



Grain impressions in ceramic vessels illustrate the extent of 1st millennium BC agriculture across the northern Central Asian steppe

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Abstract

The Syr and Amu Darya deltas and the littoral zone of the eastern Aral Sea, from Khorezm to Kyzylorda, have attracted the attention of archaeologists for nearly a century. Since the well-known Tolstov expeditions, archaeologists have discussed the establishment of early defensive architecture and elaborate irrigation systems on the periphery of the hyper-arid Kyzyl Kum Desert. Scholars have argued over whether the ancient people in this region during the 1st mill. BC, which are often culturally ascribed to the Saka, were more nomadic or sedentary and what their political organization looked like. Thus far, archaeobotanical investigations in this region have been lacking, limiting discussions about cultural adaptation, social orders, and the dispersal routes for domesticated plants and animals. In this study, we provide the first evidence for both *Hordeum vulgare* (barley) and *Panicum miliaceum/Setaria italica* (millets) cultivation in this key cultural region, dating to the first half of the 1st mill. BC. We identified barley and millet impressions on ceramics from all sites that we studied in the region, including ceramics that archaeologists classify as both Saka and Chirik-Rabat. We argue that the ubiquity of these finds indicates a greater prominence of farming practices across the steppe ecozone than scholars have previously recognized.

Keywords Central Asian steppe · Agropastoralism · Summer-sown millet · Pottery impressions · Kazakhstan · Ceramics

Introduction

Archaeologists working in Central Asia, over the past decade, have increasingly focused on the development of economic, especially dietary, traditions. This interest seems

to spur from: 1) a long-standing view that ancient peoples of this region were unique in their development of imperial systems and elaborate social hierarchies in the absence of agriculture; and 2) the acceptance of this region as being the cultural crossroads of the ancient world, and therefore, playing a key role in the formation of culinary, agricultural, and pastoralist practices for all of ancient Eurasia. Many scholars have explored the processes behind the intermingling of the knowledge of millet cultivation with wheat/barley agriculture (see Spengler 2015; and Jones et al. 2017 for discussions), and this research has raised even more engaging questions. For example, Miller et al. (2016) question how and when seasonal crop-rotation systems, often relying on winter wheat and summer-sown millets, arose. Understanding the development of various forms of multicropping systems is instrumental to any discussion of the rise of urbanism and the formation of complex hierarchical political systems. Scholars have also debated over the ways that millets have been integrated into economic practices across Eurasia; for example, several scholars have discussed the low-investment cultivation of millets in prehistory as a

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complement to mobile-pastoralists strategies (Spengler et al. 2014; Spengler 2015; Motuzaite Matuzeviciute et al. 2016; Ananyevskaya et al. 2018). This question feeds into a broader debate over the level of economic specialization within the cultures of ancient peoples of Central Eurasia, especially in the arid steppe or along its peripheries. As the littoral zones of the Caspian and Aral Seas are central to all of these debates and represent the greatest persistent lacunae in the existing data for palaeoeconomies of Central Eurasia, we have sought to fit the ancient inhabitants of this region into a broader synthesis.

Stepping down from the grand narratives, the diversity within agricultural adaptations on sub-regional scales also merits further study, especially for the broader central steppe ecozone. A highly informative study at the site of Kara-tepa (ca. AD 300–500) illustrated the reliance upon agriculture among early medieval populations within the biologically rich delta at the southern periphery of the Aral Sea, but left open questions regarding a deeper antiquity to farming practices in the region (Brite and Marston 2013). Through our study, we have sought to address these questions, and in so doing, have illustrated the presence of a mixed cultivation system in the steppe and coastal zone east of the Aral Sea by the early 1st mill. BC (the terminal Bronze to early Iron Age). Further, we show that people were consuming these crops outside the delta zone, in western Kazakhstan stretching to the mountain foothills of northern Central Asia. We draw these conclusions through a detailed study of the impressions of cereal grains in pottery, a valuable and underutilized method in the archaeological toolkit. During the past two decades, a clearer picture of ancient farming systems has developed from archaeobotanical studies of carbonized seeds (Spengler et al. 2014, 2016, 2017, 2018; Liu et al. 2016), isotopic analyses of animal and human remains (Motuzaite Matuzeviciute et al. 2015, 2016; Ananyevskaya et al. 2018; Hermes et al. 2019), as well as lipid residues on pottery. Miliacin, a biomarker for *Panicum miliaceum* (broomcorn millet), has been reported in three pieces of pottery excavated from the Akpan site (4th–2nd c. BC), which is located between the Aral and Caspian seas (Murakami et al. 2022).

These studies have shed light on the timing of dispersal and development of cereal cultivation and bread-based cuisines in various regions; in so doing, their relationship with pastoralism has become more apparent. However, scholars have pointed out limitations in these studies, such as the sporadic distribution of preserved archaeobotanical assemblages and the uneven focus of archaeological excavations across Central Asia (Spengler et al. 2017). This trend is more pronounced when looking beyond the heavily studied mountainous spine of Inner Asia (Frachetti et al. 2010; Spengler et al. 2014; Hermes et al. 2019; Endo et

al. 2023). Our goals in this study are to: 1) fit the broader Aral Sea coastal regions and the steppe ecozone into a comparative study of Central Asian palaeoeconomy and cultural development (the grand narrative); and 2) to understand the local-scale adaptations, especially relating to the origins of farming, that permitted large dense populations to form on the peripheries of the desert.

