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GR focus review

The fluctuating Aral Sea: A multidisciplinary-based history of the last two thousand years

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ABSTRACT

The Aral Sea (an intracontinental saline lake in western Central Asia) is of great interest because of its rapid shrinkage during the last 50 years, which caused catastrophic environmental and socio-economic consequences for the region and its population. Geoscientists established the existence of similar multiple fast and deep lake level fluctuations in the past; however, a comprehensive picture of these changes has been lacking. In this paper, we summarize published and new geomorphological, sedimentological, paleoenvironmental, geoarcheological, and historical data to reconstruct fluctuations in the Aral during the last two thousand years. Two deep regressions are recognized, in addition to the modern human-induced regression. The regressions occurred at ca. 2.1–1.3 and 1.1–0.35 ka cal BP according to the sedimentary and faunal data, and 2.1–1.45 and 1.0 (0.85)–0.45 ka cal BP according to the archeological and historical data. The Aral Sea lake level dropped to ca. 10 m a.s.l. during the first regression and to ca. 29 m a.s.l. during the second one. Transgressions which separated these periods reached elevations of ca. 52 m a.s.l., and 54 m a.s.l., respectively. According to the current data, the regressions lasted longer than the transgressions, or were of equal duration. Reasons considered for past Aral Sea lake level changes include both natural and human-related causes, as the region features more than 2000 years of agricultural activity.

Contents

1. Introduction

The Aral Sea, an intracontinental brackish water basin shared by Kazakhstan and Uzbekistan, western Central Asia (Fig. 1, A), was formerly ranked as the fourth largest lake on Earth. However, its water

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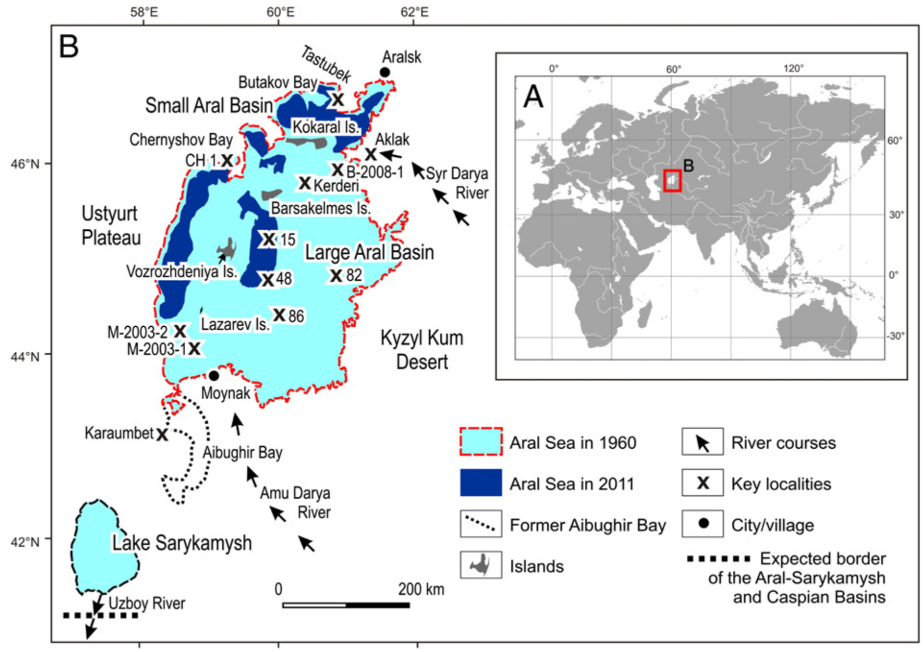

Fig. 1. The position of the Aral Sea: A — overview map; B — location map.

level has dropped precipitously during the last half century (Fig. 2) due to intensive agricultural and industrial water consumption from the Amu Darya and Syr Darya rivers that feed the Aral Sea. Its area and volume are currently ten times smaller than during its recent maximum (Aladin et al., 2009), and they continue to decrease. During this regression, the Aral Sea has become divided into three separate basins: Small Aral, Eastern Large Aral, and Western Large Aral (Fig. 1, B). The drop in Aral Sea lake level has caused persistent catastrophic ecological and social consequences despite numerous international rehabilitation efforts (e.g. Ashirbekov and Zonn, 2003; Micklin and Aladin, 2008; Zonn and Kosarev, 2010).

The modern deep regression is not unique in the Aral's history as early and more recent investigations show. Russian geographer Berg (1908) was the first to show that Aral Sea lake levels varied by 3–3.5 m since AD 1790. Since that study, the Aral Sea maintained a metastable transgressive state until the early 1960s (Fig. 3). Russian philologist Bartold (1902) collected information from historical sources about the Aral Sea from antique times. These data, especially remarks about a Medieval disappearance of the Aral Sea, provide valuable information. Soviet geologists, geomorphologists, and limnologists provided a comprehensive picture of the past Aral Sea changes (e.g., Veinbergs and Stelle, 1980; Kes, 1983; Shnitnikov, 1983; Rubanov et al., 1987), and its progressive desiccation in modern times attracted scientific interest worldwide. These data have been summarized in a series of review papers (Sevastyanov et al., 1991; Aladin and Plotnikov, 1995; Tarasov et al., 1996; Létolle and Mainguet, 1997; Boomer et al., 2000, 2009; Svitoch, 2010; Cretaux et al., 2013). Since then, it has become clear that the Aral Sea is a very young basin, dating to the late Glacial–early Holocene. The Aral Basin was firstly occupied by shallow saline lakes and salt marshes that expanded substantially in the middle Holocene. This change is marked by the appearance of a marine mollusk *Cerastoderma*, which invaded the Aral Sea from the Caspian Sea. During its history, several transgressions and regressions have been recognized (e.g., Boomer et al., 2000). The most prominent regression left peat layers in the central part of the Aral Basin at ca. 1.6 ka ^{14}C BP.

In those studies, determination of sediment ages limited the reliability of paleogeographic reconstructions. Conventional radiocarbon dating of Aral Sea bottom sediments required relatively large amounts of organic and carbonate matters, or mollusk shells. About 70 published ^{14}C dates for the Aral Basin (summarized in Krivonogov et al., 2010b) reveal ambiguities that call into question their reliability (Rubanov et al., 1987; Ferronskii et al., 2003). In 200 boreholes, only dates obtained on plant

