 37 °C for ~ 18 h (overnight). The protein digests (peptides in solution) were purified and concentrated using C18 solid phase extraction ("zip-tip", Thermo PIERCE). Dried peptides were resuspended in 0.1% trifluoroacetic acid (TFA). Aliquots of 0,5 µL of peptide solution were mixed with a solution of α-Cyano-4-hydroxycinnamic acid (HCCA) MALDI matrix, spotted on a stainless-steel plate. Each sample was spotted in triplicate and analysed in manual mode using a Bruker Microflex MALDI-TOF mass spectrometer at the Department of Veterinary Sciences, Open Lab, University of Turin. Samples were analysed in reflector mode on a MALDI-TOF mass spectrometer with the following settings: ion source 1, 18.0 kV; ion source 2, 15.1 kV; lens, 9.0 kV; reflector, 19.0 kV. Laser attenuation was set to 65 (instrument attenuation units). The spectrum collected for each sample resulted from the sum of 400–1000 laser shots. Mass range for detection was set at 800–4000 m/z, and peptide masses below 650 Da were suppressed. Peptide calibration standard #8,206,195 (Bruker Daltonics, Germany), a mixture of seven peptides (Angiotensin II $m/z=1046.541$, Angiotensin I $m/z=1296.685$, Substance P $m/z=1347.735$, Bombesin $m/z=1619.822$, ACTH (1–17 clip) $m/z=2093.086$, ACTH (18–39 clip) $m/z=2465.198$, and Somatostatin $m/z=3147.471$) was used for external mass calibration to maximize mass accuracy. Raw text files for each spectrum were exported and further analysed using mMass, an open access mass spectrometry interpretation tool (Niedermeyer and Strohalm 2012). All of the resulting spectra were processed by performing the baseline correction (precision: 100%) and peak picking with S/N threshold ≥ 6. Three spectra for each sample were averaged, except for samples KKt 13 and KKt 22, for which only one spot yielded good-quality signals. Where protein preservation and recovery were sufficient, taxonomic identification was performed checking for COL1a2 757–789 markers (*m/z* 3017.4/3033.4 for sheep and *m/z* 3077.4/3093.4 for goat; Buckley et al. 2010).

Isotope analysis

For Sr ($^{87}Sr/^{86}Sr$), O ($\delta^{18}O$) and C ($\delta^{13}C$) isotope analysis, tooth enamel was drilled sequentially along the crown length to detect isotopic variations during the formation time (i.e., about a little over a year for all tooth classes; cf. (Lazzerini et al. 2021). Samples approximately 0.1 cm wide were drilled at intervals of 0.2 cm, starting from the occlusal surface (older enamel) to the enamel-root junction (younger enamel). Depending on tooth size and preservation, between 6 and 15 enamel samples were obtained for each tooth. Following C-O isotope analysis, two additional enamel samples per tooth were drilled at positions corresponding to the lowest and the highest $\delta^{18}O$ values, representing winter and summer months, respectively (Pederzani and Britton 2019). The $^{87}Sr/^{86}Sr$ values of these samples were measured to investigate potential evidence of seasonal mobility. A total of 25 plants were opportunistically collected during the UIAP survey and archaeological excavation for the determination of the biologically available strontium (BASr) signature in the study area (Fig. 1; Online Resource 4). Nine plants were collected in the immediate vicinity of Kafir Kala (within a radius of less than 1 km from the site) to help distinguish between local and non-local fauna. Thirteen plants were collected along the Karatyube piedmont in the district of Samarkand Selski, approximately 20 km south of Kafir Kala. Two more plant samples were collected from more distant areas to get a broader geographical range of comparison. The first one comes from an archaeological site near the village of Beshar (Jambay district), ~40 km north of Kafir Kala. The second one comes from the site of Penjikent (Tajikistan), ~60 km east of the site. All samples were collected far from modern cultivation areas to avoid contaminations (Maurer et al. 2012).

Oxygen and carbon isotope analyses were performed on the carbonate moiety of hydroxylapatite at the inorganic stable isotope laboratory of the Max Planck Institute for Chemistry in Mainz. About 200–400 µg of untreated enamel powder per sample was analysed on a Thermo Delta V mass spectrometer equipped with a Gasbench-II preparation device. Within a run of 40 samples, $n=22$ replicates of two in-house tooth enamel standards (AG-Lox, MAMMY) were analysed, with a weight spanning the entire range of sample weights. The AG-Lox tooth enamel standard has a $\delta^{13}C$ value of −11.58‰ and a $\delta^{18}O$ value of −1.42‰, and the tooth enamel standard MAMMY has a $\delta^{13}C$ value of −13.49‰ and a $\delta^{18}O$ value of −14.76‰. The 11 AG-Lox replicates included in each analytical run were used to correct for isotope effects related to sample size and for scale conversion. After correction for size effects, the reproducibility of AG-Lox was 0.08‰ (1SD) for $\delta^{13}C$ and 0.11‰ (1SD) for $\delta^{18}O$. MAMMY was used as a control standard, and yielded a $\delta^{13}C$ of −13.58‰ (±0.08‰, 1SD) of and a $\delta^{18}O$ of −14.94‰ (±0.10‰, 1SD), fully consistent with the accepted values. All data were reported to the VPDB (Vienna Pee Dee Belemnite) scale (Vonhof et al. 2020). Sample preparation for $^{87}Sr/^{86}Sr$ analysis and subsequent Sr separation were carried out at the Department of Chemical and Geological Sciences of the University of Modena and Reggio Emilia. Plant samples were cleaned with MilliQ using an ultrasonic bath for 10 min and dried overnight. Then, they were ashed in a muffle furnace at 650 °C. About 5–10 mg of ash per plant sample and enamel powder per