Cultural adaptations and agropastoralism on the steppe

Archaeobotanists working in Eurasia have now accumulated enough data to develop models of cultural change over time and across a diverse array of ecosystems and cultural affiliations. For example, Spengler et al. (2021) recently explored the narratives that present the broader region, especially in the more arid steppe, as predominantly mobile pastoralist, seeking a more nuanced understanding of the integration of economic features. Similarly, a large-scale database of collagen isotope values collected from human skeletal remains has been analysed using Bayesian statistics in order to understand broad patterns in the adoption of millets into cultivation systems over time (Ventresca-Miller et al. 2023). As with archaeobotanical studies, most of the ancient isotopic research has focused on the mountain foothill zones and not the steppe proper, some exceptions include Ananyevskaya et al. (2018) and Itahashi et al. (2020). Also, studies of ancient irrigation systems in Khorezm to the south of our study sites (discussed just below), shows that intensive farming could have been practiced in the broader region, but we are cautious about transplanting these economic strategies onto small-scale sites in the arid steppe.

The Aral Sea coastal region, including Khorezm in western Uzbekistan and Kyzylorda in southwestern Kazakhstan, was among the first areas in Central Eurasia to receive detailed archaeological attention (Tolstov 1948, 1962). Wind deflation, a particularly difficult issue for archaeological interpretations in arid Central Asia, has limited the utility of archaeobotanical flotation and, therefore, the reconstruction of farming systems. The lack of stratigraphy and preserved archaeobotany has led scholars to turn to stable carbon and nitrogen isotopic analysis on human bone collagen to build estimates of the dietary components in the steppe in the past (Itahashi et al. 2020; Kurmaniyazov et al. 2023). These isotopic studies hint at the possibility of a transition to a more grain-reliant diet across much of the core areas of Eurasia during the 1st mill. BC (Ananyevskaya et al. 2018). A contradiction with traditional narratives for cultural development across Central Asia has already been pointed out by several scholars, whereas the highly mobile and economically specialized nomadic confederacies, colloquially referred to as the Scythians, are also supposed to

manifest during the transitional period of the Bronze and Iron Ages (Chang et al. 2002; Spengler et al. 2017). This 1st mill. BC transition is marked, across a much broader swath of Eurasia, by significant social and demographic shifts (Kuzmina 2007), referred to by Jaspers (1953) as the Axial Age.

More recent studies in the eastern Aral Sea region have stepped away from the link between the Bronze–Iron Age interface and the rise of a supposed Scythian confederacy, suggesting a reversal of the model—a transition from nomadism to the combination of cattle breeding and agriculture by people ascribed to the Saka Culture, with a greater labour investment into irrigation construction by people archaeologically labelled the Chirik-Rabat Culture (Utubayev 2022). However, these models are largely based on the identification of large-scale fortification works and irrigation systems; forming a clearer understanding of the role of agriculture will require further exploration through archaeobotanical research. Additionally, these models have largely been developed based on data from the mountainous spine of Inner Asia, whereas the remote oasis sites that we are interested in here are located in western Kazakhstan. The arid steppe sites that we present here are more than 500 km away from the mountain foothills. The identification of irrigation facilities by archaeologists in the 1930s through 1960s (e.g. Tolstov 1948, 1962; Andrianov 1969) provides the most compelling evidence of farming in the 1st mill. BC (Boroffka 2010; Brite et al. 2017; Utubayev 2022). Branching irrigation constructions have been reported to be linked to the Chirik-Rabat and Babish Mola sites, and the ceramics from both of these sites were analysed for this study (Utubayev 2022). “The expansion of large-scale irrigation systems in the winter-wet, summer-dry zone is characteristic of the 1st mill. BC. Irrigation systems for winter-cropping wheat and barley were already in place; the introduction of the millets allowed for a novel economic system, incorporating for the first time summer-cropping in hot, arid-summer regions” (Miller et al. 2016, p 1573). The importance of irrigated farming in the Amu Darya delta has been further supported based on close cultural affiliations with the Khorezm area on the south coast of the Aral Sea, argued for based on similarity of the mausoleum and other features (Utubayev et al. 2023).

Stable carbon and nitrogen isotopes from human and herbivore bones recovered from three sites of the Chirik-Rabat Culture (ca. 500–1 BC) suggest that the animals were fed on C₄ plant material (Ananyevskaya et al. 2020). Some of the humans also expressed a relatively high carbon isotope ratio, which the analysts inferred to be due to protein intake from animals that consumed C₄ plants. The C₄ plants could either represent millet stubble in post-harvested fields or straw used as winter fodder after grain harvesting. As C₄

photosynthesis tends to be an adaptation for hot climates and water loss, plants expressing this respiratory trait tend to be more naturally abundant in arid regions so grazing of wild plants cannot be excluded (Ananyevskaya et al. 2020; Kurmaniyazov et al. 2023). As these isotope specialists are clear in pointing out, wild arid-land-adapted species, notably in Amaranthaceae, likely attributed in part or in full to the elevated carbon isotope ratios in the animals (Ananyevskaya et al. 2020).

Isotope analyses have also been conducted on ancient human and animal remains from three sites also in the lower Syr Darya basin, Sortobe 1 (AD 882–1007) and Sortobe 2 (AD 1040–1272) of the Oguz Culture, and Shirkeily Kos-Asar (AD 255–416) of the Dzhetyasar Culture. The faunal samples showed elevated $\delta^{13}\text{C}$, and the researchers conducting the study avoided differentiating between the consumption of wild C₄ plants by herd animals or the use of millets as human food and/or fodder (Kurmaniyazov et al. 2023). While these studies provide tantalizing evidence for millet consumption on the outskirts of the Syr Darya, further work, such as what we present in this paper, is needed to clarify the extent of inputs from wild C₄ plants.