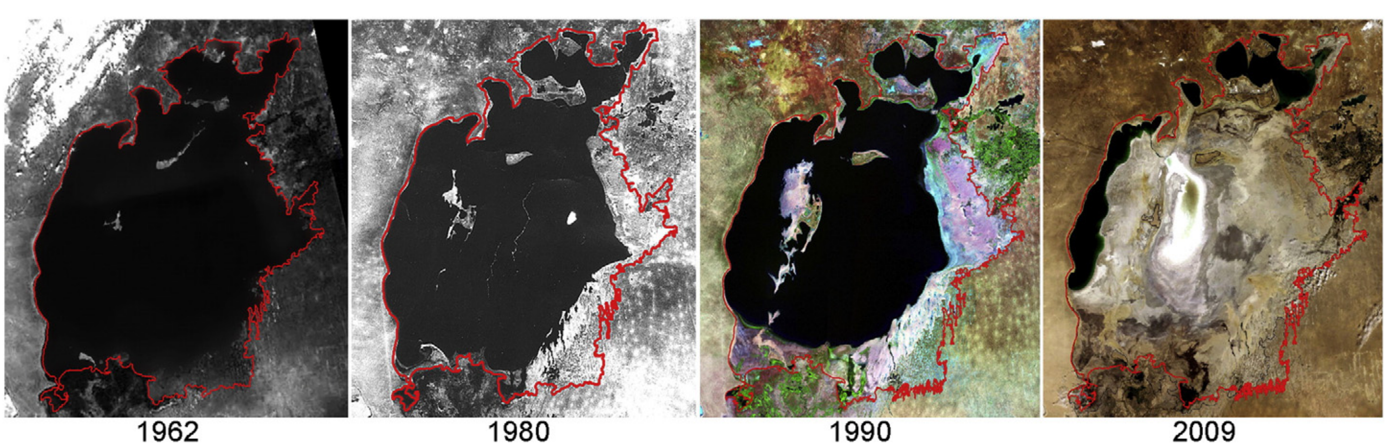

Fig. 2. Desiccation of the Aral Sea illustrated by satellite imagery: 1962 — unknown satellite; 1980 — Meteor; 1990 — Landsat; 2009 — Modis. Red outline is a metastable lake level of the Aral Sea prior to 1960 from a nautical chart.

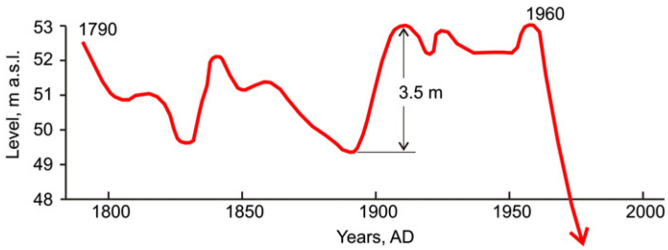

Fig. 3. Changes of Aral Sea lake level during the last transgressive phase recorded from AD 1790 until the early 1960s.
Modified from Berg (1908) and Shermatov et al. (2004).

remains and mollusk shells from a limited number of cores substantiate the sediment stratigraphy (Khrustalev et al., 1977; Rubanov et al., 1987; Zhamoida et al., 1997; Boomer et al., 2003). Two reference Cores, 15 and 86 (Fig. 1), have been used in detailed paleolimnological and paleoclimatic reconstructions (Maev et al., 1983; Sevastyanov et al., 1991; Maev and Karpychev, 1999; Ferronskii et al., 2003). Several other cores lack adequate ^{14}C dates (e.g., Boomer, 1993; Le Callonnec et al., 2005; Filippov and Riedel, 2009). In these circumstances, researchers used paleontological, geomorphological and archeological approaches to establish the timing of reconstructed events and to correlate between cores.

The situation improved considerably in the 2000s when two international research projects were launched: the European INTAS (2002–2005), and Russian–US RFBR-CRDF[1] (2008–2010). More than 30 new, well-dated sediment cores were obtained through these programs. Some of these cover the whole Aral Sea lacustrine sediment sequence (Krivonogov et al., 2010a,b), but most of the cores focus on the last two thousand years (e.g., Nourgaliev et al., 2003; Sorrel et al., 2006; Austin et al., 2007; Nourgaliev et al., 2007; Oberhänsli et al., 2007; Sorrel et al., 2007; Boomer et al., 2009; Píšková et al., 2009). Combined archeological and geological studies highlighted a number of lake level fluctuations, but the most exciting findings were archeological monuments on the dried bottom of the Aral Sea (Smagulov, 2001, 2002; Catalogue of monuments of the Kazakhstan Republic history, 2007; Sorokin and Fofonov, 2009) which proved unambiguously a deep Medieval regression similar to the one we observe today (e.g., Boroffka et al., 2005a,b, 2006; Baipakov et al., 2007).

Despite at least two recent reviews that accounted for older and newly obtained data (Boomer et al., 2009; Cretaux et al., 2013), a critical reconsideration and integration of this information is still lacking. Our paper presents a comprehensive analysis of all available data to fill this gap. We present new results concerning distinct changes of Aral Sea lake level during the last two millennia, and integrate these with geomorphological, sedimentological, paleoenvironmental, geoarcheological, and historical data from the region. The chronology of the Aral Sea sediments in our study was established with the help of AMS ^{14}C dating. Calibrated ^{14}C dates were calculated with the Calib 7.0 program (Reimer et al., 2013). The data on reservoir age correction for Aral Sea used for calibration are based on ^{14}C dates of aquatic organisms (Kuzmin et al., 2007). The calibrated ages in our paper are quoted in thousands of calendar years before present (ka cal BP). The quoted time intervals include both dating and calibration uncertainties (e.g., ca. 1.6–1.4 ka cal BP). Details of the approaches used in this study can be found in our previous publications (Krivonogov et al., 2010a,b).

[1] INTAS — The International Association for the Promotion of Co-operation with Scientists from the New Independent States of the Former Soviet Union (EU); RFBR — Russian Foundation for Basic Research (Russia); CRDF — Civil Research and Development Foundation (USA).

2. The Aral Sea terraces

The number and age of the Aral Sea terraces are still being debated. Researchers distinguish several terrace levels (with elevations in meters above the Baltic Sea level, a.s.l.) which can be combined into three groups: 1) lower "late Aral" and "ancient Aral" terraces, 1–3 m higher than the modern one (corresponding to 53 m a.s.l. level in AD 1960); 2) higher terraces (10–20 m), with elevations of ca. 60–72 m a.s.l.; and 3) formerly submerged shore bars in the range of 30–45 m a.s.l. (e.g. Lymarev, 1967; Gorodetskaya, 1978). A sequence of eight terraces, accepted by Aladin and Plotnikov (1995) and Boomer et al. (2000) has drawn criticism. What is certain is the occurrence of well-documented sandy bench deposits with abundant mollusk shells representing Aral Sea lake levels at elevations of 53–56 m a.s.l. Berg (1908) concluded that it was impossible to form terraces above 54 m a.s.l. because this altitude marks the level of a spillway from the Aral–Sarykamysh Basin to the Caspian Basin (Fig. 1). In order to reconcile these contradictory facts, some scientists have suggested that a topographic border between the basins existed in the past (Khondkarian, 1977; Fedorov, 1980). However, there is no geomorphological evidence for such a barrier. Reinhardt et al. (2008) suggested the possibility of an Aral Sea lake level as high as 56 m a.s.l. because this altitude marks a divide between the Aral and Sarykamysh Basins represented by the Amu Darya deltaic plain. However, observations in support of these ideas fail to confirm the existence of Aral Sea terraces above 54 m a.s.l.