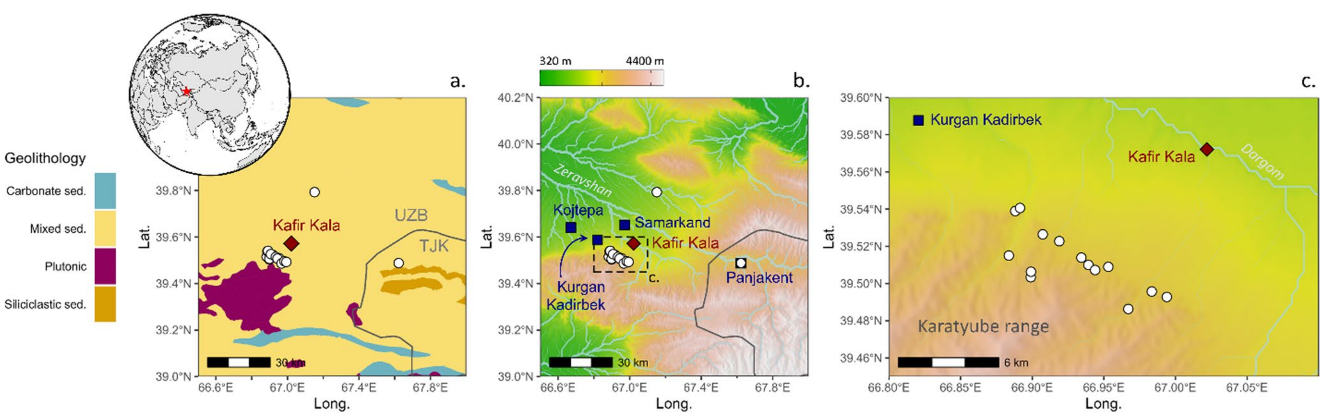

Fig. 1 Location of plant samples collected to determine the BASr in the study area. (**a**) Geolithological map (from GliM; (Hartmann and Moosdorf 2012) with sampling location overlain (white dots). The site of Kafir Kala is marked with a red diamond. (**b**) Samarkand and the archaeological sites of Kojtepa and Kurgan Kadirbek are marked with blue squares. The site of SAM-174 is located approximately 1 km northwest of Kafir Kala (see Online Resource 2). Plant samples collected in the surroundings of Kafir Kala (<1 km) are represented by the red diamond. Plant samples collected in the village of Beshar (north to Samarkand), in the site of Penjikent (Tajikistan) and along the Karatyube piedmont are marked with white dots. The dashed line marks the zoom shown in **c**)

tooth was weighed for analysis (Lugli et al. 2017a). After being dissolved in 3M HNO_3, all samples were processed by liquid chromatography using Teflon columns filled with 30 µl of Eichrom Sr spec resin (Argentino et al. 2021). The resin was washed multiple times using MilliQ water and conditioned with 3M HNO_3. The dissolved samples were loaded, and the cations of the matrix were desorbed by percolating 3M HNO_3 to eliminate all isobaric interferents that may hinder the subsequent analysis. Strontium was then eluted using several reservoirs of MilliQ water and collected in 15 ml vials. The Sr solutions were then diluted with 4% HNO_3 at 50 ppb and analysed on the Multi-Collector Inductively Coupled Plasma Mass Spectrometer (Thermo Fisher Neptune) housed at the Centro Interdipartimentale Grandi Strumenti of the University of Modena and Reggio Emilia (Armaroli et al. 2024; Lugli et al. 2017b, 2018). Samples were reported to an accepted NIST-SRM987 value of 0.710248 (McArthur et al. 2001) (Online Resource 4 and 6).

Results

Proteomics (ZooMS)

Most samples (16 out of 20) yielded spectra with characteristic collagen peaks. Of these, most were identified as sheep ($n=12$), while $n=4$ were identified as goats. Three spectra (samples KKt 2, KKt 12 and KKt 16) showed the presence of peaks indicating ruminants, belonging to the bovid or cervid families (*m/z* 1105.6, 1427.7, 1648.8, 2131.1, 2883.4), but the necessary markers to distinguish between sheep and goat were missing. Only one sample (KKt27) did not yield collagen (Fig. S1; Online Resource 5). All identifications are based on previously published markers (Buckley 2018; Desmond et al. 2018; Welker et al. 2016). Overall, the species ratio is in agreement with the results of traditional zooarchaeological analysis, which identified more sheep than goats in the faunal record of Kafir Kala (Serrone et al. 2021).

Isotope analysis

All isotopic data are provided in Online Resource 4 and 6. Overall, $\delta^{13}C_{VPDB}$ values of the samples show a mean of −9.4‰ (1SD = 2.1‰), ranging between −12.4‰ and −1.7‰ (Online Resource 6). These values encompass the $\delta^{13}C$ ranges of both C_3 and C_4 plants (Bocherens and Drucker 2007). Indeed, following the initial expansion of C_4 plants in Central Asia during the Miocene-Pliocene transition (Shen et al. 2018), C_4 plants are now naturally present in the environment, although their distribution is limited to arid and desert regions (Still et al. 2003; Toderich et al. 2007). In addition, C_4 plants were incorporated in agricultural practices starting from the Bronze Age (Hermes et al. 2019). Interestingly, goats showed a narrower range of $\delta^{13}C$ values, consistent with a C_3 plant-based diet. $\delta^{18}O_{VPDB}$ values of all samples range between −11.85‰ and +0.25‰, with a mean of −6.05‰. This broad range reflects the $\delta^{18}O$ variation in sheep and goats' food and water sources, in turn linked to (1) the husbandry regime (Makarewicz and Pederzani 2017) and (2) the strong climate seasonality of Central Asia (Wu et al. 2019). Specifically, the Samarkand region is characterised by an arid and continental climate with seasonal extremes and low annual precipitation (350–400 mm/year) (Mantellini 2015; Rondelli and Tosi 2006). Considering the whole dataset, both species exhibited varying $\delta^{18}O$ values, although sheep provided lower values on average, which can be linked to an eventual difference in drinking behavior (Al-Ramamneh et al. 2010; Levin et al. 2006). Pronounced intra-tooth signal amplitude (‰) was detected in both $\delta^{13}C$ and $\delta^{18}O$ profiles, with variations up to 6.7‰ (sample KKt 22 – sheep) and 8.3‰ (sample KKt 8 – sheep), respectively (Fig. 2).

Interestingly, when intra-tooth carbon and oxygen isotope values are plotted together (Fig. 3), at least three different patterns of C-O profiles can be distinguished: (1) flat $\delta^{13}C$ vs. sinusoidal $\delta^{18}O$; (2) cyclical variation in both $\delta^{13}C$ and $\delta^{18}O$, where the highest and lowest measured values occur together (hereafter referred to as co-variation); (3) inverse cyclical variation, in which the highest measured $\delta^{13}C$ values correspond to the lowest measured $\delta^{18}O$ values, or vice versa (hereafter referred to as anti-covariation) (Fig. S2).