Material and methods

Research area

In this study, we present data from nine archaeological sites spanning the 1st mill. BC and spread across southern Kazakhstan, of which six are located in the eastern Aral Sea littoral zone. The eastern Aral Sea region refers to the middle and lower reaches of the Syr River, which is one of the two, along with the Amu Darya, largest rivers in Central Asia. The deltas of both rivers turn into braided and marshy fluvial systems as they meet the Aral Sea. This dynamic landscape would have been more expansive in the past, when greater glacial melt fed into more prominent rivers and there was less diversion of water for industrial irrigation (Boroffka 2010; Brite and Marston 2013; Brite et al. 2017). The rivers would have been directly tied to climatic conditions in the high mountains hundreds of kilometres away and were likely prone to flooding, bringing in rich sediments and creating a highly arable landscape. The broader region is marked by a continental arid-desert environment, with extremes in both cold winters and hot summers, averaging less than 200 mm of rainfall per annum (Peel et al. 2007). The xerophytic and halophytic shrubby vegetation around the deltas is dominated by arid-adapted Amaranthaceae, such as *Haloxylon* spp. (saxhaul) and *Salsola* and *Atriplex* (saltbush). Even though dry farming would not have been possible in the past, the Syr and Amu

Darya would have provided sufficient water and their braiding delta would have exhibited an ideal slope for harnessing the water through basic gravity irrigation (Ananyevskaya et al. 2020). It is also possible that wetter areas near the rivers, by springs, or in natural water catchments on the landscape could have been utilized for low-investment farming, as is ethno-historically attested in some parts of Central Asia (see Spengler 2015). In this region, a cultural repertoire that archaeologists call the Chirik-Rabat Culture existed in the second half of the 1st mill. BC, following on the early 1st mill. BC Saka Culture-type (Utubayev 2022). Sengir-Tam 2 is the only site in our study that is both ascribed to the Saka Culture and located in the eastern part of the Aral Sea. In addition to this, we also conducted a comparative survey of materials excavated from three Saka Culture sites located in the foothills of Semirech'ye in southeastern Kazakhstan, where the annual rainfall is abundant and the environment is highly arable.

Archaeological sites

In this study, we investigated pottery excavated from four sites of the early 1st mill. BC, namely Sengir-Tam 2 (7th to 6th c. BC), Balakungei (8th to 5th c. BC), Kainar (4th to 3rd c. BC), and Rurrt (5th to 3rd c. BC), and five sites of the later 1st mill. BC, namely Mynaral, Babish-Mola, Balandy, Inba-Bale, and Shiri-Rabat (all spanning the 4th to 2nd c. BC). The pottery sherds that we analysed in this study were excavated from various contexts, including the burial remains

at Sengir-Tam, the settlement at Mynaral, the settlement, fortress, and temple at Babish Mola, the temple and pit at Chirik-Rabat, and the settlement at Balandy. Furthermore, the Kainar and Rurrt sites are also sites of the Saka Culture, located in southeastern Kazakhstan, not in the eastern Aral Sea (Fig. 1, Table 1).

Sengir-Tam 2 burial: Sengir-Tam 2 is a cemetery of earthen burial mounds located on the eponymous hill on the left bank of the lower Syr Darya, 6 km northeast of the Sengir-Tam 1 burial ground and 23 km west of the Chirik-Rabat settlement. The site was discovered in 2014 during survey work conducted by the Chirik-Rabat archaeological expedition; excavation at the location began in 2015, during which the mortuary monument was systematically excavated. There are 23 barrows in the necropolis, which can easily be clustered into western and eastern groups. Both groups of barrows stretch in a chain from west to east and from southwest to northeast. All mounds are rounded in shape, 8 to 25 m in diameter, and 0.2 to 1.3 m high. In the field season of 2016, four of the mounds were investigated, providing the ceramics that we analysed for this study.

Chirik-Rabat settlement: The ancient occupation site is located 300 km southwest of the city of Kzyl-Orda, on the left bank of the dry channel of the Zhanadarya. The mound occupies the whole area of a natural hill, with a diameter of $850 \times 600 \text{ m}^2$ stretching from north to south, and the tell or kala site is fortified (a kala is a large-scale fortified structure associated with elite residential or administrative activities). Excavations were undertaken in 2004, during a new stage



Fig. 1 Location of the studied sites in this paper

Table 1 Summary of the information about the sites studied in this paper

Site	Site code	Region	a.s.l. (m)	Period (c. BC)	Culture	Context	Environment	Precipitation (mm)
Babish-Mola	BBM	Eastern Aral	34	4th–2nd	Chirik-Rabat	Settlement, citadel, shahristan, temple	Desert	101–108
Mynaral	MYN	Eastern Aral	85	4th–2nd	Chirik-Rabat	Settlement	Desert	101–108
Balandy	BAL	Eastern Aral	35	4th–2nd	Chirik-Rabat	Settlement	Desert	101–108
Inkar-kala	INK	Eastern Aral	85	4th–2nd	Chirik-Rabat	Settlement	Desert	101–108
Chirik-Rabat	CHR	Eastern Aral	96	4th–2nd	Chirik-Rabat	Citadel	Desert	101–108
Sengir-Tam	SEN	Eastern Aral	97	7th–6th	Saka near east Aral	Burial ground	Desert	101–108
Kainar	KAN	Almaty	1100	4th–3rd	Saka Zhetysu	Kurgan	Desert	860
Rurrt	RUR	Almaty	900	5th–3rd	Saka Zhetysu	Sanctuary	Mountainous	600–650
Balakungei	BAK	Zhetysu Semirechye	1135	8th–6th	Saka Zhetysu	Settlement	Mountainous	450–650

of research of ancient settlements of the Aral Sea region, the main objective of study was to better understand the ancient settlement of Chirik-Rabat. Excavations were undertaken in the northern part of the settlement, inside the area of the third defensive wall, between the royal barrows.

Babish-Mola settlement: This occupation site is located between two side channels of the Zhanadarya, 40 km to the northwest of Chirik-Rabat. Babish-Mola was first surveyed by the air reconnaissance team of the expedition in 1946. At the same time, the large settlement Babish-Mola 1 and a separate building, labelled Babish-Mola 2, were mapped, the plan of the fortress was taken and surface materials were collected. Additional surveys at Babish-Mola were carried out in 1948, 1949, and 1957. The site was revisited and a detailed survey of the entire oasis area was conducted in 2018 (Utubayev et al. 2023).