Geomorphologists dated the lower "late Aral" and "ancient Aral" terraces to ca. 1.5–2.5 and 2.5–3.5 ka BP, respectively (e.g., Boomer et al., 2000). However, radiocarbon dating of these terraces contradicts this age assignment, with ^{14}C dates of 745 $\pm$ 80 BP and 730 $\pm$ 80 BP (Lab numbers not provided) for the "ancient Aral" terraces, and 2860 $\pm$ 80 BP (Tln-104) and 1320 $\pm$ 120 BP (Lab number not provided) for "late Aral" terraces (Veinbergs and Stelle, 1980; Veinbergs, 1986).

Submerged shore bars have been suppositionally correlated to a single regression of the Aral Sea in late Glacial to early Holocene times (Veinbergs and Stelle, 1980). This correlation appears to be unreliable in the light of modern knowledge of sedimentation in the Aral Sea. An important consideration is why such old landforms should be so well preserved, and not covered by a thick layer of lacustrine deposits? A visual examination of satellite images of the modern dry bottom of the Aral Sea shows many shore bars left by the retreat of the lake in modern times. By extension, any recent transgression or regression could leave a pattern of shore bars as those observed by Veinbergs and Stelle.

3. Aral Sea lake level minima as recorded in bottom sediments

Available sediment cores can be divided into three groups according to their geographic position (Fig. 1), elevation, and lithology. These cores have been described in different publications which may result in slight incompatibilities in sediment type definitions (Fig. 4). However, the facies structure of the Aral Sea bottom sediments (Brodskaya, 1952; Zhamoida et al., 1997) allows us to distinguish layers formed in near-shore, shallow-water and deep-water conditions, i.e., to define low and high lake levels. Indicators of deep-water conditions are clayey silts and muds that lack remains of aquatic organisms such as mollusk or ostracod shells. An abundance of shells and sandy sediment composition indicate shallow-water conditions. Other lines of evidence of a shallow lake are layers of salts (calcite, gypsum, and mirabilite) and peat. Paleontological and geochemical data are also informative in terms of past Aral Sea lake levels. Determination of shallow-water intervals in the georeferenced cores gives us altitudinal estimates of former low stands of the lake. Fortunately, shallow-water layers provide good material for dating which is a basis for sediment correlation.

Correlation of the Aral Sea bottom sediments and their corresponding high and low levels during the last two millennia are shown in Fig. 4. Cores 15 and 86 were obtained in the deepest central part of the Eastern Large Aral Basin (Maev et al., 1983; Sevastyanov et al., 1991; Maev and

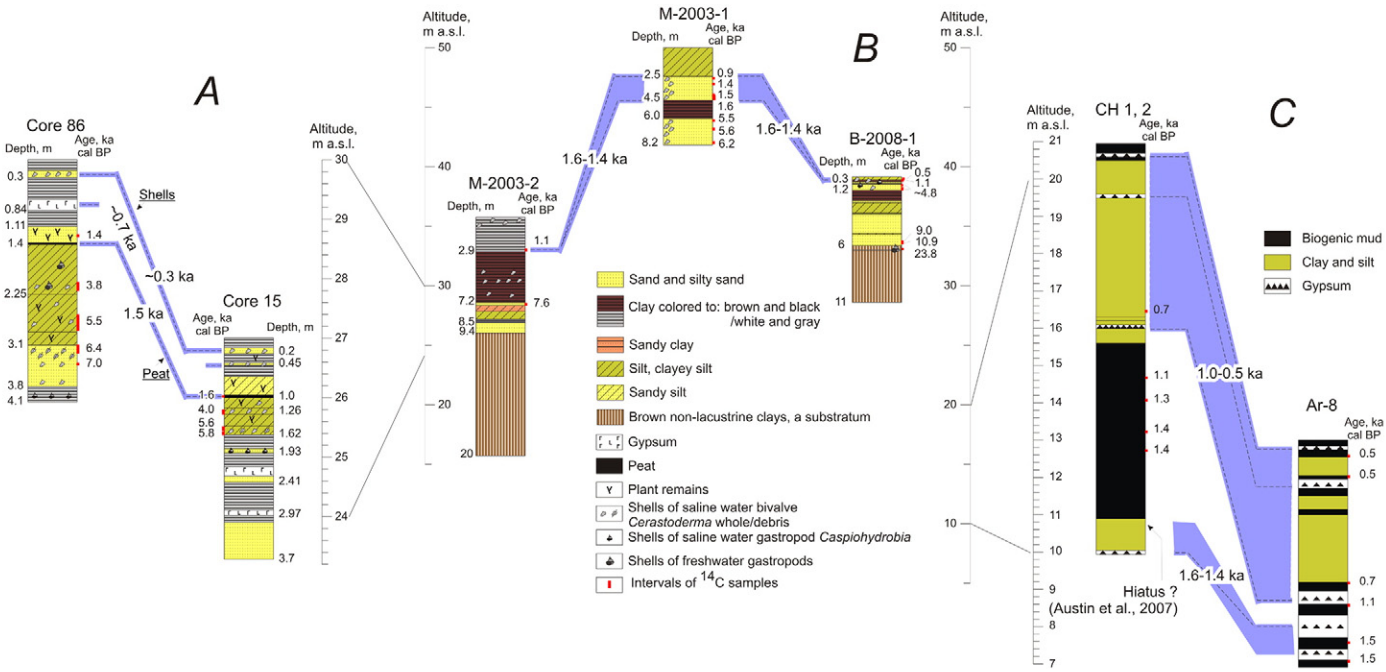

Fig. 4. Sedimentological data on the Aral Sea regressions (blue bars between the sediment columns). Cores: A — from the central part of the Eastern Large Aral (Maev et al., 1983; Sevastyanov et al., 1991; Maev and Karpychev, 1999; Ferronskii et al., 2003); B — from peripheral parts of the Eastern Large Aral (Krivonogov et al., 2010a,b); C — from the Chernyshov Bay, Western Large Aral (Nourgaliev et al., 2003; Sorrel et al., 2006; Austin et al., 2007; Sorrel et al., 2007).

Karpychev, 1999; Ferronskii et al., 2003) at elevations of 27 and 30 m a.s.l., respectively (Fig. 1). The cores have three shallow-water layers in the interval of interest. Their radiocarbon and tentatively interpolated ages show synchronism of low levels which occurred at ca. 1.5–1.4, 0.8–0.65, and 0.3–0.2 ka cal BP. In these times, Aral Sea lake level fell to 26–27 m a.s.l. (Table 1). The low-level interval of 1.5–1.4 ka cal BP in both cores is evidenced by layers of peat, whose formation requires a low-saline water near-shore environment (see discussion of the diatom record from Core 86 below).

Cores M-2003-1, M-2003-2, and B-2008-1 (Krivonogov et al., 2010a, b) were obtained in the shallower peripheral parts of the Large Aral Basin at elevations of 50, 36, and 39 m a.s.l., respectively (Fig. 1). Two boreholes, M-2003-2 and B-2008-1, penetrated through the entire Aral Sea sediment profile, and entered basal, brown-colored dense clays of non-lacustrine origin. Alternation of deep and shallow water facies in the upper parts of the cores is similar to those in cores 15 and 86 (Fig. 4). Correlation of the sediments by radiocarbon dating shows recessions of the Aral Sea at ca. 1.6–1.3 and 0.5 ka cal BP.