Plants collected in the vicinity of the site to determine the local BASr signature of Kafir Kala yielded a mean $^{87}Sr/^{86}Sr$ of 0.71051, with values ranging between 0.70991 and 0.71096. The other BASr samples (hereafter referred to as off-site) were mainly collected along the Karatyube piedmont and showed partially overlapping values with those of the site. Overall, they yielded a mean $^{87}Sr/^{86}Sr$ of 0.70980, ranging from 0.70932 to 0.71065 (Fig. 4; Online Resource 4). The high variability observed agrees with the geolithological diversity of the area, ranging from recent Quaternary sedimentary cover to old Precambrian/Palaeozoic intrusive rocks (e.g., Karatyube mountain range). Notably, BASr values from the Karatyube piedmont are broadly comparable to those of the site itself, indicating that the geological complexity of the area is not directly or uniformly expressed in the local strontium isotope signatures, likely in part due to mixing associated with alluvial fan processes and irrigation networks. All off-site samples are considered collectively to provide a broader comparative range for interpreting local values. Most samples exhibited similar $^{87}Sr/^{86}Sr$ values between summer and winter ($\Delta^{87}Sr/^{86}Sr < 0.0003$). Only three samples (KKt 5 – goat,

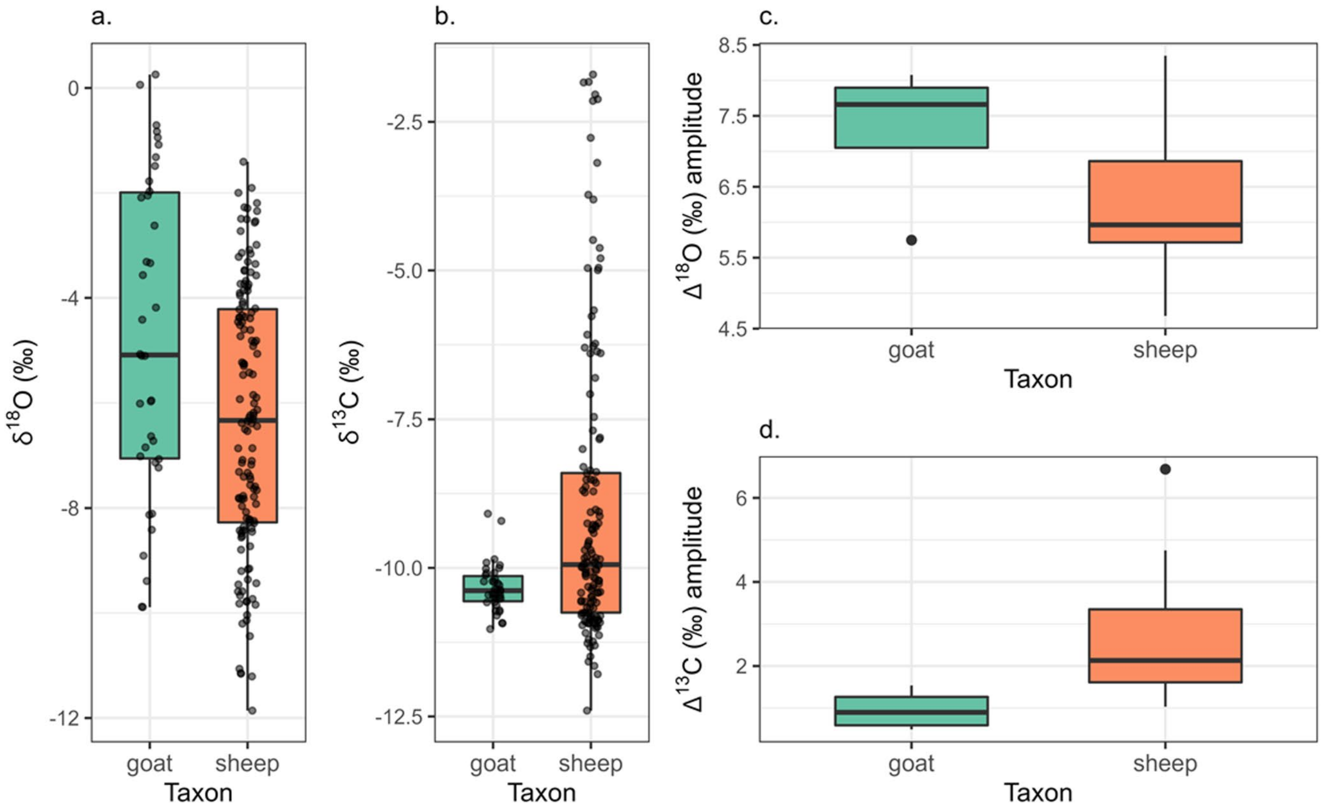

Fig. 2 Oxygen and carbon isotope data. **a**, **b**) Box plots showing $\delta^{18}O$ and $\delta^{13}C$ values (‰ vs. VPDB) of goats (green) and sheep (orange); dark grey dots represent individual samples and the distribution of their values. **c**, **d**) O and C signal amplitude (i.e., highest-lowest value per tooth). Black dots represent statistical outliers

$\Delta^{87}Sr/^{86}Sr=0.001$; KKt 12 – NA, $\Delta^{87}Sr/^{86}Sr=0.0009$; KKt 31 – sheep, $\Delta^{87}Sr/^{86}Sr=0.0009$) yielded more variable $^{87}Sr/^{86}Sr$ values, possibly indicative of seasonal mobility (Fig. 4; Online Resource 6).

Interestingly, despite the limited variability in $^{87}Sr/^{86}Sr$ values, most samples yielded at least one value not corresponding to – or was borderline with – the Sr BASr of the site. Many samples showed at least one value compatible with the off-site BASr signature. In cases where only one value matched the off-site range, the other is compatible with the BASr range of Kafir Kala. However, in a few instances, the second value did not align with any BASr value (KKt 12 – NA; KKt 22 – sheep). Notably, three samples fell completely outside the established BASr range. Sample KKt 2 (NA) and KKt 9 (sheep) displayed less radiogenic values, while sample KKt 31 (sheep) yielded more radiogenic values compared to the Sr BASr. The latter is also one of three samples (KKt 5 – goat; KKt 12 – NA; KKt 31 – sheep) showing a notable variation in $^{87}Sr/^{86}Sr$ values between summer and winter, possibly indicating seasonal mobility. Sample KKt 5 yielded summer and winter $^{87}Sr/^{86}Sr$ values corresponding to the upper and lower limits of the site BASr, respectively. Sample KKt 12 showed a summer value outside the broader BASr and a winter value corresponding to the lower limit of the site BASr. Overall, C-O correlation patterns seem not to be related to Sr isotopic values (Fig. 5). Indeed, $^{87}Sr/^{86}Sr$ values are evenly distributed across the three groups defined by C-O correlation. Moreover, the three individuals exhibiting greater seasonal mobility display distinct $^{87}Sr/^{86}Sr$ values, with each falling into a different C-O group (Fig. S3).

