A hydromorphic reevaluation of the forgotten river civilizations of Central Asia

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The Aral Sea basin in Central Asia and its major rivers, the Amu Darya and Syr Darya, were the center of advanced river civilizations, and a principal hub of the Silk Roads over a period of more than 2,000 y. The region's decline has been traditionally attributed to the devastating Mongol invasion of the early-13th century CE. However, the role of changing hydroclimatic conditions on the development of these culturally influential potamic societies has not been the subject of modern geoarchaeological investigations. In this paper we report the findings of an interdisciplinary investigation of archaeological sites and associated irrigation canals of the Otrār oasis, a United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage site located at the confluence of the Syr Darya and Arys rivers in southern Kazakhstan. This includes radiometric dating of irrigation canal abandonment and an investigation of Arys river channel dynamics. Major phases of fluvial aggradation, between the seventh and early ninth century CE and between 1350 and 1550 CE coincide with economic flourishing of the oasis, facilitated by wet climatic conditions and higher river flows that favored floodwater farming. Periods of abandonment of the irrigation network and cultural decline primarily correlate with fluvial entrenchment during periods of drought, instead of being related to destructive invasions. Therefore, it seems the great rivers of Central Asia were not just static "stage sets" for some of the turning points of world history, but in many instances, inadvertently or directly shaped the final outcomes and legacies of imperial ambitions in the region.

floodwater farming | Otrar | OSL dating | Syr Darya | fluvial geomorphology

While the great river civilizations of the Old World (1) have been the subject of archaeological and scientific study for more than a century, the ancient irrigation based urban cultures that developed along the great rivers of Central Asia (Fig. 1) are virtually unknown in the West. Soviet archaeologists in the 1950s–60s (2, 3) demonstrated that the Amu Darya (Oxus) and Syr Darya (Jaxartes) rivers, that flow northwest from the Pamir and Tien Shan Mountains and drain to the Aral Sea (Fig. 1), were the centers of flourishing potamic urban societies from prehistory to the late Middle Ages (4, 5). The 50,000-km^2 area of floodwater irrigated land was estimated to have been twice that of Mesopotamia (2). The region's stagnation at the end of the Medieval Period is generally attributed to a combination of the destructive early-13th century CE Mongol invasion and the progressive decline of the Silk Roads trade network (5–7). However, the hydroclimatic and hydromorphic contexts of these changes are largely unknown with only a handful of sites having been radiometrically dated (8–10).

In this paper we report the findings of an interdisciplinary investigation of archaeological sites and associated irrigation canals of Otrār oasis, a United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage site located at the confluence of the Syr Darya and Arys rivers in southern Kazakhstan (Fig. 1). This includes radiometric dating of irrigation canals and geomorphological investigations of river channel and flood regime dynamics, on which the success and failure of floodwater farming in these so-called "oasis" urban centers depended.

Study Area

Archaeological and Historical Context. Historically, the northern foothills of the Tien Shan and Pamir mountains have been an important cultural cross-road, where pastoral nomads and sedentary floodwater-farming people interacted (4, 11, 12), and where regional superpowers collided (Fig. 1; extended setting in *SI Appendix*, S1.1). Early western historical references to the region come from the time of Alexander the Great's conquest, halting at the Jaxartes River in 329 BCE, which was then perceived as the northern limit of urban civilization. The region flourished during classical Antiquity and became known as Transoxania—beyond the Oxus. It was described as the "land of the thousand cities" (13); archaeological surveys have identified hundreds of fortified towns in the region, dating from the mid-first millennium BCE to the Late Medieval Period (4, 14).

Significance

Our paper challenges the long-held view that the fall of Central Asia's river civilizations was determined by warfare and the destruction of irrigation infrastructure during the Mongol invasion. An integration of radiometric dating of long-term river dynamics in the region with irrigation canal abandonment shows that periods of cultural decline correlate with drier conditions during multicentennial length periods when the North Atlantic Oscillation had mostly positive index values. There is no evidence that large-scale destruction of irrigation systems occurred during the Arab or Mongol invasion specifically. A more nuanced interpretation identifies chronic environmental challenges to floodwater farming over the last two millennia, punctuated by multicentennial-length periods with favorable hydromorphic and hydroclimatological conditions that enabled irrigation agriculturists to flourish.