Parallel cores CH 1 and 2 and Core Ar-8 (Nourgaliev et al., 2003; Sorrel et al., 2006; Austin et al., 2007; Sorrel et al., 2007) represent sediments in the deep-water northwestern part of the Large Aral Basin, the Chernyshov Bay (Fig. 1). The cores were drilled at elevations of 21 and 13 m a.s.l., respectively. The sediments opened to a depth of 11 m are rather different from those in the eastern part of the Large Aral. They are laminated biogenic muds and terrigenous clays and silts (Fig. 4). Radiocarbon dating of biogenic mud layers showed a very young age, less than 2 ka cal BP, for the sediments of Chernyshov Bay, and a very fast accumulation rate with an average of 4–6 mm per year. Varve-like alternation of biogenic and terrigenous layers may reflect environmental variations; however, their sequences in the cores are ill-matched. Gypsum-rich layers were used for correlation because precipitation of gypsum marks progressive salinization of the lake (Sorrel et al., 2006; Oberhänsli et al., 2007). The gypsum-rich layers indicate increased salinization and, therefore, declines in Aral Sea lake level at ca. 1.4, 0.8, and 0.5 ka cal BP, and also in modern times.

Paleontological and geochemical data from the discussed cores also provide valuable information about Aral Sea lake level changes which can be used in conjunction with the lithological proxies. The diatom record from Core 86 (Aleshinskaya, 1991) shows three stages of Aral Sea development with prominent boundaries at ca. 4.2 and 1.3 ka cal BP. Stages I and III represent brackish and saline-water basins, which were typical of the recent Aral in the nineteenth–twentieth centuries AD. Stage II (dated to 4.2–1.3 ka cal BP) represents desalinization of the basin which is indicated by the dominance of freshwater diatoms. Aleshinskaya (1991) explained this phenomenon by a decrease in Aral Sea lake level and progradation of the Amu Darya delta. In detail, Stage II includes two peaks of freshwater diatoms which may represent deep regressions of the Aral Sea at ca. 4.2–3.2 and 2.1–1.3 ka cal BP. The latter one matches the 1.5–1.4 ka cal BP minimum level marked by peat layers in Cores 86 and 15.

Table 1
Age of sediment layers in Cores 15 and 86 representing low Aral Sea lake levels.

Core 15				Core 86			
Depth, m	Age, ka cal BP	Sediments	Level, m a.s.l.	Depth, m	Age, ka cal BP	Sediments	Level, m a.s.l.
0.16–0.21	0.2–0.3[a]	Sand with shells	~27	0.17–0.3	0.2–0.3[a]	Sand with shells	~30
0.43–0.45	0.65–0.7[a]	Sand with shells	~27	0.66–0.84	0.7–0.8[a]	Gypsum	~29.5
0.98–1.00	1.5[b]	Peat	26	1.39–1.41	1.4[b]	Peat	~28.5
				3.1–3.77	6.6–7.0[b]	Beach sands with shells	26

[a] Interpolated.
[b] Based on ^{14}C date.

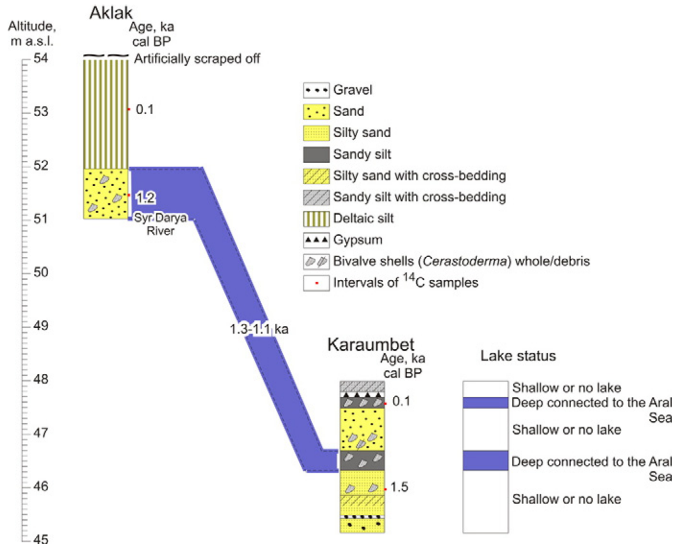

Fig. 5. Transgressions (blue bars) recorded in the shore sediment outcrops (Reinhardt et al., 2008; Krivonogov et al., 2010b).

Nikolaev (1987, 1991) and Nikolaev et al. (1989) studied the oxygen isotope composition of carbonates in several cores of the central part of Large Aral Basin, including the geochronologically-referenced Core 15. They suggested that increases of ^{18}O in bottom sediment carbonates reflect regressions (Nikolaev et al., 1989) which occurred at ca. 2.1–1.3, 0.9–0.7, and 0.2–0.4 ka cal BP during the last two millennia.

Cores CH 1 and 2 provided data on lake level changes in the Chernyshov Bay, which did not dry out during the last 1.6 ka cal BP. The dinoflagellate cysts and chlorococcalean algae records suggest low levels and existence of saline basins at ca. 2.1–1.6, 1.1–0.7, 0.6–0.3, and 0.05–0 ka cal BP (Sorrel et al., 2006). Diatom-inferred salinity indicates low levels at ca. 1.6, 0.8–0.7, and 0.2–0 ka cal BP (Austin et al., 2007). The authors constrained the diatom record to ca. 1.6 ka cal BP because of an abrupt transition in the diatom flora and magnetic susceptibility (Sorrel et al., 2006) which suggests a hiatus, i.e., the lowering of the Western Large Aral Basin to ca. 10 m a.s.l.

The age model of the CH 1 and 2 cores was recently updated by their first investigators (Chen et al., 2010) by including a 170-yr correction value for the Aral Sea reservoir effect (Kuzmin et al., 2007).[2] The resulting high salinity (low level) interval became 1000–1400 AD, i.e., 1.0–0.6 ka cal. BP.

Píšková et al. (2009) published the diatom data from Core C2/2004 retrieved by Nourgaliev et al. (2007) in Chernyshov Bay, 25 km southeast of the core CH 1, 2 locality at a water depth of ca. 3 m (elevation of ca. 27 m a.s.l.).[3] Changes of the diatom assemblages testify to low Aral Sea lake levels at ca. 2.0–1.75, 1.1–1.0, 0.6–0.55, and 0.1–0 ka cal BP.

The ostracod data from the sediments of the Small Aral Basin suggest a considerably decreased lake level at ca. 0.5–0.3 ka cal BP (Boomer et al., 2003, 2009). The drop was estimated to have reached as deep as 27–29 m a.s.l. This is the first paleontological evidence for the Medieval catastrophic regression. Boomer et al. (2009) summarized the recently obtained microfaunal data, and proposed a scheme of Aral Sea lake level changes during the last 2000 years, with low levels at ca. 2–1.6, 1.1–0.65, 0.5–0.35, and 0.2–0 ka cal BP.