Discussion

Pastoralism has a long tradition in Inner Central Asia, including Uzbekistan, attested as far back as 6,500 BCE (Frachetti 2012; Ventresca Miller et al. 2020a, b). Historically, livestock mobility – including seasonal movement to high-altitude pastures – was a central component of herding strategies. Such mobility ensured access to higher-quality forage throughout the year while supporting sustainable pasture management (Mirzabaev et al. 2016; Ventresca Miller et al. 2020a, b). Today, agropastoral communities continue to rely heavily on livestock husbandry, although this sector faces several challenges (Mirzabaev et al. 2016). The combined practice of farming and herding remains a defining feature of these groups, expressed through various

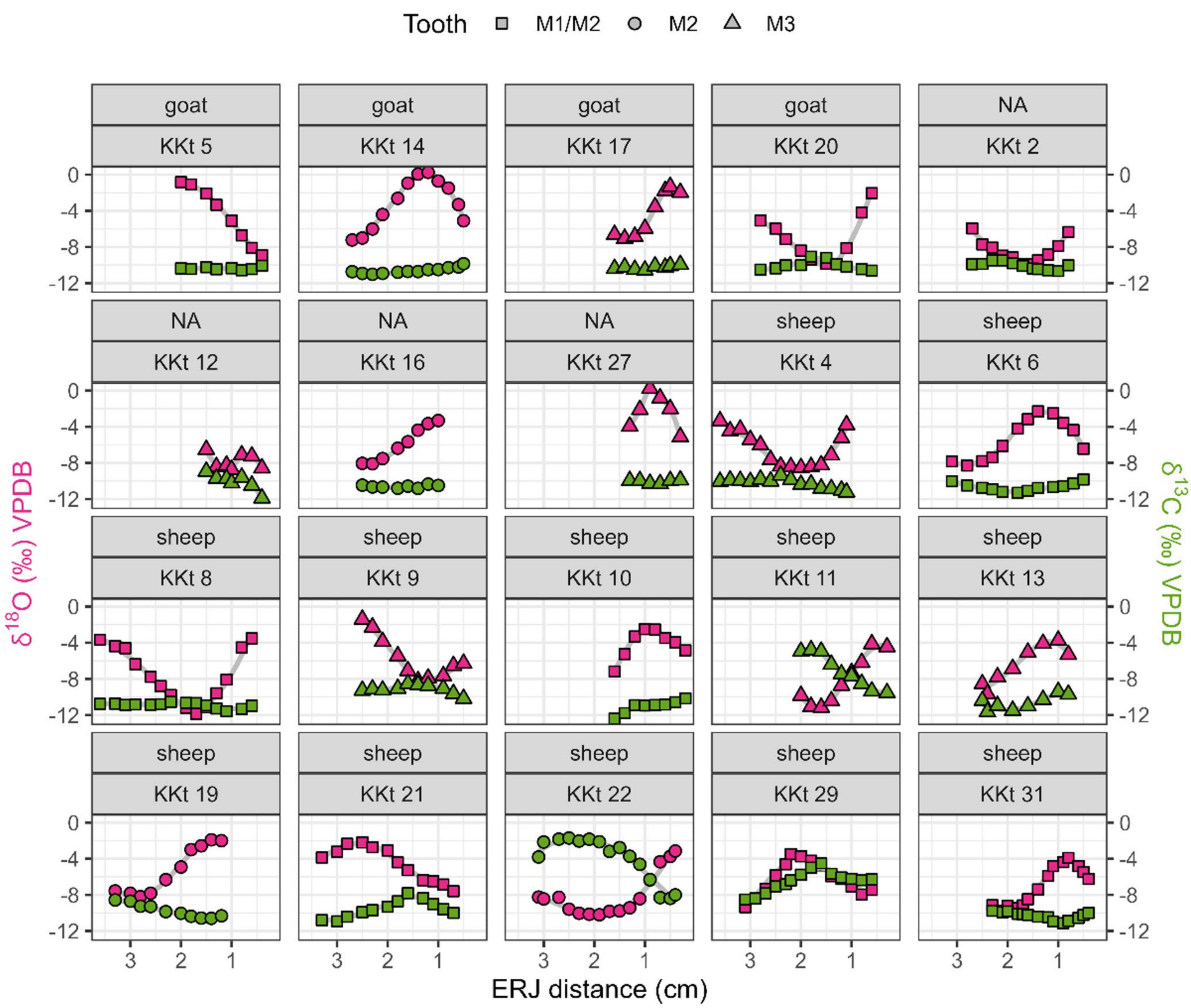

Fig. 3 Intra-tooth $\delta^{18}O$ (pink) and $\delta^{13}C$ (green) values (VPDB ‰). Square symbols represent M1/M2, circles M2 and triangles M3. The distance from the enamel-root junction is shown on the x-axis

regional and local adaptations (Dubova et al., 2021) and reflecting long-standing cultural traditions (cf. Frachetti and Maksudov 2014).

Herds in Central Asia generally consist of multiple species, including sheep, goats, cattle and horses in proportion strongly dependent by regional environment, but also affected by cultural factors. Historical (19th – early 20th century) and modern data show a greater number of sheep and goats in the herds, and a higher proportion of the former over the latter in many countries, including Uzbekistan (Bendrey 2011; Krader 1955). The results of ZooMS analysis presented here, showing a greater proportion of sheep ($n=12$) over goats ($n=4$), are in line with this framework. Although the sample analysed was small and for $n=4$ individuals was not possible to determine the species, it is likely that our data reflect the general herd composition at Kafir Kala and are useful to better interpret the isotopic results.