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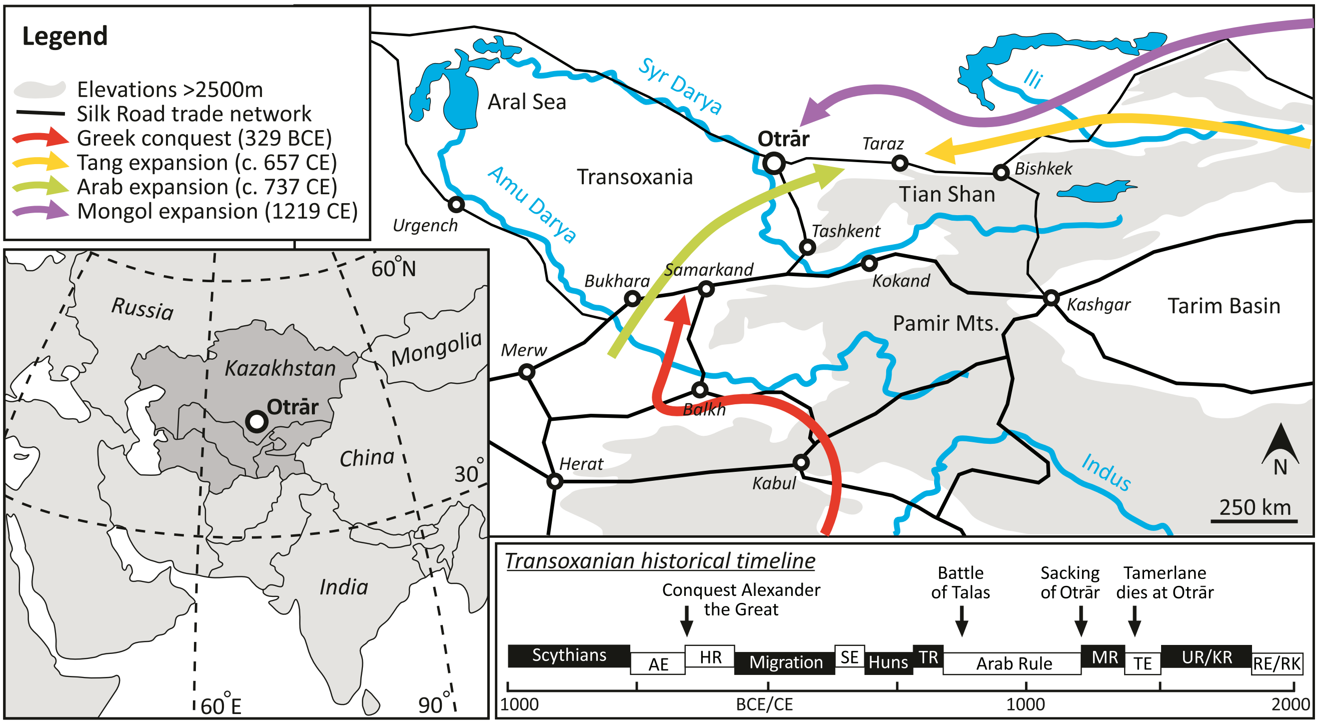

Fig. 1. Research area in Central Asia. Transoxanian historical timeline: Achaemenid Empire (AE), Hellenic rule: initial conquest and successor states (HR), Sassanid Empire (SE), Turkic rule (TR), Mongol Empire and later Khanates (MR), Timurid Empire (TE), Uzbek and Kazakh rule (UR/KR), Russian Empire, its successors and the current Republic of Kazakhstan (RE/RK). Black bars indicate nomadic pastoralist cultures; white bars indicate sedentary cultures. The period of migration refers to the displacement of Saka, Kangju, Yuezhi, and Wusun nomadic confederacies in the region (*SI Appendix*, S1.1).

The Arabs invaded Transoxania between 650 and 760 CE and consolidated control after defeating the Chinese Tang armies in the battle of Talas near the city of Taraz in 751 CE (15). The region flourished throughout the Medieval Period and was a center of the Early Medieval Islamic renaissance (16). A pivotal moment in world history took place in 1218 CE at the city of Otrār. A Mongol ambassador of Chinggis Khan was murdered on the orders of Otrār's governor. In response, Mongol armies invaded and sacked Otrār, but also other major cities in the region, including Samarkand and Bukhara (17). This incident triggered a change in the direction of Mongol expansion from southeast to west, resulting in large-scale and profound societal transformations in the Middle East and Eastern Europe (18). After a partial recovery during the Timurid Period (1370–1507 CE), Otrār finally demised in the 16–17th centuries CE (6). Until the annexation of the region into the Russian Empire in the late-19th century CE, the oasis remained largely depopulated and agriculturally moribund.

Physiographic and Hydrological Context. The ancient irrigation networks of Otrār oasis were fed by flow from the Arys River, which is ~378 km long, drains a 14,900-km^2 catchment, and is bounded to the southeast by the Karzhantau Range of the Tien Shan mountains, with elevations reaching over 4,000 m above sea level (Fig. 2*A*). The region has an arid to semiarid climate with cold winters and dry, hot summers. There is a marked south to north precipitation gradient, ranging from an annual rainfall of ~575 mm in Shymkent to less than 200 mm at Otrār (19). Most precipitation falls between October and May as snow, whose thaw, in combination with rainfall in early spring and glacier runoff, generates peak flow. Mean discharge of the Arys River is ~50 m^3 s^{-1}, with the largest recorded peak discharge of ~740 m^3 s^{-1} in 1969 CE.