In addition, Filippov and Riedel (2009) analyzed the mollusk fauna in ten short cores obtained in the eastern part of the Aral Sea (Zhamoida et al., 1997). Despite lack of age control, Filippov and Riedel (2009) suggest considerable variations in Aral Sea lake levels during the last 1 ka, with minima at ca. 0.85 and 0.5 ka cal BP.

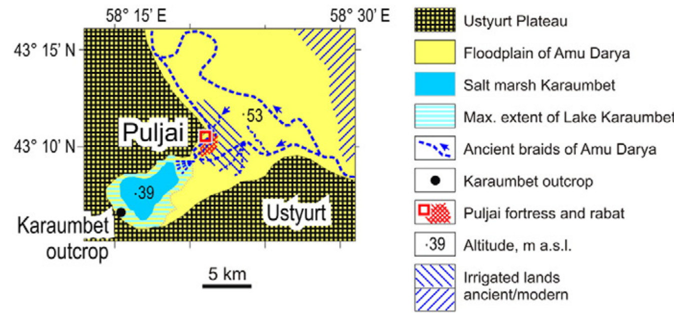

Fig. 6. Map of the Karaumbet Basin and surroundings of the Karaumbet and Puljai localities showing general geomorphology, the Aral Sea extent, and past and present irrigated lands.

4. Aral Sea lake level maxima as recorded in shore outcrops

Although deep-water sediments do not provide altitudinal information about high lake levels, this data can be obtained from shore outcrops. Most of the recently generated datasets indicate high stands with elevations of less than 54 m a.s.l., while higher levels remain problematic. Reinhardt et al. (2008) investigated sediments at the 60–65 m a.s.l. high Tastubek Peninsula, northern shore of the Aral Sea, in a ravine south of Tastubek Village (Fig. 1). The 3.5 m high outcrop consists of sandy, silty, and clayey sediments of continental (i.e., non-lacustrine) origin including wind erosion horizons. No evidence of lacustrine deposits was found. The probable age of the sediments has an upper limit of ca. 30 ka BP according to Paleolithic artifacts found in the vicinity (Boroffka et al., 2005a). This suggests that the Aral Sea lake level never rose to elevations of 60–65 m a.s.l.

A high stand in the Aral Sea lake level at 52 m a.s.l. is recorded in the Aklak outcrop, situated on the left bank of the Aklak Reservoir, recently constructed near the mouth of the Syr Darya River (Fig. 1). The outcrop shows littoral sand facies of Aral Sea sediments covered by deltaic silts of the Syr Darya River (Fig. 5). The lacustrine deposits contain many shells of *Cerastoderma* and *Dreissena* bivalve mollusks. The ^{14}C age of a *Cerastoderma* shell 1510 ± 35 BP (AA-83390) suggests a transgression at ca. 1.3–1.1 ka cal BP (Krivonogov et al., 2010a,b). The deltaic sediments contain plant remains with very recent ^{14}C ages of 160 ± 35 BP (AA-83391) and 165 ± 35 BP (AA-83392) BP corresponding to 280–0 cal BP

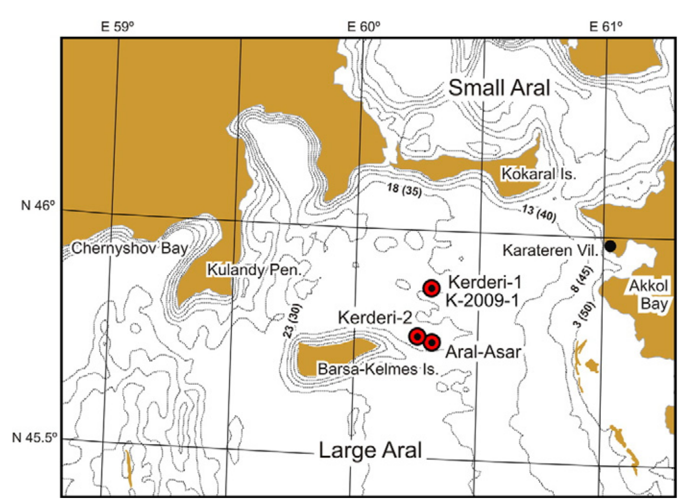

Fig. 7. Position of the Kerderi site cluster on the dry bottom of the Aral Sea. Topography is from a nautical map of AD 1960. Isobaths are labeled by depth and elevations a.s.l. (in brackets).

[2] The 170-yr value used in Chen et al. (2010) approximates the 168 ± 53 mean apparent ^{14}C age of modern shells from the Aral Sea (R).

[3] Unfortunately, the paper by Nourgaliev et al. (2007) does not mention core C2/2004, thus, its exact location is unknown.

that suggests a period of interrupted sedimentation in the modern Syr Darya River mouth.

Evidence of two high levels of the Aral Sea is recorded in the Karaumbet outcrop about 70 km south of the mid-twentieth century bank of the Aral Sea (Fig. 1). The Karaumbet Basin (elevation of 39 m a.s.l.) is a sinking tectonic structure along the eastern scarp of the Ustyurt Plateau which is separate from the Aral Sea during low stands (Fig. 6). In the periods of high stands, the Karaumbet Basin was connected to the Aral Sea via the Aibughir Bay (Fig. 1).

The outcrop is a 2 m deep gully which was cut by running water in the sloped bottom of the Karaumbet Basin, and its elevation is ca. 45 m a.s.l. The sediments consist mostly of fluvial and eolian series, whereas the lacustrine facies are subordinate (Fig. 5). The typical Aral Sea mollusk shells of *Cerastoderma* and *Dreissena* are in situ in the lake sediments, and are apparently reworked in the non-lacustrine sediments. The outcrop contains two layers of sandy silt of lacustrine origin with mollusk shells, and these silts represent the highest stands of the Aral Sea for the last 2 ka (Reinhardt et al., 2008). The ^{14}C date 300 ± 30 BP (POZ-Lab number not provided) indicates the age of the younger layer of ca. 0.15–0 ka cal BP. Dates 1720 ± 30 BP (AA-59338) and 1810 ± 30 BP (POZ-Lab number not provided), corresponding to ca. 1.6–1.3 ka cal BP, were obtained from non-lacustrine sediments below the older lacustrine layer, and this allows us to correlate the older layer with the Aklak high stand event, which occurred at ca. 1.3–1.1 ka cal BP (Krivonogov et al., 2010b).