Isotope analyses are key in the study of husbandry practices, providing information on landscape use and management strategies of past populations (Makarewicz 2018). Specifically, carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotope analysis can provide insights into seasonal vertical movements. Incrementally growing tissues such as teeth record seasonal shifts in the stable carbon and oxygen isotope compositions of an animal's diet. These shifts, in turn, reflect changes in environmental conditions, possibly associated with mobility between different environmental settings (Fricke and O'Neil 1996; Lazzerini et al. 2021; Makarewicz et al. 2017). However, interpreting intra-tooth $\delta^{13}C$ and $\delta^{18}O$ isotope values in faunal teeth is not always straightforward. Stable isotope variations in herbivore bioapatite depend on several factors,

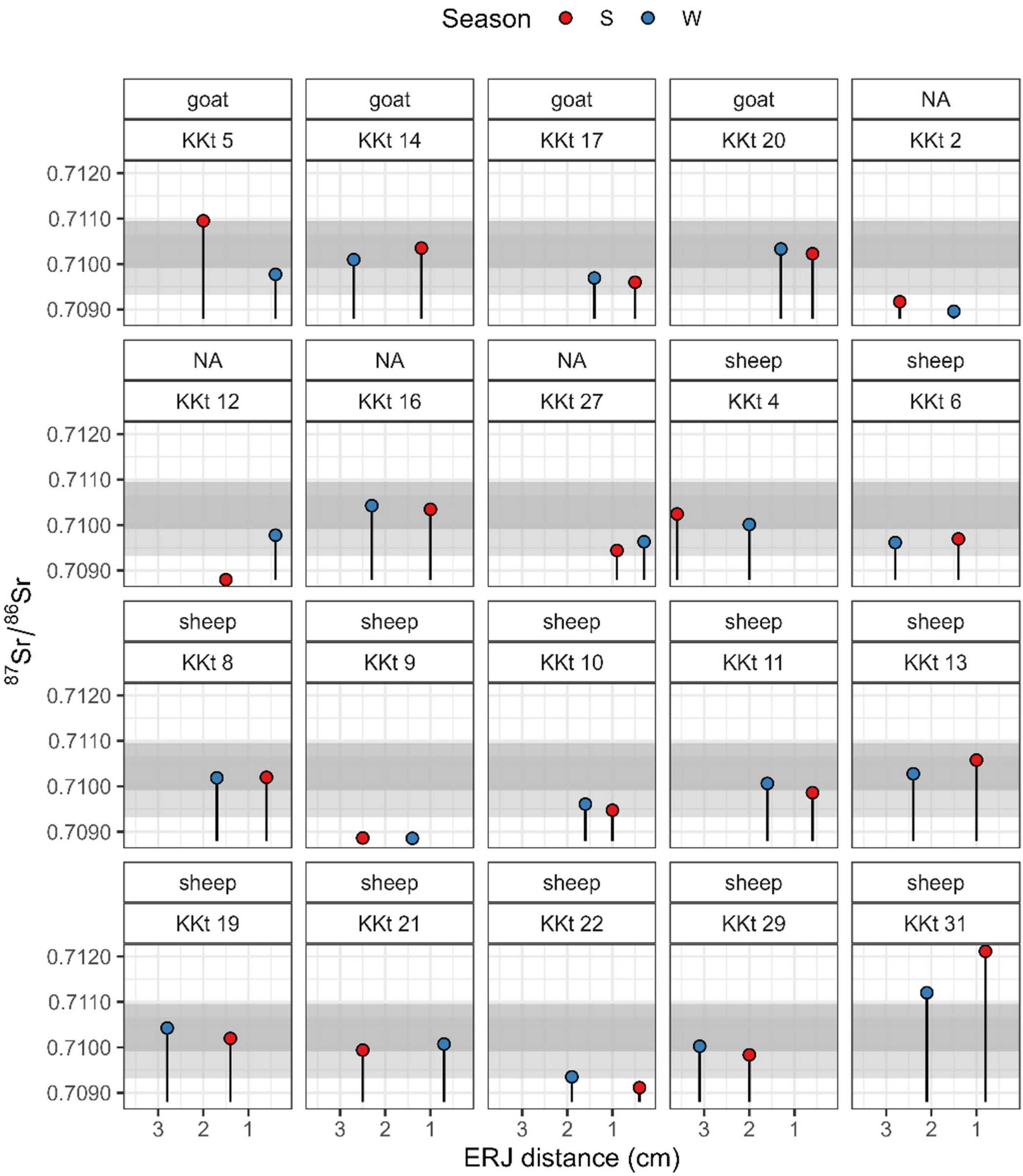

Fig. 4 $^{87}Sr/^{86}Sr$ isotope values of winter (blue) and summer (red) samples. Dark grey bar represents the Sr BASr values of Kafir Kala. Light grey bar represents the Sr values of BASr samples collected off-site, mainly along the Karatyube piedmont. The distance from the enamel-root junction is shown on the x-axis