The valleys of the Arys and its tributaries have well-developed fluvial terraces created by phased Late Pleistocene and Holocene channel entrenchment. At Otrār, the present river is situated ~6 m lower than the surface of the oasis on which the ancient irrigation system was constructed (20). There is a northward downslope division of canals that feed a complex patchwork of fields covering an area of ~200 km^2 with several large fortified towns and numerous small villages (Fig. 2 *E* and *I*). Fortified settlements are located at the bifurcations of principal feeder canals (Fig. 2*G*), presumably for regulation and protection (21). Otrār was the administrative center; the fortified city covered an area of ~0.2 km^2 and stood 18 m above the surrounding urban development (Fig. 2*F*), housing >20,000 people (20).

Methods

Late Quaternary hydromorphic reconstructions of the Otrār oasis were based on geomorphological investigations of three areas; the Badam River (a principal tributary of the Arys), the middle reach of the Arys, and in Otrār oasis itself (Fig. 2*A*). For the Arys and Badam river bank sections of Late Pleistocene and Holocene river terraces enabled the phasing of valley aggradation and incision to be reconstructed. Twenty samples were collected for Optically Stimulated Luminescence (OSL) dating, targeting major changes in alluvial architectures and coarse-grained flood units. In Otrār oasis, seven trenches were dug using a mechanical excavator to date the abandonment of irrigation canals (Fig. 2*B*). Five OSL samples and nine charcoal samples for accelerator mass spectrometry (AMS) radiocarbon dating were taken from the canal-fill sediments positioned above the coarse-grained canal base to provide the most accurate date for canal abandonment (*SI Appendix*, S2.1).

OSL samples were collected in metal tubes from sandy units, and prepared and measured at the Oxford Dating Laboratory, University of Oxford. Standard laboratory treatments (22) were undertaken to isolate purified quartz, and 1-mm-diameter aliquots of sediment were used to measure equivalent doses (D_e), using the single-aliquot regenerative dose protocol (23). Quartz OSL signals were screened using a suite of rejection criteria (24, 25). Between 32 and 72 aliquots were used for final D_e determination. For