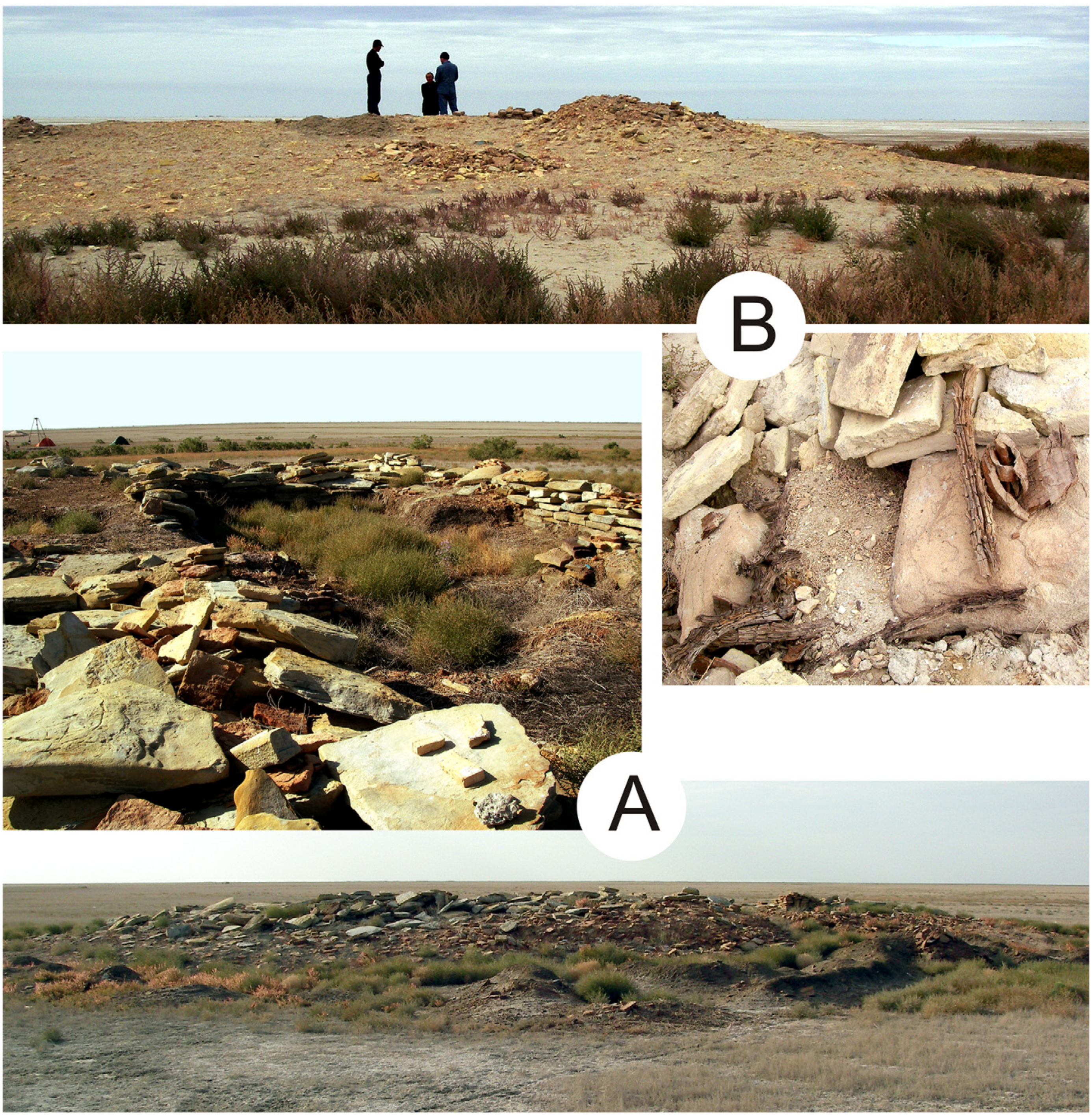

Fig. 8. Photographs of the Kerderi-1 (A) and Kerderi-2 (B) mausolea. Middle right photo of (B) shows wood material excavated from a grave and ^{14}C-dated. Photos by S.K. Krivonogov.

5. Archeological data on the Aral Sea lake level changes

Archeological sites are widely spread around the Aral Sea, and they have been used to establish the timing of lake level changes by geologists and geomorphologists (e.g., Yanshin, 1953; Kes, 1969, 1983; Rubanov et al., 1987; Sevastyanov et al., 1991). The distribution of different age sites has been summarized in several publications (e.g., Tolstov, 1962; Vinogradov, 1968; Levina, 1998). With respect to the Aral Sea lake levels, Yanshin (1953) and Vinogradov (1981) mentioned a small number of Mesolithic sites around the Aral Sea as compared to relatively abundant Neolithic sites, and they suggested that this indicates the presence of ancient populations closer to the Aral Sea coast since ca. 10–9 ka BP. This was interpreted as a change from climatically unfavorable conditions with a poor water supply to more favorable ones. The Neolithic sites constrain the period of the warm and wet Lavlakan phase dated to ca. 9–5 ka cal BP (Mamedov, 1991a). Studies have shown the presence of archeological sites of different ages, from the Late Paleolithic (ca. 50–30 ka BP) to late Middle Ages and younger near the Aral Sea shore (Baipakov et al., 2004; Shirinov et al., 2004; Boroffka et al., 2005b). This provides evidence that these sites were never submerged, except those situated below 54 m a.s.l. (Boroffka et al., 2005a, 2006). More recent work has identified several sites that were obviously flooded by the Aral Sea during the last 1.5 ka.

One of them is the Puljai site near the eastern edge of the Ustyurt Plateau (Fig. 1). It has a fortress with a higher position on the promontory of the Ustyurt cliff, and a civil settlement, or rabat, below the fortress (Fig. 6). The rabat occupies a deltaic plain of the Amu Darya River at an elevation of 53 m a.s.l. It consists of several manors placed at a distance of 50–90 m along one of the river channels, which flowed into the terminal Karaumbet Lake. The rabat's adobe brick buildings now look like clayey mounds because their ruins were flooded by the Aral Sea. This is clear from abundant *Cerastoderma* and *Dreissena* shells on the tops of the ruins. Artifacts date the rabat to the twelfth–end of fourteenth centuries AD, i.e., ca. 900–600 cal BP (Shirinov et al., 2004; Boroffka et al., 2005a,b, 2006). Therefore, the transgression occurred after ca. 600 cal BP, and this was probably the highest Aral Sea lake level of the last millennium.

The Kerderi site cluster is situated on the former bottom of the Aral Sea east–northeast of Barsa-Kelmes Island, and consists of the mausoleum and mosque Kerderi-1, mausoleum Kerderi-2, and the Aral-Asar settlement (Figs. 1, 7). These sites were found by local hunters, and excavated by archeologists in the early 2000s (Smagulov, 2001, 2002; Catalogue of monuments of the Kazakhstan Republic history, 2007; Sorokin and Fofonov, 2009). Their elevations of ca. 34 m a.s.l. point to a deep regression similar to the modern one.

Baipakov et al. (2007) suggested a very short period of existence (several decades only) for the Kerderi–Aral-Asar civilization which ended with a sudden rise of the Aral Sea. However, the investigators describe a rather developed industrial and agricultural community. The findings from the Aral-Asar, which probably appeared as a settlement on the Great Silk Road, indicate extensive livestock, plant agriculture, and trade. The settlement has a necropolis, and its people were rich enough to construct two impressive mausolea (Figs. 8, 9). The mausolea were ornamented with terracotta, blue-colored ceramics, and mosaics, similar to the architecture and decorations used in sacred buildings from Samarkand and other cities in Khorasan, Middle Iran, and

Fig. 9. Archeological findings from the Aral-Asar settlement and Kerderi-2 mausoleum (two photos in the center) illustrating levels of agricultural (millstones and pots for corn) and cultural (gold earrings and blue-colored ceramic ornamentations) developments. Photos by D.A. Voyakin and S.K. Krivonogov.