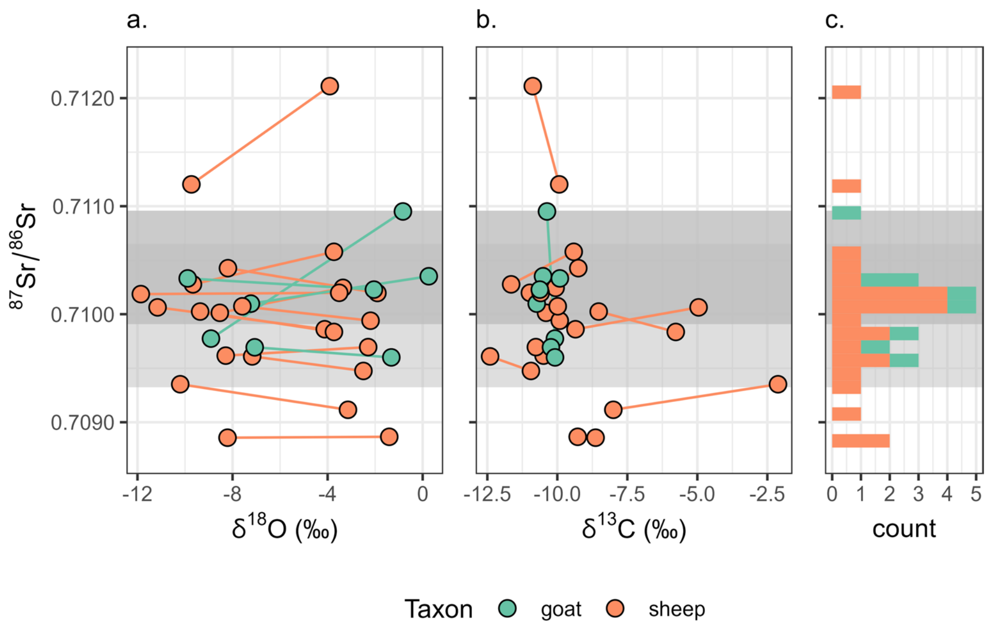

Fig. 5 $^{87}Sr/^{86}Sr$ values of goat (green) and sheep (orange) compared against $\delta^{18}O$ and $\delta^{13}C$ values (‰ vs. VPDB). Dark grey bar represents the Sr BASr values of Kafir Kala. The light grey bar represents the Sr values of the off-site BASr samples. **a**, **b**) Each individual is represented by two dots (i.e., winter and summer $^{87}Sr/^{86}Sr$ values) connected by a line highlighting the differences and similarities in their $\delta^{18}O$ and $\delta^{13}C$ values. **c**) Histogram representing the distribution of $^{87}Sr/^{86}Sr$ values among species

including type of plant ingested (i.e., mainly C_3 and C_4), water sources (different between obligate and non-obligate drinkers) and animal physiology (Cerling and Harris 1999; Kohn 1996; Sponheimer and Lee-Thorp 1999). Plants and water isotope values are strictly dependent on environmental factors, including temperatures, rainfall amount, humidity, altitude and latitude (Bowen et al. 2005; Heaton 1999; Körner et al. 1991; Pederzani and Britton 2019). Therefore, interpreting $\delta^{13}C$ and $\delta^{18}O$ isotope values of faunal teeth requires careful consideration of the region's geographical, topographical, and environmental characteristics. In the case of domestic animals, human husbandry strategies – such as feeding strategies, water sources, and transhumance – must also be taken into account (Makarewicz and Pederzani 2017; Pederzani and Britton 2019).

In nature, sheep are generally more selective in their diet than goats, being essentially grazer and favouring herbaceous taxa. In contrast, goats are mixed-feeders, consuming a broader range of plants, including a higher proportion of woody species (Bartolomé et al. 1998; Lu 1988; Osoro et al. 2013). As semi-obligate drinkers, both sheep and goats meet their water needs from both open water (largely reflecting values of local precipitation) and leaf water, which is ^{18}O-enriched relative to precipitation due to evaporation and transpiration effects (Barbour et al. 2004; Cernusak et al. 2016; Levin et al. 2006). In addition to source water taken up by roots, the oxygen isotope composition in plants depends on their physiology, local temperature, and humidity (Barbour 2007; Rawson et al. 1977). Therefore, the sinusoidal $\delta^{18}O$ patterns in both species are likely a reflection of similar contributions of the seasonally variable $\delta^{18}O$ values in water sources, with the highest values in summer and the lowest values in winter months (Balasse et al. 2002). However, it is essential to consider the implications of husbandry practices on these domestic animals, as evidenced by the combined intra-tooth C-O isotope profiles of our samples (Fig. 3).

The anti-covariation of $\delta^{13}C$ and $\delta^{18}O$ values (e.g., sample KKt 22 – sheep) is often interpreted as evidence of vertical transhumance practice (Makarewicz et al. 2017). However, especially in regions where both C_3 and C_4 plants are present (or cultivated), it is not always easy to distinguish between vertical mobility and foddering of non-mobile animals (Makarewicz, 2017; Makarewicz et al. 2017). Therefore, the possibility that values above −8‰ are indicative of C_4 foddering is usually taken into consideration (Bocherens et al. 2001). In particular, the anti-covariation pattern with high $\delta^{13}C$ values corresponding to low $\delta^{18}O$ values (e.g., sample KKt 22 – sheep) is often interpreted as C_4 fodder provisioning during winter months. In the Central Asian steppe, this practice is widely attested among agropastoral communities since the Early Bronze Age, and even earlier, when the integration of millet ($\delta^{13}C \sim -12$‰) cultivation within husbandry practice has begun (Ananyevskaya et al. 2020; Hermes et al. 2019; Ventresca Miller et al. 2020a, b). In Kazakhstan, decreasing $\delta^{13}C$ values leading into summer after C_4 peak (i.e., fodder provisioning) in winter has been interpreted as evidence of shifting to spring-summer pastures of steppe and mountain environment. $\delta^{13}C$ values from ~ −6‰ to ~ −3‰ have been interpreted as C_4 plant contributions to the diet between 44% and 74% (Hermes et al. 2019). The $\delta^{13}C$ values of wild animals in Central Asia also suggest interpreting the decrease in $\delta^{13}C$ values in summer as vertical transhumance (Hermes et al. 2022). This is likely the case of our strongly anti-correlated samples (Figs. 4 and S1), showing winter $\delta^{13}C$ values up to −1.7‰. After winter, they probably fed on C_3 steppe plants located in the mountainous area of the Karatyube, south of Kafir Kala. Here, C_4 plants are expected to be absent or almost absent both because of their natural distribution in Central Asia (Shen et al. 2018; Winter, 1981) and their general decrease with increasing altitude (Makarewicz et al. 2017). On the other hand, previous research has interpreted the co-variation of $\delta^{13}C$ and $\delta^{18}O$ values (e.g., sample KKt 29 – sheep) as evidence of residential animals kept near the site and thus registering seasonal variations in the local environment in their bioapatite (Lazzerini et al. 2021). The $\delta^{18}O$ values reflect the climate seasonality typical of this region (Hermes et al. 2022; Isaakidou et al. 2019; Knockaert et al. 2018), while $\delta^{13}C$ values of C_3 plants growing in semi-arid regions exhibit seasonal variability driven by fluctuations in water availability, with a 2–5‰ ^{13}C enrichment during the summer months (Makarewicz et al. 2017). The same husbandry technique may also have been applied to individuals such as sample KKt 14 (goat) and sample KKt 16 (NA), which exhibit sinusoidal $\delta^{18}O$ profiles combined with nearly flat $\delta^{13}C$ values (~1‰ variation or less), suggesting continuous feeding on C_3 plants. Environmental seasonality, altitude or animal mobility would have led to greater intra-tooth $\delta^{13}C$ variability. Therefore, this pattern likely reflects close management near the site, including foddering practices (Chazin et al. 2019; Hermes et al. 2022).