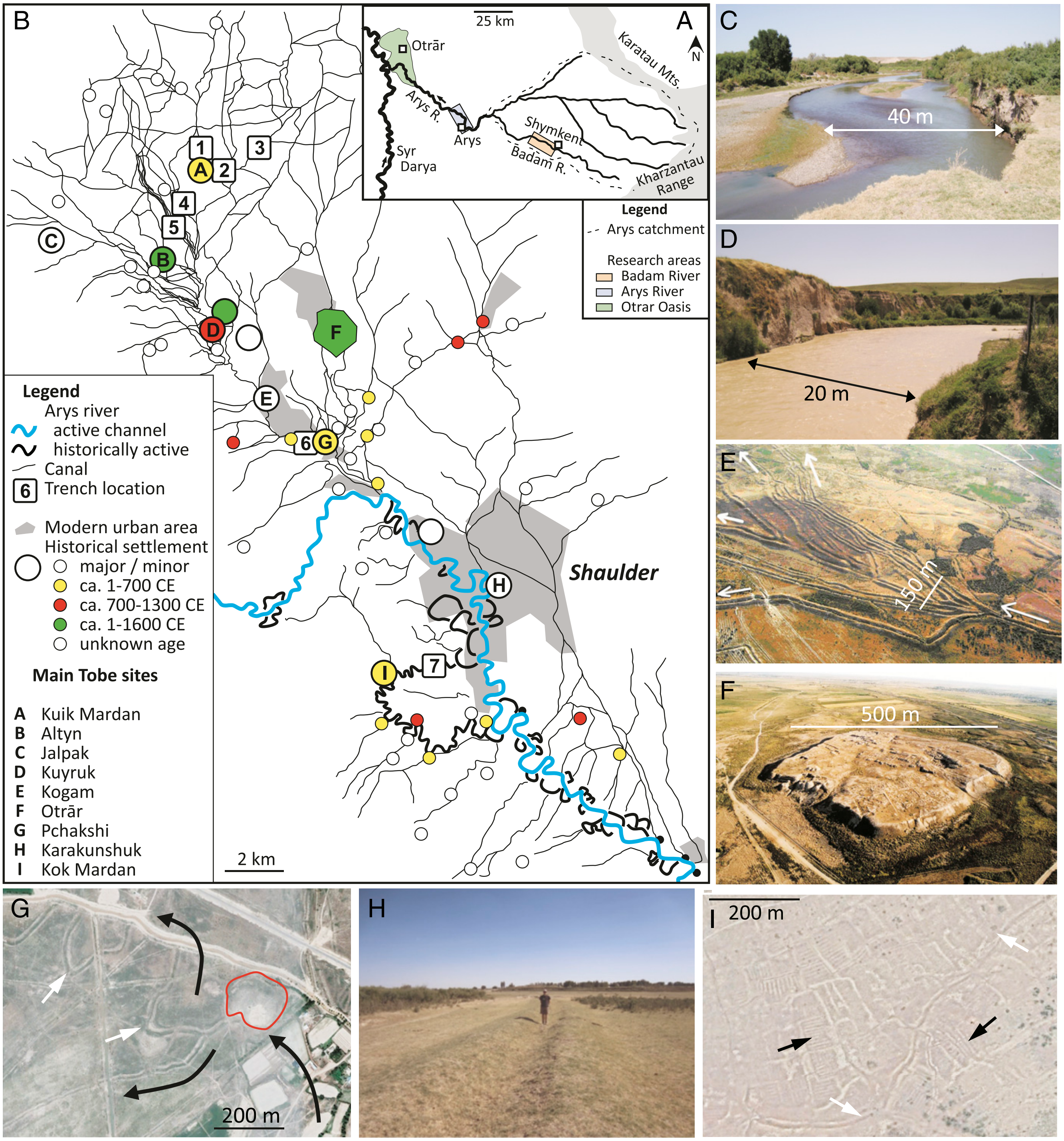

Fig. 2. Geomorphology and archaeology of the Arys river catchment and Otrār oasis. (*A*) The Arys river catchment and research areas; (*B*) Otrār oasis with main irrigation canals and archaeological sites; (*C*) the Arys River at low flow; (*D*) the Badam River during peak discharge; (*E*) aerial view of irrigation canal bifurcations southeast of Altyn (Reproduced from ref. 45, with permission from the copyright holders, IWA Publishing.); (*F*) aerial view of Otrār (Reprinted with permission from ref. 20); (*G*) irrigation canal bifurcation with a fortified settlement (outline in red: Pchakshi) (46); (*H*) ancient irrigation canal near Arys town; (*I*) abandoned canals (white arrows) and abandoned agricultural field plot (black arrows) east of Kuik Mardan (46).

most samples, a minimum age model (26) was used as dose distributions suggested incomplete bleaching of luminescence signals. For one sample (Table 1 and *SI Appendix*, S2.2), the finite mixture model (27) was more appropriate due to low-dose outliers. Environmental dose rates were derived from radionuclide concentrations measured using inductively coupled plasma mass spectrometry, and DRAC software was used for dose rate calculation (28).

Results

Late Pleistocene–Holocene Fluvial Development. The Badam River has five river terraces, located at 10, 8, 6, 5, and 2.5 m above present low-flow stage (Fig. 3). The three highest terraces have a similar stratigraphy; their lower part is composed of imbricated coarse gravels that are overlain by well-sorted fluvial silts. The

Table 1. Radiometric dating results

OSL Arys	Terrace	Depth, m	Age	OSL Badam	Terrace	Depth, m	Age
A8	Ta2	0.7	1345 ± 80 CE	B4	Tb1	2.3	9925 ± 1140 BCE
A10	Ta1	3.6	9565 ± 760 BCE	B6	Tb1	5.8	16485 ± 1410 BCE
A4	Ta2	2.3	895 ± 200 BCE	B2	Tb1	6.2	15165 ± 1630 BCE
A2	Ta3	0.7	1745 ± 40 CE	B8	Tb2	2.7	5525 ± 690 BCE
A1	Ta3	0.8	1755 ± 50 CE	B5	Tb3	4.2	1295 ± 210 BCE
A3*	Ta3	1.4	1515 ± 80 CE	B1	Tb3	0.4	1818 ± 30 CE
A5	Ta3	1.3	1565 ± 50 CE	B7	Tb5	0.6	1275 ± 90 CE
A9	Ta3	2.3	1325 ± 360 CE	B3	Tb4	1.2†	665 ± 170 CE
A6	Ta3	4.0	1415 ± 90 CE	B9	Tb4	2.0	1355 ± 80 CE
A7	Ta4	0.9	1965 ± 10 CE	B10	Tb4	4.2	805 ± 150 CE
OSL Otrar	Trench	Depth, m	Age	AMS Otrar	Trench	Depth (m)	Cal. Age, 2σ
OSL1	1	1.4	1237 ± 59 CE	AMS1	1	2.1	1123 ± 84 CE
OSL2	1	2.1	1378 ± 43 CE	AMS2	2	1.8	1062 ± 88 CE
OSL3	2	2.1	1276 ± 50 CE	AMS3	3	2.1	1150 ± 104 CE
OSL4	7	3.0	662 ± 100 CE	AMS4	3	2.5	1156 ± 104 CE
OSL5	4	1.3	1161 ± 70 CE	AMS5	6	1.3	592 ± 56 CE
AMS radiocarbon dates calibrated with IntCal13 (29) in OxCal4.3 (30).				AMS6	6	2.2	1542 ± 92 CE
				AMS7	4	1.5	1085 ± 70 CE
				AMS8	5	1.6	774 ± 96 CE
				AMS9	5	1.8	794 ± 100 CE

*OSL date calculated using the finite mixture instead of the minimum age model.