The fortified structure of Balandy: Balandy is located 40 km southeast of Chirik-Rabat. The Balandy complex includes three mounds or tells: a fortress (Balandy 1) with an adjacent rural settlement and two funerary structures (Balandy 2 and 3). For this study, we avoid trying to interpret the function of the fortified sites of Balandy and Inkar-Kala, whether a castle, citadel, or palace structure (Utubayev 2021).

The fortified structure of Inkar-Kala: The fortification mound is located on the main canal branching from the bed of the Zhanadarya River in the vicinity of Ak-kyr. It was discovered in 2006 during survey work by the Chirik-Rabat Archaeological Expedition, and excavations at the site began in 2011. Within the fortifications there appears to be several large houses or rooms; the best preserved of them is a rectangular structure on the left bank of the canal. The remains of its walls are 2.2 m high, and the ruins cover an area of $50 \times 30 \text{ m}^2$. On the surface of the settlement, there are abundant scatters of redeposited ceramics, and the ceramic complex of Inkar-Kala is identical to that of Chirik-Rabat.

Mynaral settlement: In 2022, the Chirik-Rabat Archaeological Expedition began archaeological excavations at the

rural settlement of Mynaral. The settlement is located 25 km east of Babish-Mola 1, on the eastern bank of the dry bed of the Zhanadarya River. The total area of the settlement is approximately $250 \times 150 \text{ m}^2$. Traces of buildings have been identified in this area, and the excavators have interpreted the site as a cattle-breeding settlement. On the basis of the results of the commissioned investigations of the site, it is highly probable that it was an unfortified, dispersed settlement with light frame buildings functioning as house dwellings.

Impression casting method for archaeological pottery

We present quantifications and descriptions of grain impressions identified in pottery, employing a relatively novel approach to the technique of ceramic impression analysis, which combines silicon casting and Scanning Electron Microscopy (SEM). This method has already been successfully applied on other Central Asian material, and promises to rapidly clarify questions regarding the extent of farming in prehistory (Endo et al. 2023). The study of impressions in ceramics has been implemented for nearly a century in Eurasian archaeology, relying primarily on impressions in pottery vessels and to a lesser extent in mudbrick. The improved procedures that we have developed following Ushino and Tagawa (1991), allow us to go beyond the limitations of visual identifications that hindered much of this past research. By filling the impression with high-precision silicon and observing the mold with the aid of an SEM, we can identify the seed morphology with a far greater degree of reliability than earlier impression studies, which relied on unaided visual identification of the impression. Additionally, the molds are more durable and, therefore, store better allowing for future analyses. We used the following procedure: (1) start with visually searching for impressions on the surface and cross-section of pottery fragments using a magnifying glass. (2) Pay particular attention to impressions

that are not fully exposed, as their shape is mostly enclosed inside the pottery fabric and is only accessible through a small hole on the surface. (3) Carefully remove any sediments in the holes using a soft brush. (4) Coat the impression and the surrounding area of the pottery surface with acetone containing 5% Paraloid B72 to protect the pottery surface. (5) Fill the voids with silicone (Tokuyama Fit Tester, Tokuyama, Japan). (6) Remove the cast from the hole after it has hardened. (7) Clean the surface by removing the coating liquid using 100% acetone. (8) Observe and identify using SEM (in our case, a KEYENCE VE-8800 in Tokyo, Japan) with a low accelerating voltage observation (0.5–20 k). Over the last decade, these new methods have been more widely implemented and the results speak for themselves (see Nakayama 2014; Fukuda et al. 2019; Grippedis 2019; Leipe et al. 2021; Endo et al. 2022, 2023; Sasaki et al. 2022). Similar methods were also used by Doumani Dupuy et al. (2023) to identify textile weaving patterns of impressions on ceramic sherds from late 2nd mill. BC sites in southern Kazakhstan.

Results

At Sengir-Tam (7th to 6th c. BC) near the eastern Aral shoreline, we examined 2.94 kg of Saka-type pottery and identified four grains of *Panicum miliaceum* and one grain of hulled *Hordeum vulgare* (barley). We processed 149 g of Saka-type pottery from Balakungei and identified one grain of *P. miliaceum*. Also, at Kainar in southeast Kazakhstan, 1.05 kg of pottery was analysed, and one grain of *P. miliaceum* was identified. From a few centuries later in time, sites with Chirik-Rabat-type ceramics produced more impressions. A total of 133.12 kg of pottery was examined from five sites in the eastern Aral region, and *P. miliaceum*, *Setaria italica* (foxtail millet), and hulled *Hordeum vulgare* barley were identified. Some of the barley grains in this study appear to have been processed for consumption, while some retained their glumes. All of the millet grains were

articulated with palea and lemma adhered. A breakdown of the full listing of identified cereals by site is presented in Table 2. The + notation for weight indicates that some other unmeasured pottery was observed. SEM images of some of the cereal impressions from each site are shown in Fig. 2, allowing readers to further judge the identifications and the reliability of our method.

Hulled barley grains (Fig. 2a, e, j–m, r, t, w–x) were identified based on the morphological criteria described by Motuzaite Matuzeviciute et al. (2021). The visibly attached glumes of the barley grains and their slightly angular cross-sections served as useful criteria for identifying them as being of a hulled morphotype. The margins of the grains are angular along the edges, as opposed to being smooth, a characteristic feature of adhered glumes. In addition, the ventral furrow on each grain is wide, deep, and rigid, also a characteristic feature of adhered glumes. All of the *P. miliaceum* (Fig. 2b–d, f–i, n–o, q, u–v, y–z) and *S. italica* (Fig. 2p, s) grains still retained their palea (inner) and lemma (outer) or glume-like structures, showing that threshing was incomplete. The surfaces of *P. miliaceum* grains are overall smooth and glossy without papillae. Unlike *P. miliaceum*, which is pointed at both ends, the frontal view of *S. italica* is circular, and the row of papillae can be observed on palea and lemma. Furthermore, recent research has confirmed the co-occurrence of both millets of East Asian origin, *P. miliaceum* and *S. italica*, in southeastern Kazakhstan in the 2nd mill. BC (Endo et al. 2023).