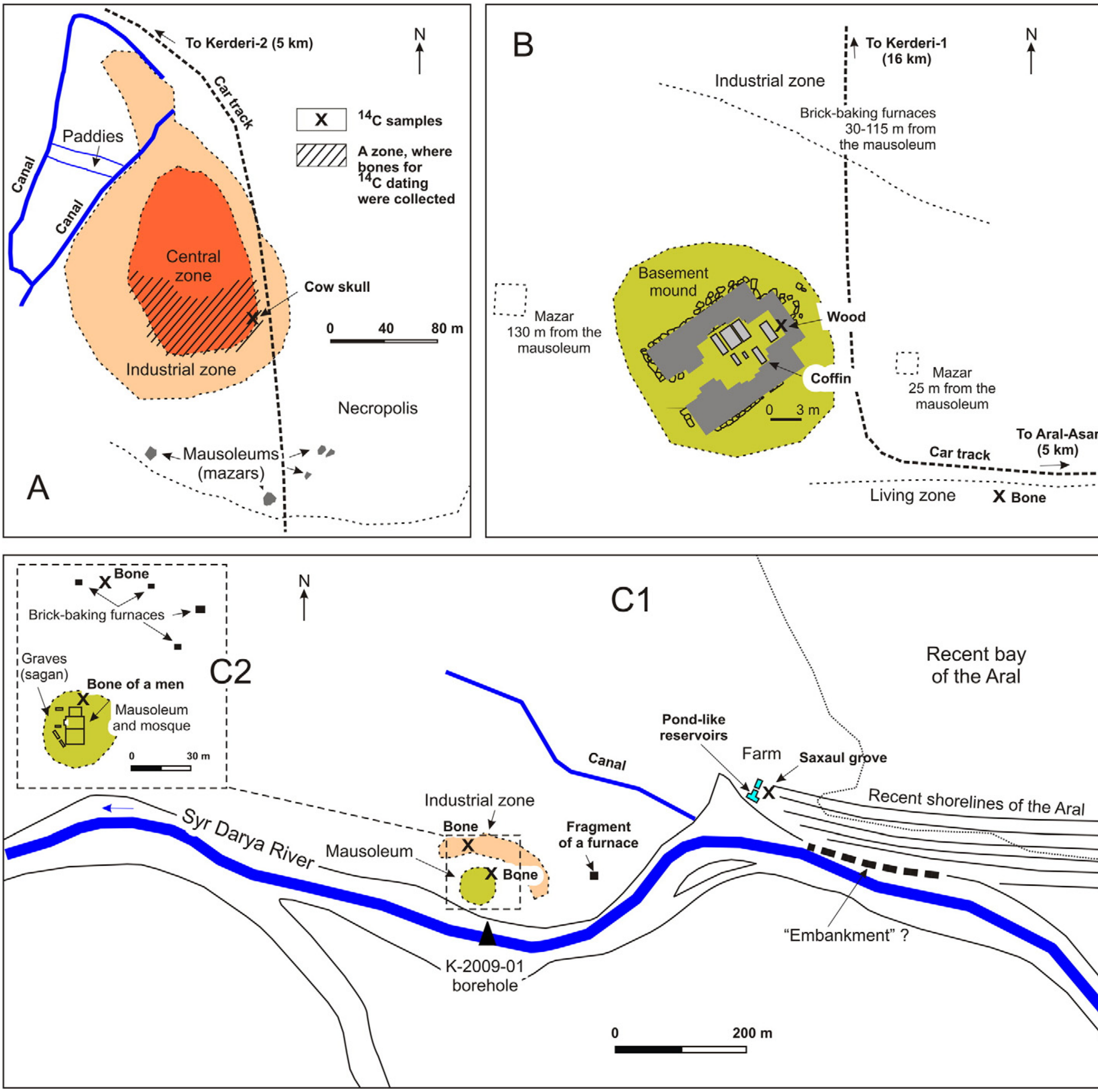

Fig. 10. Sketches of the Aral-Asar (A), Kerderi-2 (B) and Kerderi-1 (C1 and C2) localities. A and B — the modified data by Smagulov (2002) and Catalogue of monuments of the Kazakhstan Republic history (2007). C — from original survey by S.K. Krivonogov. The drawings show general topography and location of archeological objects and of ^{14}C-dated samples.

Azerbaijan (Sorokin and Fofonov, 2009). The Kerderi mausolea were built on weak silty sediments of the Aral Sea, and therefore required reinforced basements made of Paleogene sandstone slabs. The nearest source of this material is the Kokaral Peninsula ca. 50 km north of the Kerderi cluster (Smagulov, 2001). Thus, the Medieval people who occupied the dried Aral Sea bottom had to have sufficient time to settle and develop the area economically, and to construct the mausolea and associated structures.

Extensive plant agriculture is evidenced by large pots used for storage of rice and wheat, and also by millstones, which are abundant at the Aral-Asar settlement (Fig. 9). Paddies and irrigation canals were also constructed in the vicinity of the Aral-Asar settlement and the Kerderi-1 mausoleum (Fig. 10). Evidence of agriculture in this area implies a sufficient amount of freshwater for cultivation taken from the Syr Darya River (Krivonogov, 2009; see Section 7).

Various authors offer slightly different interpretations for the archeological age of these sites. The Kerderi-1 mausoleum–mosque is dated to the twelfth–fourteenth centuries AD by Smagulov (2002), to the fourteenth–sixteenth or fourteenth–early fifteenth centuries AD by Boroffka et al. (2005a, 2006), and to the thirteenth–fourteenth centuries AD by Boomer et al. (2009). The Kerderi-2 mausoleum has been assigned an age of late thirteenth–middle fourteenth (Catalogue of monuments of the Kazakhstan Republic history, 2007) or fourteenth–fifteenth centuries AD (Sorokin and Fofonov, 2009). The Aral-Asar settlement is dated by

Table 2
Radiocarbon dates from the Kerderi cluster.