†Sample B3 was taken from a quarried terrace section; its assumed stratigraphic context is shown in Fig. 3.

two lower terraces are composed of laminated sands overlain by silts.

OSL dating shows that channel bed and floodplain aggradation occurred toward the end of the Last Glacial Maximum (16485 ± 1410 and 15165 ± 1630 BCE in terrace Tb1) and in the periods leading up to the dated end of aggradation at 5525 ± 690 (Tb2) and 1295 ± 210 BCE (Tb3). A phase of river channel incision occurred between the late-second millennium BCE and the mid-first millennium CE, followed by rapid deposition of well-bedded sands at ~665 ± 170 CE – 805 ± 150 CE (Tb4). Large-scale incision occurred after the 9th century but before the 14th century CE with the formation of Tb5. Exceptionally large flood events, evidenced by sand units capping Tb1, Tb3, and Tb4, occurred at 9940 ± 1140 BCE, 1355 ± 80 CE, and 1818 ± 30 CE. The mid-14th CE flood would have inundated the Badam valley floor 5–6m above current river levels (Fig. 3).

The Arys valley (Fig. 2*A*) has four distinct terraces, located at 8 m (Ta1), 6 m (Ta2), 5 m (Ta3), and 2–3 m (Ta4) above present day low-flow level. The highest terraces consist of coarse silt and the lowest terraces are formed of well-bedded sands (Fig. 3). A flood unit in the middle part of Ta1 dates to 9565 ± 760 BCE and corresponds in age to the topmost section of Tb1 (9925 ± 1140 BCE) in the Badam River. A flood unit in Ta2 was dated to 895 ± 200 BCE, and corresponds with the end of a period of channel aggradation that formed Tb3. Another sandy unit capping Ta2 is associated with a high-magnitude flood dated