Discussion

Agriculture in the first mill. BC northern Central Asia

Macrobotanical methods are rapidly becoming accepted across Central Asia and will likely be commonplace on most excavations in the near future; however, there remains a dearth of data from most regions outside the montane zones. The fact that there is currently a concentration of data in

Table 2 Summary of the results

Site	Period (c. BC)	Culture	Weight of pottery (kg)	Taken impression	Grain types		
					<i>P. miliaceum</i>	<i>S. italica</i>	<i>H. vulgare</i>
Babish-Mola	4th–2nd	Chirik-Rabat	44 +	17	6	–	3
Mynaral	4th–2nd	Chirik-Rabat	13.02 +	41	14	2	3
Balandy	4th–2nd	Chirik-Rabat	22.5	23	10	–	3
Inkar-kala	4th–2nd	Chirik-Rabat	9.6	6	1	–	1
Chirik-Rabat	4th–2nd	Chirik-Rabat	44.0 +	41	10	–	2
Sengir-Tam	7th–6th	Saka near east Aral	2.94	8	4	–	1
Kainar	4th–3rd	Saka Zhetisu	1.051	3	1	–	–
Rurrt	5th–3rd	Saka Zhetisu	1.050	5	–	–	–
Balakungei	8th–6th	Saka Zhetisu	0.149	3	1	–	–
Total			138.31 +	147	47	2	13

only one region and along one ecotone—the foothills—significantly biases all discussions of paleoeconomy. Similarly, the data from the 1st mill. BC, the key transitional period—supposedly marking the development of Scythian nomadism—remains limited. These gaps in the data leave open the possibility that the models of paleoeconomy that have grown in popularity over the past decade are only applicable to certain regions. Notably, a near complete lack of data from the steppe ecozone, proper, especially from the period typically ascribed to the Scythian nomads, has plagued recent scholarship. While carbon isotope studies on human and animal bone collagen have made considerable strides towards filling in these gaps, the few studies that have been conducted are limited in scope. Additionally, detecting the intake of C_4 plants through isotope analysis requires that an ancient individual had consumed roughly 20% or more of their diet as such plants or meat from animals that have consumed C_4 plants. Another obstacle to the use of carbon isotopes to reconstruct past economies is the fact that the ecology of this region is characterised by a mixed C_3/C_4 vegetation community, and clarifying which parts of the C_4 signal are wild or millet is complicated. On the other hand, 1) pottery impression analyses do not require excavations and can be carried out on pottery sherds that are stored and curated, so comprehensive data can be accumulated in a relatively short period of time and at a low cost. 2) Impressions in pottery are predicted to have been formed by seeds accidentally dropped on the floor and incorporated into clay during the production of pottery within the home, securing the identification of the grains as a domestic resource. And 3) impressions can be made on grains that have not been carbonised, expanding the possibility of what we can discover archaeologically. Therefore, this method can significantly contribute to the interpretive potential of other archaeological datasets.

As we demonstrate in this study, the pottery impression method can be used to further link the grains to consumption by humans, because of their formation process in household contexts (Endo et al. 2022). This means that the seed impressions left on pottery excavated from the burial context are unrelated to the burials. Furthermore, since most grains identified from pottery impressions were incorporated into the clay just before the final processing stage of the grains, human consumption can be predicted, as animal feed does not require threshing or processing operations.

Spengler et al. (2017; see also Chang et al. 2002; Spengler et al. 2013) have pulled together data that support an increased reliance on farming in the economies of 1st mill. BC in northern Central Asia. They argue against the long-standing narrative of an increased reliance of mobile pastoralism at this time, and instead archaeologists working on these time periods are increasingly favoring models that suggest

mixed agropastoral systems (Chang et al. 2002; Spengler et al. 2013; Motuzaite Matuzeviciute et al. 2015; Wu et al. 2015; Brite et al. 2017; Chang 2017). Archaeobotanical analyses conducted at the sites of Tuzusai, Taldy Bulak 2, Tseganka 4 and 8—all on the Talgar Alluvial Fan in southeastern Kazakhstan, and spanning the 1st mill. BC—have led to the identification of free-threshing *Triticum aestivum* (bread wheat), hulled *H. vulgare*, *S. italica* and *Vitis vinifera* (grapes). Suggesting that at least one long-generation perennial was cultivated in combination with both long-season cereals and short-season millets. Archaeobotanical studies at Kyzyltepa in northern Uzbekistan led to the identification of hulled six-row *Hordeum*, free-threshing *Triticum*, *S. italica*, *P. miliaceum*, *Lens* (lentil), a single seed of *Linum* cf. *usitatissimum* (flax), and a single seed of cf. *Lathyrus sativus* (grass pea), as well as four fragments of *V. vinifera* pips and a pit of *Prunus* sp. (cherry or plum.) (Wu et al. 2015). A zooarchaeological analysis of the Kyzyltepa bones identified sheep and goat, cattle, pig (likely domesticated), horse, donkey, and camel, chicken (*Gallus gallus*), dog, and a single cat (*Felis* sp.). Wu et al. (2015) suggest that the occupants of the site during the 1st mill. BC were tied into Achaemenid imperial reign, and therefore may have been connected to a wider exchange network. Preliminary results at the coeval site of Bash Tepa on the edge of the Bukhara Oasis, is fuller illustrating the complex mix of agricultural and pastoralists activities employed across Inner Asia (Stark et al. 2019). Likewise, archaeobotanical studies at Paykend, also in the Bukhara Oasis, are illustrating how important intensive agricultural systems were for the rise of urbanism in the more highly populated areas of Central Asia during the late 1st mill. BC (Mir Makhamad et al. 2021).