Interestingly, $\delta^{13}C$ values compatible with C_4 plants consumption were detected only in sheep, while goats exhibited slightly variable values consistent with a C_3 plant-based diet. This suggests that different herding strategies between sheep and goats existed at Kafir Kala, with summer vertical transhumance coupled with winter foddering on C_4 plants applied only to sheep. Therefore, the difference in diet and mobility – exposing them to a wider variety of food and water sources across different environments – could explain the greater $\delta^{13}C$ and $\delta^{18}O$ amplitude observed in sheep samples (Mashkour 2003). Additionally, sheep tend to access open water sources more frequently due to their higher water requirements (Makarewicz, 2017). The decision to practice seasonal transhumance with sheep and to supplement their diet with C_4 fodder may be related to their greater flexibility in feeding behaviour. Although sheep are generally more selective than goats, they are more likely to alter their diet and consume less desirable food when grazing availability is limited (Nicol et al. 1987). However, this practice was not applied uniformly to all sheep. For instance, samples KKt 19 and KKt 31 showing a strong anti-correlation, as well as samples KKt 6 and KKt 21 showing a weaker anti-correlation, display minimal changes in $\delta^{13}C$ values (Online Resource 6). This suggests that these individuals were primarily fed C_3 plants, with only a minor contribution of C_4 plants during autumn and winter.

Sr analyses are commonly recommended to resolve concerns about altitudinal mobility (Hirose et al. 2021; Makarewicz et al. 2017). However, they have not been entirely conclusive in this context. As demonstrated by the BASr dataset from Kafir Kala and its surrounding landscape, such approaches are not always conclusive in geologically complex settings. Plants collected in the immediate vicinity of the site define a local BASr signature with a mean $^{87}Sr/^{86}Sr$ of 0.71051, while off-site samples from the Karatyube piedmont exhibit partially overlapping values and only a slightly lower overall mean. The substantial overlap between on-site and off-site BASr ranges indicates that movement between the piedmont and the site would not necessarily produce a clearly distinguishable isotopic signal. Notably, BASr values from the Karatyube piedmont are broadly comparable to those of the site itself, suggesting that the pronounced geological complexity of the region is not directly or uniformly reflected in local bioavailable strontium isotope signatures. This masked geological signal is likely the result of sediment homogenization within alluvial fan systems, further amplified by the long-term redistribution and mixing of sediments through irrigation networks, thereby limiting the resolution of Sr isotope analysis for detecting short-range or altitudinal mobility in this landscape. The homogeneous $^{87}Sr/^{86}Sr$ values of tooth enamel corresponding to both winter and summer months do not suggest a high degree of seasonal mobility. However, in many cases these values support interpretations based on C-O isotope correlation patterns. Several individuals showing both flat $\delta^{13}C$ vs. sinusoidal $\delta^{18}O$ (e.g., sample KKt 14 – goat; sample KKt 16 – NA) and C-O covariation patterns (e.g., samples KKt 13 and KKt 29 – sheep) yielded $^{87}Sr/^{86}Sr$ values consistent with the local Sr BASr of Kafir Kala. Conversely, samples KKt 10 (sheep) and KKt 27 (NA), initially interpreted as non-mobile, yielded both $^{87}Sr/^{86}Sr$ values falling within the lower range of the broader regional Sr BASr (i.e., values not overlapping with Kafir Kala). This discrepancy may reflect a higher degree of local Sr isotope variability around the site – variability that is difficult to detect due to modern agricultural activity in the surrounding area.

The $^{87}Sr/^{86}Sr$ analysis generally supports the lower mobility of goats compared to sheep. Nearly all goat samples (KKt 5, KKt 14, KKt 17, KKt 20) yielded consistent intra-tooth $^{87}Sr/^{86}Sr$ values that mostly align with the local BASr of Kafir Kala. This includes sample KKt 20, which displays a C-O isotope anti-correlation pattern. Given the homogeneity in $\delta^{13}C$ values, this pattern may reflect a winter diet characterised by a small proportion of C_4 plants, or water-stressed C_3 plants harvested in summer. Sample KKt 17 yielded values that fall within the broader Sr BASr. Again, this may be related to a greater Sr variability around the site, making firm conclusions difficult at this stage.

Sample KKt 5 is the only individual showing more variable intra-tooth $^{87}Sr/^{86}Sr$ values, though still within the site's BASr. This could indicate either: (1) this animal dwelled around the site covering the whole Sr variability of the area, or (2) since the summer value (corresponding to the first, and thus older, intra-tooth enamel sample) lies almost outside the upper edge of the local BASr, this individual may have been brought to Kafir Kala from a different area. Additional $^{87}Sr/^{86}Sr$ measurement from teeth formed before and after the analysed one would help clarify this scenario.

Unfortunately, unlike previous cases where Sr isotopes complemented the interpretation of C-O isotope data, this was not observed among individuals potentially involved in seasonal mobility. The partial overlap between the bioavailable Sr values of Kafir Kala and Karatyube piedmont prevented a definitive identification of transhumance practice (see e.g., samples KKt 11, KKt 19, KKt 21 – sheep). A different case is represented by individual KKt 22 (sheep), who appears to have spent most of the lifetime represented by the tooth in an area entirely outside the BASr range. Similarly, sample KKt 12 (NA) may have been raised far from the site and brought to Kafir Kala while the tooth was forming. The most interesting individuals are samples KKt 2 (NA), KKt 9 (sheep) and KKt 31 (sheep), all of which show $^{87}Sr/^{86}Sr$ values incompatible with the entire BASr range (i.e., including samples collected north of Samarkand and from Tajikistan). Notably, sample KKt 31 is the only individual that yielded more radiogenic $^{87}Sr/^{86}Sr$ values. This suggests that the measured values likely represent a period before these animals arrived at the site. Due to the scarcity of published $^{87}Sr/^{86}Sr$ data from Uzbekistan, determining the provenance of these individuals remains challenging. Nonetheless, the less radiogenic values of non-local individuals (~0.7088–0.7089) are partially consistent with $^{87}Sr/^{86}Sr$ values reported for natural samples from southern Uzbekistan. In contrast, the more radiogenic values of sample KKt 31 (0.7112–0.7121) are compatible with the geological units represented by the mountains of the same area, bordering the actual Afghanistan and Tajikistan (Kroll et al. 2022). Since these regions are at least 250 km away from Kafir Kala, a less distant place of origin, possibly linked to other pasture locations, could be more realistic. This may be particularly true for sample KKt 2, showing summer $^{87}Sr/^{86}Sr$ values close to the off-site Sr BASr. However, considering the strategic location of Kafir Kala, just a few kilometres from the main junction of the Silk Road – and the central role played by Central Asian territories in this vast network (Mishra 2020) – we cannot rule out more distant origins as well. Likewise, the possibility of interactions between the sedentary population of Kafir Kala and semi-mobile pastoralists in the piedmont steppe must also be considered (cf. Kurmaniyazov et al. 2023). Expanding the discussion within a broader Central Asian perspective, symbiotic relationships between sedentary and nomadic communities, including those from the highlands, are well documented throughout the centuries playing a key role in the complex trade system connecting the main nodes of the Silk Road (Frachetti 2012; Frachetti et al. 2017).