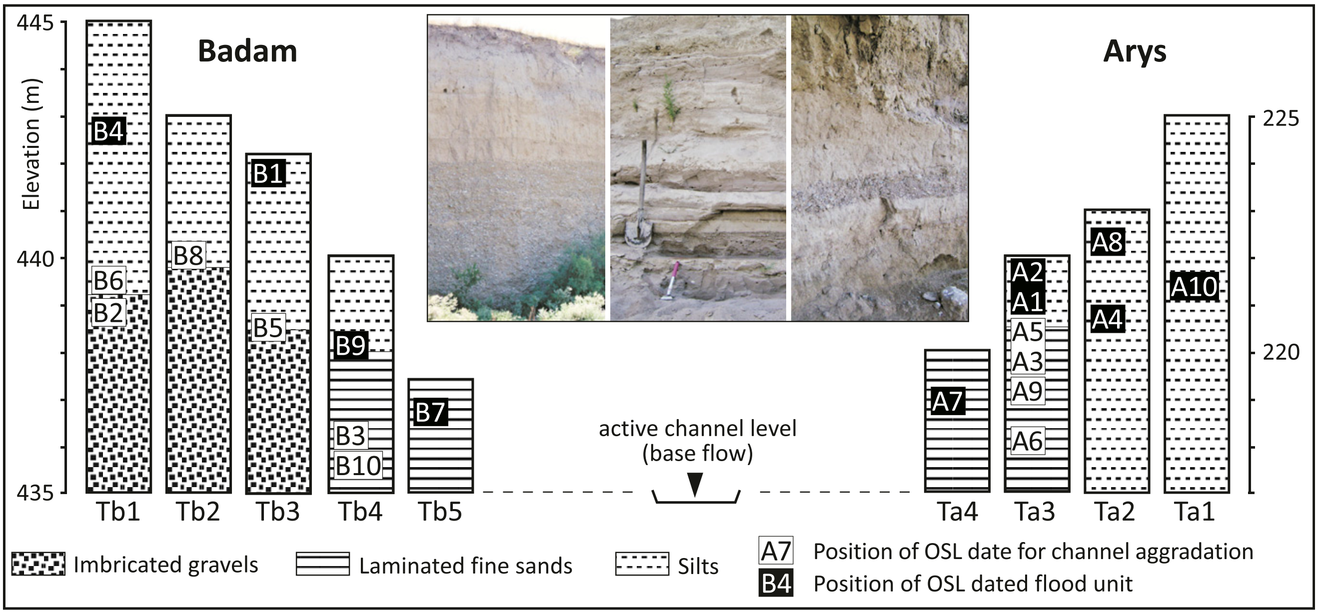

Fig. 3. Schematic representation of Late Pleistocene and Holocene river terraces in the Badam and Arys valleys. Inset pictures: (*Left*) Stratigraphy of Tb1-Tb3; (*Middle*) laminated sandy sequences of terraces Tb4, Tb5, Ta3, and Ta4; (*Right*) the coarse-grained ~1350 CE Late Medieval flood unit (Tb4, Tb5, and Ta3).

to ~1345 ± 80 CE, similar to observations in the upstream Badam. Four OSL dates in the sandy lower part of Ta3 date a period of rapid aggradation to the 14–16th century CE (Table 1). Fine-grained overbank deposition in the top section of Ta3 relates to channel bed incision between the 16th and 18th century CE. The most recent cut and fill sequence (Ta4) began after the late-18th century CE; a sandy flood unit dated to 1965 ± 10 CE matches perfectly with the largest recorded Arys river flood of 1969 CE.

A single OSL sample was taken from a sandy point bar scroll within the abandoned lower Arys river course in the southern part of Otrār oasis (Fig. 2*B*). A date of 662 ± 100 CE for active flow corroborates with the channel aggradation recorded in Tb4 upstream. The net fluvial incision of ~4–5 m in the following period coincides with the abandonment of settlements located on banks of this section of the Arys River.

Abandonment of Otrār Irrigation Canals. Radiocarbon ages from postabandonment canal deposits are systematically >200 y older than those based on the OSL dates from the same depths (trenches 1 and 2; Table 1). Dates derived from charcoal reflect the period of tree growth and provide, therefore, a *terminus post quem* (TPQ) for canal abandonment, whereas OSL dates are more likely to accurately date the final operation of the canals.

Radiocarbon TPQ dates fall in three periods; the late eighth century, between the mid-11th and mid-12th century, and the mid-16th century CE. Sample AMS5, dated to 592 ± 56 CE, is rejected based on the much younger date of 1542 ± 92 CE in the lower part of the same canal fill (*SI Appendix*, S2.1). OSL dating shows that several main feeder canals ceased functioning between the 12th and late-14th centuries CE.

Canal abandonment followed the Arab (650–760 CE) (21) and Mongol (1219 CE) destruction of settlements in the Otrār oasis only sporadically. AMS9 produced a TPQ date of 794 ± 100 CE, but considering the observed offset in radiocarbon dating, canal abandonment likely occurred much later than the Arab invasion. OSL3 (1276 ± 50 CE) and OSL5 (1161 ± 70 CE) could fit with the timing of the Mongol invasion. The latter was, however, taken from the middle part of sedimentary fill (*SI Appendix*, S2.1), so the canal probably started its abandonment already before the early-12th century CE. Our dating results, therefore, do not suggest a wholesale destruction of the irrigation network during the Arab and Mongol invasions, and indicate that additional factors played a significant role.

Fluvial Responses to Hydroclimatic Variability

Late Pleistocene and Holocene aggradation phases in the Arys catchment correspond with relatively cold and wet periods associated with glacier advance in the region (31–33). Similarly timed phases of fluvial aggradation have been reported in the Tien Shan piedmont of eastern Kazakhstan (10). Conversely, river entrenchment and slow rates of overbank sedimentation coincide with shifts to warmer conditions and reduced rainfall. The onset of incision, dated to shortly after ~15150, 5525, and 1300 BCE in the Badam, match warming conditions that immediately postdate minima in northern hemispheric temperatures (34).

Arys river bed aggradation between the seventh and early-ninth centuries CE correlates with relatively cold and wet conditions (Fig. 4). High water levels (35), low salinities, and wet-taxa pollen assemblages are recorded in the Aral Sea during this period (36). These coincide with a multicentury decrease in regional temperatures (38) and a persistent strongly negative mode of the North Atlantic Oscillation (NAO) (39). The latter influences westerly cyclonic tracks and precipitation over the midlatitudes of Central Asia (*SI Appendix*, S1.2), including the Aral Sea basin and the Arys catchment, in combination with the position and strength of the Siberian High (40, 41).

Major channel incision (~5 m) in the Arys valley between the 9th and early-14th century CE coincided with warm and dry conditions in Central Asia, reflected in Altai tree-ring records (38), low moisture conditions over arid Central Asia (37), high salinity of the Aral Sea (36), and matching a shift toward a strong NAO positive mode (39) (Fig. 4). The well-documented Aral Sea low-stand between the 12th and 16th centuries CE—the medieval "Kerderi" regression (35)—fits these observations. The continuation of low lake levels after the early-15th century CE is attributed to Amu Darya flow diversion toward the Caspian Sea until the late-16th century CE (42).