Steppe sites (Saka Culture) of the first half of the 1st mill. BC

Nearly all archaeologists working in the broader eastern Aral Sea region have emphasized the cultural links between ancient peoples in this region and those across the broader steppe ecozone (Tolstov 1948; Andrianov 1969; Kidd et al. 2008; Boroffka 2010; Kidd and Brite 2015; Betts et al. 2016; Brite et al. 2017). The presence of kurgans and a ceramic tradition similar to steppe peoples has led some recent researchers to push for more nomadic interpretations of the palaeoeconomy of the region, feeding into what Spengler et al. (2021) recently referred to as “nomadic narratives”. For example, Negus Cleary (2013, 2015) has challenged the economic model established by Tolstov and most archaeologists working in the region before the 2010s (Tolstov 1948, 1956, 1962; Andrianov 1969; Negmatov 1994; Rapoport 1994; Khozhaniyazov 2006) that the irrigation systems, large-scale fortifications, and a complex array of

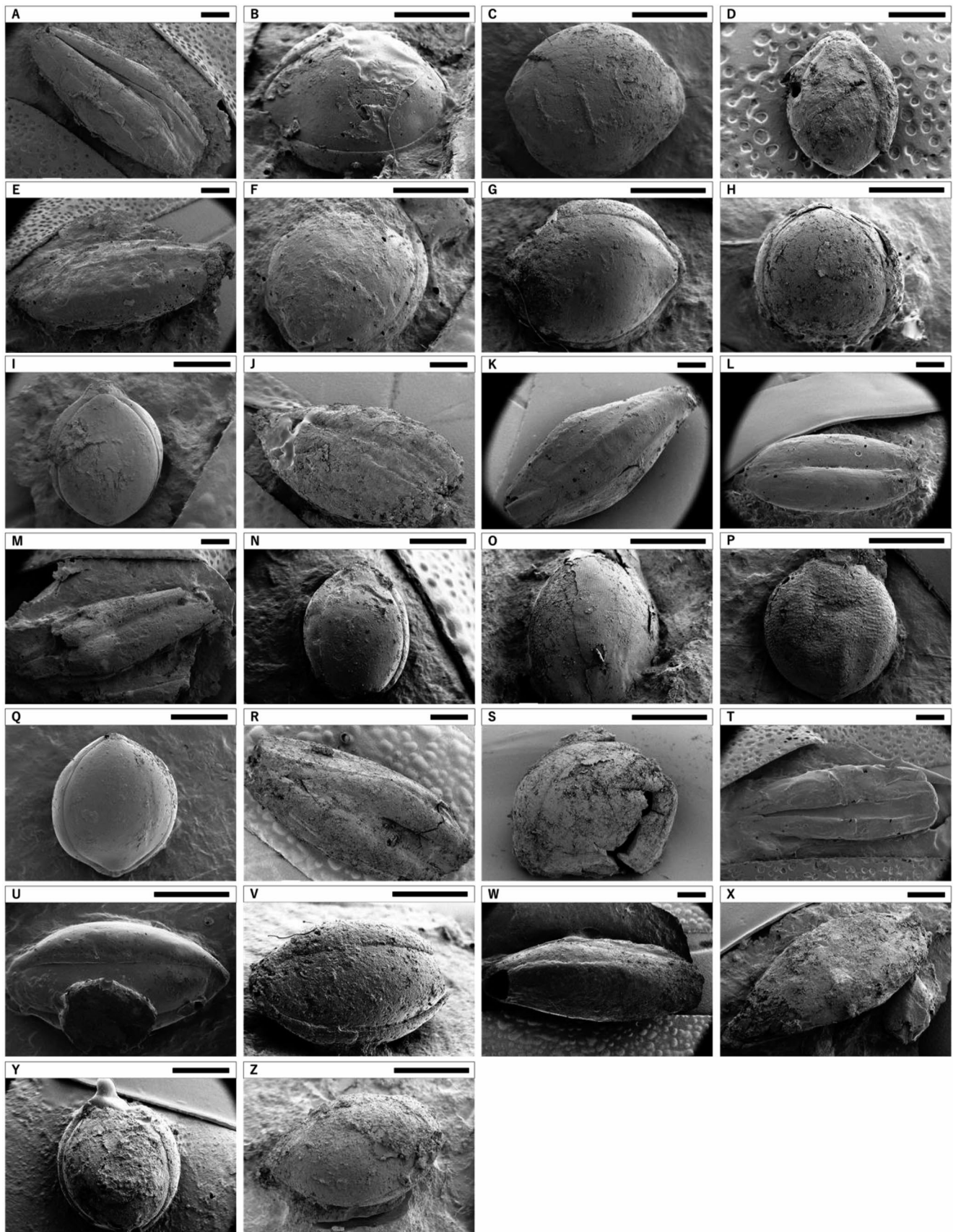


Fig. 2 SEM images of grain impressions in pottery. **a–e** Balandy; **f–l** Babish-Mola; **m, o** Chirik-Rabat; **p–s, x** Mynaral; **t, u** Inkar-kala; **v, w** Sengir-Tam; **y** Balakungei; **z** Kainar. **a, e, j–m, r, t, x** *Hordeum vulgare*; **b–d, f–i, n, o, q, u, v, y, z** *Panicum miliaceum*; **p, s** *Setaria italica*; scale bars = 1 mm

sedentary architecture is indicative of sedentism and some form of political unification. While we do not expect to test any of the prevailing models for palaeoeconomy or political development in this study, we do believe that a better understanding of the role of agriculture is essential before further speculation can be made.