Conclusion

This work provides new insights into livestock management strategies at the site of Kafir Kala through the analysis of tooth enamel and dentine/bone collagen of twenty ovicaprid individuals from the Islamic phase (early 8th – 12th century AD). Species determination performed by ZooMS revealed differences in herding practices between sheep and goats. Sheep were more frequently moved to summer pastures – likely located along the Karatyube piedmont ~ 10 km south of the site – and provisioned with C_4 crops in winter. A clear C_4 $\delta^{13}C$ signal was absent in goats, suggesting they were likely kept near the site year-round. Non-mobile individuals were also identified among sheep, but with some proportion of C_4 plants in their diet. Overall, the topic of transhumance practice is not easy to solve through C-O stable isotopes solely. Multiple factors including physiological, climatic and environmental variables, as well as human action (e.g., food and water supply), contribute to the highly variable intra-individual $\delta^{13}C$ and $\delta^{18}O$ isotope patterns of our samples. In some cases, it is possible that the highest (i.e., summer) and lowest (i.e., winter) signals were absent due to dental wear or fragmentation during the sampling procedure as a result of the preservation state. Unfortunately, due to the partial overlap between the Sr BASr of the site and that of the Karatyube mountain area, $^{87}Sr/^{86}Sr$ analysis did not provide conclusive results in distinguishing mobile from non-mobile individuals. Future research could benefit from the analysis of C-O stable isotopes of obligate drinkers' tooth enamel (e.g., cattle) to track more precisely the $\delta^{18}O$ values of local meteoric water (Makarewicz, 2017). Additionally, expanding the sample size of sheep and goats, as well as increasing the Sr BASr samples from the Samarkand region and its surroundings, will enhance our understanding of herding strategies at Kafir Kala and support broader investigations into mobility and provenance across Uzbekistan.

The combination of agriculture and seasonal (vertical) mobility of livestock has long been a common strategy and continues to be practiced today as an adaptation to the diverse and mosaic environments of Central Asia (Ventresca Miller et al. 2020a, b). In our view, the variability observed in the C-O isotope patterns cannot be fully explained by simple mobile-stationary or sheep-goat pairs, because many factors influence breeding practices in agropastoral communities. For instance, the proportion of C_3 and C_4 fodder in the diet may vary depending on species, age and sex, as well as forage availability and specific production goals (Makarewicz and Pederzani 2017). The distinct herding strategies observed for sheep and goats may reflect differing functional roles within the local economy – such as the exploitation of specific by-products – or may represent a risk management approach aimed at reducing dependence on a single species (Hirose et al. 2021). The versatility of economic strategies, combining multi-animal herds and plant cultivation, is still evident among steppe pastoralists and agropastoral communities (Dubova et al., 2021; Hermes et al. 2019). In the Samarkand region, transhumance continues to be practiced during spring-summer months, and a preference of sheep over goats has also been documented (local shepherds pers. comm.). We believe that a similar way of life characterised the people inhabiting Kafir Kala during the Islamic period. Although we cannot completely rule out that all the animals were kept year-round near site and fed on different amounts of C_3 and C_4 plants depending on species and season, our results pointing to at least two different animal management strategies are consistent with Central Asian economic strategies and traditions. Similarly, the presence of non-local $^{87}Sr/^{86}Sr$ values in some samples – primarily sheep – suggests the existence of trade networks with foreign people, although their provenance remains difficult to establish for the time being. Overall, our results reinforce the interpretation of Kafir Kala as a key and dynamic settlement within the Samarkand oasis, where the agropastoral community lived at the heart of a complex exchange system connected to the ancient Silk Road.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12520-026-02516-3.

Acknowledgements Analytical costs were covered by the internal funds of the Metallomics and Geochemistry Research lab (MeGic; https://www.geochem.unimore.it/) of the Department of Chemical and Geological Sciences of UNIMORE. BD received funding through ERC COG 2023 (101125532) and PRIN 2020 HERDS (2020EP24PP). The UIAP is funded through annual grants by the University of Bologna, Alma Scavi programme, The International Association for Mediterranean and Oriental Studies – ISMEO, Rome, the Italian Ministry of Foreign Affairs and International Cooperation. We sincerely thank Dr. Elena Maini for her valuable support in the analysis of the faunal materials, Prof. Bruno Genito for kindly granting access to the materials from the site of Kojtepa, and Emanuele Grotto Maffiotti for help with ZooMS analyses.

Author contributions EA, FL, ES and SM designed the research. SSu and AB provided access to archaeological materials. EA, ES, SSu, AB and SM conducted fieldwork and sample collection. EA, FL, MM, SSa, BD and HV performed the experiments and collected data. EA and FL analysed the data and interpreted the results. EA wrote the first draft with contributions from all co-authors. SM and AC coordinated research activities and ensured project completion. BD, HV, AC and SM secured funding and managed financial resources.

Funding Open access funding provided by Università degli Studi di Modena e Reggio Emilia within the CRUI-CARE Agreement.

Data availability The authors declare that the data supporting the findings of this study are available within the paper and its Supplementary Information files. ZooMS data are available at 10.5281/zenodo.17278621.

Declarations

Competing interests The authors declare no competing interests.

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