The ~14–16th century CE shift to fluvial aggradation in the lower Arys catchment coincides with an exceptionally large flood recorded in both the Badam and Arys rivers around ~1350 CE, at which time high precipitation and a relatively low salinity is recorded in the Aral Sea basin (36) (Fig. 4). This period marks the beginning of the Little Ice Age, with colder and wetter conditions in the Altai and Pamir mountains (38, 43) and during which the NAO mode changed to being strongly negative (39).

The final phase of river entrenchment (~2 m) occurred before the 18th century CE and coincided with a shift to a weak positive NAO mode (39) and relatively low rainfall (36). Water levels in the Aral Sea remained relatively high until recent times (35). In the last 300 y, the timing of large flood events (~1750, 1820, and 1960 CE) fall within relatively short, multidecadal length episodes of negative NAO (39) (Fig. 4).

A Hydromorphic and Hydroclimatological Perspective on the Growth and Decline of the Otrār Oasis

The total area and number of hydraulic oasis settlements in both the lower Syr Darya valley and Otrār oasis peaked in the sixth–eighth centuries CE (44). The decline of Otrār oasis started between the eighth and ninth centuries CE during which there was a 68% fall in the number of settlements and a 32% reduction in occupied area (Fig. 4) (44). A second phase of settlement contraction occurred during the 12th century CE, followed by a progressive decline until the late-16th century CE. Abandonment of irrigation canals in Otrār oasis tracks the downturns in settlement area (Fig. 4), as would be expected in periods of economic and agricultural hardship.

There is a clear correspondence between a population boom between the sixth and eighth centuries CE, high water levels in the Aral Sea, negative NAO favoring increased rainfall in the autumn and winter months, and floodplain sedimentation in the lower Arys valley, all of which would have facilitated irrigation-based farming. Conversely, major settlement contraction in the ninth century CE coincides with a shift to a positive NAO mode and a reduction in westerly cyclonic rainfall, low water levels in the Aral Sea, and the onset of fluvial incision in the Arys catchment. These hydroclimatic conditions persisted until the 14th century CE, and coincide with the main period of irrigation canal abandonment in Otrār oasis (Fig. 4).

As the direct consequence of major phases of river channel entrenchment in the Arys valley during the early-12th through mid-14th century CE, and later again in the 17th–18th century CE, the offtake from the river Arys to feed irrigation canals in the Otrār oasis was moved upstream (20). Between these periods, a final and short-lived agricultural and economic recovery of the Otrār oasis occurred, which coincided with a shift to negative NAO conditions, high water levels in the Aral Sea, and accelerated sedimentation in the lower Arys valley.

For floodwater farmers of Otrār oasis, and most likely more generally for similar irrigation agriculturists elsewhere in Central Asia, periods of enhanced rainfall and reliable river flow, both shown in this study to be associated with multicentennial-length periods of negative NAO, were clearly facilitators of farming especially at the apogee of settlement in the region during the sixth–eighth centuries CE. On the other hand, long-term and chronic stress on irrigation-based agriculture, as evidenced by widespread canal abandonment between mid to late-11th and