Mudbrick and rammed earth (paksha) fortified sites dot the braided river systems of the Syr and Amu deltas, spanning from the 6th c. BC until the collapse of the regional population in the 3rd c. AD. These Kala structures are often interpreted as being indicative of localized polities or city-states, and the large-scale labour investments that went into constructing them and their accompanying irrigation systems have been used to make logical arguments for localized collective labour and political authority. It is well reported in the archaeological literature, after nearly a century of investigation, that sites in the Amu River delta, ascribed to the Chirik-Rabat Culture, consist of fortified defences, kala sites, presumably surrounded by an expansive agricultural landscape (much of which is lost due to extreme wind deflation) (Tolstov 1948; Negmatov 1994; Rapoport 1994; Khozhaniyazov 2006). The expansive settlement patterns, with farmsteads dispersed along irrigation canals, has been discussed in detail for the Khorezm region just to the south of our western-most study sites (Tolstov 1948; Khozhaniyazov 2006). While we cannot confirm whether the grains we identified were cultivated through low-investment systems or as part of an irrigated agropastoral economy, the low local rainfall, especially in the summer, would have made any farming challenging. Dispersed farmstead-like settlement patterns likely existed across much of southern Central Asia at this time, what Hiebert (1992, p 111) calls a “non-nucleated oasis settlement pattern”. Most scholars discussing these fortified kala structures have interpreted them as elite residences and/or administrative centres (Lamberg-Karlovsky 1994).

While our data do not allow us to quantify the inputs of grains in the diet, we have identified four grains of broomcorn millet (Fig. 2s) and one of barley (Fig. 2u) from Sengir-Tam (7th to 6th c. BC). These are the earliest cereals identified in this region, showing that cereals had already arrived in the eastern Aral Sea by the first half of the 1st mill. BC. At least one previous study hypothesizes a transition from nomadism by people of the Saka Culture to the combination of cattle-breeding and agriculture with irrigation by the Chirik-Rabat Culture (Utubayev 2022). Additionally, one grain of *P. milicaeum* was identified in the ceramic assemblage

from both Balakungei and Kainar, coeval to Sengir-Tam and ascribed to the Saka Culture. While the nature of these data do not permit us to discuss the intensity of farming, the seasonality of cultivation, or how farming was integrated into an agropastoral system, the presence of domesticated grains implies that people were growing crops, as the possibility that they might have been transported long distances across the steppe is less likely than local cultivation. *Hordeum* and *Panicum* represent both a long and two short-season grains; although, as many scholars have already pointed out for Central Asia, millets can be cultivated on a low-investment scale as a complement to pastoralism (see detailed discussion in Spengler 2015). *Hordeum* also tends to be a more tolerant crop than *Triticum*, therefore, leaving open the likely possibility that these grains represent a low-investment cultivation, possibly is particularly well-watered ecotopes across an otherwise arid landscape.

Aral sea sites (Chirik-Rabat Culture) of the second half of the 1st mill. BC

Domesticated grains were identified at 100% ubiquity at all five sites of the second half of the 1st mill. BC. While reiterating that this method does not allow us to quantify the value of these grains in the overall diet, we cautiously suggest that the presence of grains at all sites does attest to the widespread cultivation of cereals from the mountain foothills of Inner Asia west to the eastern Aral Sea, and, of course, across all arable microenvironmental pockets to the south of this region in Central Asia. Uncharred *P. miliaceum* grains were previously reported at Babish Mola (Utubayev 2022); however, the quantities of grains and a clear attribute of their age are lacking. Carbon and nitrogen isotope analyses of humans and herbivore bones recovered at several of the sites that we studied in this paper, including Babish Mola-7, Chirik-Rabat, and Balandy, support such conclusions. Both humans and herd animals expressed slightly elevated carbon isotope levels, even after accounting for the mixed vegetation community around these sites, this seems to suggest that humans were consuming millets and that herd animals were grazed on millet stubble or foddered in the winter with millet straw (Ananyevskaya et al. 2020). Our study further illustrates that these grains were part of the household repertoire and that they were abundant enough to inadvertently become incorporated into clay during domestic pottery production. We further argue that the grains were part of the human diet, in that some of the grains had been removed from their loose chaff and inflorescences, suggesting that they had already been threshed. That said, the millet grains are all adhered in their protective structures, as are some of the hulled barley grains, illustrating that they were not yet ready for human consumption and that another processing

phase would have been required. We hypothesize that this indicates that grains would have been stored within the household and processed as they were needed. The loss of grains during processing, which was likely a daily activity, would account for their unintentional incorporation into the clay. This style of grain store is most common among small-scale farming systems or among smaller populations of people, whereas large-scale communal threshing floors become more prominent when larger villages or urban centres develop. Understanding how these ancient agropastoralists stored, processed, and consumed grain helps us envision what life would have looked like on the edge of the hyper-arid deserts and steppe of northern Central Asia.

The westward dispersal of foxtail millet has received less attention than other grains, likely due to the less frequent finds of this grain in early sites in Central Asia. Nonetheless, it was clearly cultivated by people in Central Asia by the end of the 2nd mill. BC (Spengler 2015; Endo et al. 2023). In a previous ceramic impression study, eight grains of *P. miliaceum* and six of *S. italica* were identified at three late 2nd and early 1st mill. BC sites in the montane ecologies of Central Asia (Endo et al. 2023). Given that 47 *P. miliaceum* grains (89% ubiquity by site) were identified from eight sites in the present study, while only two *S. italica* grains (11%) were noted from the Mynaral site alone, we speculate that *S. italica* was less prominent. One possible interpretation is that farmers selected more drought-tolerant *P. miliaceum* in drier areas, leading to a decrease in *S. italica*. Still, given the old adage about absence of data, it is currently not possible to rule out the possibility that this observation is due to a paucity of data. In Ventresca-Miller et al. (2023) model of millet dispersal across northern Central Asia, they note that the increase in carbon isotope values peaked in southern Kazakhstan around 500 BC. While these results are consistent with our findings, there are no archaeological sites in which archaeobotanical or isotopic samples have been analysed in the vast area west of 70°E to the Caspian Sea, including the eastern Aral Sea region, with the exception such as at the Dam Dam Chesme Rockshelter (Charles 2010). Therefore, we are filling a massive gap in the data, both on a local-scale and a regional-scale in this study.

Irrigation agriculture along the eastern Aral Sea in the 1st mill. BC

While it dates to nearly a millennium later in time than the sites that we present in this paper, detailed excavations and scientific research at the site of Kara-tepe in Khorezm provide a glimpse into the intensity of irrigated farming that existed in this region during the early medieval period. The occupation at Kara-tepe dates to the 4th and 5th c. AD (Brite and Marston 2013; Brite et al. 2017). While it is clear from

this study that hulled barley and both millets were still cultivated in the region in the medieval period, a number of other, more water and labour-demanding crops were also recovered, including *Lathyrus sativus*/L. *cicera* (grass pea/chickpea), *Gossypium* sp. (cotton), *Vitis vinifera* (grape), and possibly *Cucumis* sp. (melon). The researchers conducting this study also suggest possible cultivation of *Avena sativa* (oat) and *Medicago sativa* (alfalfa); although, both of these plants are prominent weeds in agricultural contexts across Central Asia, making them extremely difficult to identify as a crop. The 861 cottonseeds from the site are particularly telling of the intensive investment in irrigated farming among these peoples, and recently a team of scholars has argued that the earliest cotton cultivated in Central Asia was likely an Indian arborescent form, requiring considerable water inputs (Mir Makhamad et al. 2024). The detailed investigations at Kara-tepe also integrate zooarchaeological data, noting that sheep (*Ovis aries*), goat (*Capra hircus*), and cow (*Bos taurus*) were raised. In the same way that it is difficult to identify cultivation of *M. sativa* and *A. sativa*, the few horse (*Equus* sp.) and pig (*Sus scrofa*) bones may represent either hunting or husbandry of these animals, as red deer (*Cervus elaphus*) bones were also identified (Brite et al. 2017).

While the Kara-tepe study provides a detailed glimpse into the palaeoeconomy of the early medieval period, it cannot be projected back further in time. Brite et al. (2017) also compile references from earlier site reports that mention finding seeds from cultivated plants in sites dating to earlier periods, albeit without direct dates. They note that millet, barley, and grapes were reported from contexts purported to date to the 6th to 5th c. BC site of Dingild'zhe, millet and grapes were noted in the report from Djanbas kala, supposedly dating to the 4th c. BC, and millet, wheat, grapes, *Eleagnus angustifolia* (Russian olives), *Prunus persica* (peach), and a possible *Cucumis* seed, were identified at Koy-Krilgan-Kala, broadly dating somewhere in the millennium-span from the 4th c. BC to the 4th c. AD. While these data allow us to start reconstructing the mixed agropastoralist economy of the region in the past, the fragmentary and insecure nature of these find limits their interpretative potential. Many archaeologists working in the broader eastern Aral Sea region have emphasized a continual phase of irrigation construction from the 6th c. BC to the 3rd c. AD (Andrianov 1969; Brite et al. 2017). After the 3rd c. AD, most scholars seem to agree that a shift in the natural water catchment basin led to a collapse or dramatic reduction in populations across this region, further illustrating their reliance upon intensive irrigated farming (Tolstov 1948; Andrianov 1969; Boroffka 2010).

Both barley and millet were identified at all five sites in the eastern Aral Sea in the late 1st mill. BC. While the ways

that these differing grains were cultivated can only be speculated at, the construction of irrigation systems might hint at the possibility of seasonal crop rotations, mingling East and West Asian cereals, which have different sowing (spring and fall) and growing seasons, to maximize yields on restricted amounts of arable land. The introduction of irrigation in this region occurred under the strong cultural influence of the Khorezm region (about 200 km southwest) on the southern coast of the Aral Sea, where irrigation agriculture was already prevalent (Utubayev 2022). On the other hand, around the same time, archaeobotanical investigations of Iron Age sites belonging to the Saka or Wusun cultures in the Talgar alluvial fan of southeastern Kazakhstan predicted intensive agriculture of multiple crops with different growing seasons with the introduction of irrigation (Wu et al. 2015; Spengler et al. 2017), presenting an alternative origin of the irrigation system.

Conclusions

Although this study covered only a portion of the excavated pottery from nine sites, six grains of *Panicum miliaceum* and one grain of *Hordeum vulgare* were identified from two sites dating to the first half of the 1st mill. BC, and 42 grains of *P. miliaceum*, two grains of *Setaria italica*, and 12 grains of *H. vulgare* were identified from five sites dating to the latter half of the 1st mill. BC. These findings confirm the existence of agriculture across the steppe belt by this time, which had previously only been assumed based on the existence of coetaneous irrigation systems and limited ancient isotopic data. Some of the cereals identified from the pottery impressions were threshed, implying their use as food instead of fodder, which is also supported by their presence in domestic contexts. It appears probable that agriculture in the arid eastern Aral Sea region began in the first half of the 1st mill. BC, with the spread of irrigation farming into the deltas of the Syr and Amu Darya. While our data cannot be used to clearly reconstruct cultivation practices, intensity of agricultural investment, or the nature of political systems, we contribute data to all of these ongoing debates. We leave open the question of whether millets were cultivated as a low-investment complement to more pastoral-focused systems or if millets were used as a spring-sown irrigated crop to complement a fall-sown cereal. Millet harvesting in the fall might have been a valuable complement to pastoralism, as it would have provided either post-harvesting field stubble or straw fodder for penned herd animals during the cold winter months. Regardless of the intensity of the agricultural systems practiced across this millennium in the middle and lower reaches of the Syr Darya, it is clear

that the subsistence strategy combined both pastoralism and agriculture.

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Declarations

Conflict of interest The authors declare that there are no financial nor non-financial interests directly or indirectly related to the submitted manuscript.

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