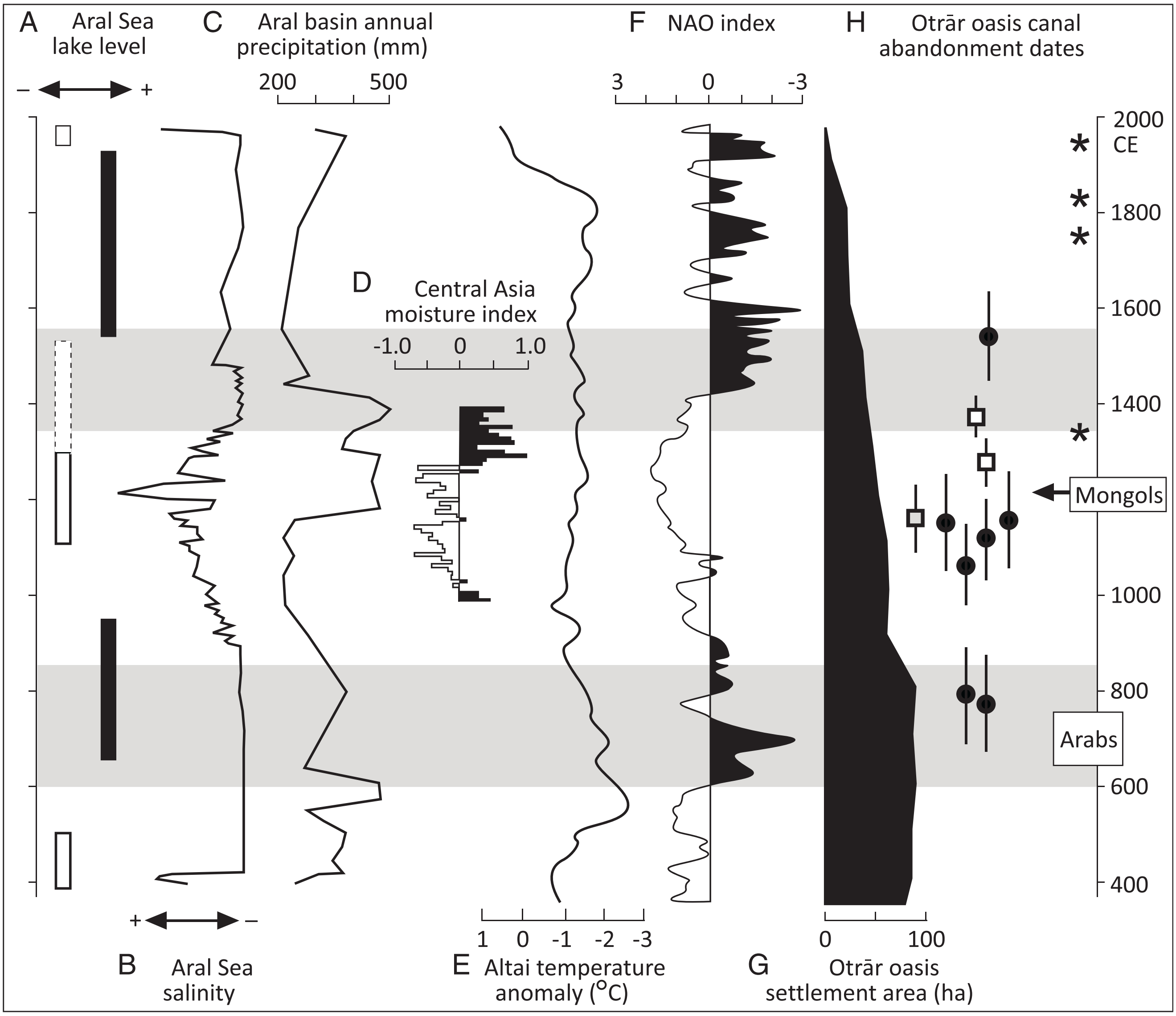

Fig. 4. Compilation of hydrological, climatic, and archaeological data for the last 1,600 y. (*A*) Aral Sea levels (35); (*B*) Aral Sea salinity (36); (*C*) Pollen-based precipitation reconstruction of the Aral Sea basin (36); (*D*) Central Asian arid zone decadal moisture index (37); (*E*) Tree-ring–based temperature reconstructions from the Altai Mountains (38); (*F*) NAO index series (39); (*G*) Settled area in Otrār oasis (44); (*H*) radiometric dates for canal abandonment in Otrār oasis (this study): squares refer to OSL dates; circles to calibrated radiocarbon dates; a black fill refers to a TPQ date; a gray fill to a *terminus ante quem* date; a white fill to an accurate date for the onset of canal abandonment. Background: The gray shading highlights main phases of fluvial aggradation in the Arys catchment (this study); asterisks on the right-hand axis indicate OSL-dated extreme flood events in the Arys river catchment.

late-14th centuries CE, resulted from drier conditions caused by reduced westerly cyclonic circulation associated with the positive phase of the NAO. Although there were attempts to overcome the impacts of fluvial entrenchment through reconfiguration of the hydraulic-control infrastructure on the Arys River, the subsequent long-term viability of floodwater farming in the Otrār oasis remained dependent on favorable hydrological conditions.

Taking the long view, it is clear that recovery or settlement contraction trajectories following both Arab and Mongol invasions were contingent on regional hydroclimatic conditions. The Arab conquest took place at a time that was probably one of the most favorable for floodwater farming in the last millennia (Fig. 4). Despite the documented destruction of settlements (21, 44), many sites in the Otrār oasis persisted until the drought-related contraction in the ninth century. The Mongol invasion and destruction of Otrār in 1219 CE, however, came after more than 200 y of reducing rainfall, with evidence of large-scale canal abandonment. With hydrological stress continuing at least until the 14th century CE, as well the scale of destruction and loss of life following the fall of Otrār (16), it was hardly surprising that recovery took between 100 and 150 y and was on a much more limited scale. The great rivers of Central Asia it seems were not just static stage sets on which some of the turning points of world history were played out, but in many instances inadvertently or directly shaped the final outcomes and legacies of imperial ambitions in the region.

Data Availability. All study data are included in the article and *SI Appendix*.

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