^{14}C age, BP	Lab code	Material	δ^{13}C, ‰	Calibrated age, BP
Kerderi-1				
470 ± 35	AA-93688	Saxaul-tree wood[a]	−23.1	475–545
620 ± 45	AA-93685	Domestic animal bone[b]	−22.1	540–660
640 ± 45	AA-93686	Domestic animal bone[c]	−15.7	550–670
860 ± 35	AA-93687	Shell of *Cerastoderma*[c]	−0.7	490–670
770 ± 45	AA-103140	Human femur[d]	−14.2	660–780
Kerderi-2				
580 ± 35	SOAN-8175	Domestic animal bone[e]		530–650
600 ± 65	SOAN-7688	Thin wood stick[f]		525–675
820 ± 55	SOAN-7687	Thick wooden plank[f]		675–805
Aral-Asar				
540 ± 45	SOAN-8174	Cow skull		510–650
630 ± 35	SOAN-8173-1	Domestic animal bone[g]		555–665
910 ± 80	SOAN-7686	Domestic animal bones[h]		685–955
1050 ± 90	SOAN-8173-3	Domestic animal bone[g]		765–1175

[a] The sample was collected from a stump of the saxaul tree, the farm eastward of the mausoleum.
[b] The sample was collected within the industrial zone northward of the mausoleum.
[c] The sample was collected in the cultural layer under the saxaul tree, the farm eastward of the mausoleum.
[d] The sample was collected on the northern slope of the mound of the mausoleum. Probably the bone is from a grave of the sagan surrounding the mausoleum and robbed before archeological excavations.
[e] The sample was collected within the living zone of the mausoleum.
[f] The material was collected in the north-eastern part of the mausoleum near a grave with a coffin (Fig. 10B) opened by archeologists (Catalogue of monuments of the Kazakhstan Republic history, 2007).
[g] The samples SOAN-8173-(1 and 3) were selected from a collection of bones used for paleontological identification. The bones were collected in the southern part of the Aral-Asar settlement (Fig. 10A). They belong to domestic animals: cow, horse, and sheep/goat (Krivonogov et al., 2010b).
[h] The sample consists of material from several bones.

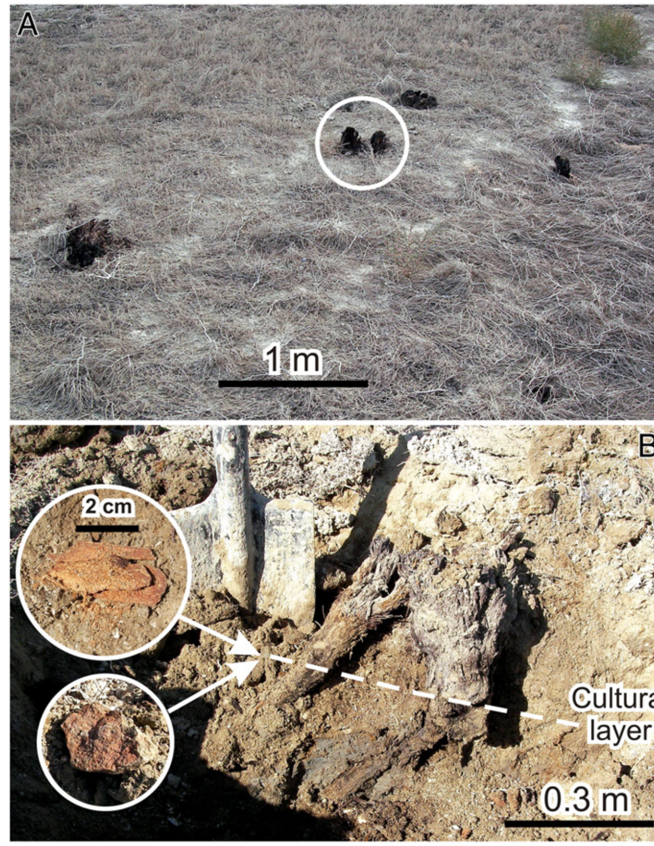

Fig. 11. Stumps of the saxaul trees at the Kerderi-1 site. A — general view; B — stump excavated for ^{14}C dating. Positions of cultural layer and findings of pieces of a bone and a brick in it (in circles) are shown. Photos by S.K. Krivonogov.

coins to the mid-fourteenth century AD (Catalogue of monuments of the Kazakhstan Republic history, 2007). All these dates constrain the Medieval "Kerderi" regression to ca. 0.8–0.4 ka cal BP.

We conducted ^{14}C dating on a variety of materials from the Kerderi cluster (Krivonogov et al., 2010b; Table 2, Fig. 10). These include bones and wood collected primarily from the surface. The Aral-Asar settlement contains abundant bones from domestic animals (cow, horse and sheep/goat). These provided the major part of the dating samples. Wood samples left after the archeological excavations of grave with coffin (Figs. 10B and 8B), were dated at the Kerderi-2 mausoleum. A human femur was found on a burial place alongside the Kerderi-1 mausoleum (Fig. 10C).

We also dated a *Saxaul* wood sample from a grove of trees situated around 400 m from the Kerderi-1 mausoleum which we interpret as a farm (Fig. 10C1). Six tree stumps are preserved from the grove, adjacent to a human-made pond. A cultural layer with pieces of bricks and animal bone was found at a depth of 30 cm below the surface. The stumps are 10–25 cm in diameter, and one of them was collected for ^{14}C dating (Fig. 11). The better preserved lower part of the stump returned an age of ca. 0.5 ka cal BP (Table 2).

Most of the dates obtained from the Kerderi archeological sites are in the range of 1.0–0.5 ka BP.

6. Historical evidence for Aral Sea lake level fluctuations

The Aral Sea (also known as Kurder, Khorezm, or Jend Lake) has been mentioned in geographic treatises, chronicles, and other documents since ancient times. Available manuscripts were carefully analyzed by Bartold (1902), whose findings were used by Berg (1908) and other researchers in their reconstructions of Aral Sea history. However, most of these documents are poor witnesses of the Aral Sea lake level changes. Some reliable information recorded since the Middle Ages is available.

A famous example often cited in the geological literature is attributed to the Mongolian ruler Genghis Khan, whose troops conquered Urgench (Gurganj) City, the capital of northern Khorasan, in AD 1221. During the military campaign an earthen dam that protected the city from flooding by the Amu Darya River was destroyed, and as a result the river changed course toward the Sarykamysh Basin rather than the Aral Sea (Fig. 12). Many scientists believe that this event was a major contribution to the Medieval recession of the Aral Sea. However, our ^{14}C dating of the Kerderi cluster suggests an earlier onset for the regression, at ca. 1 ka cal BP.

Hafizi-Abru, a chronicler and geographer at the court of central Asian ruler Tamerlane, wrote in AD 1417 that the Aral Sea "does not exist now" and that the Amu Darya River flows to the Caspian Sea (Bartold, 1902). Berg (1908, p. 268) considered this evidence of an extremely low Aral Sea lake level to be exaggerated, and for decades it was dismissed. However, the witness of Hafizi-Abru coincides with the main period of the Kerderi cluster development based on modern data.

The subsequent rise of the Aral Sea was evidenced by Abulgazi, the ruler (khan) of Khiva, who noted that the Amu Darya River turned back to the Aral Sea 30 years before his birth, i.e., around AD 1573 (Bartold, 1902). By the end of the sixteenth century AD, the Aral Sea became fully filled. In "Kniga glagolemaya Bolshoi Chertezh" ("A Book of the Great Map"), AD 1627, which is a description of the first map of the "entire Moscow state", the Aral Sea was called "the Blue Sea" with a latitudinal length of 250 versts[4] (Berg, 1908). It was depicted as a big lake on maps by S. Remezov in AD 1697 (Berg, 1908), and by A.

[4] The definition of a verst, an ancient Russian measure of length, changed through time. It consisted of 1000 sazhens (approximately 2 km) in the mid-seventeenth century and of 500 sazhens (approximately 1.07 km) in the mid-eighteenth century.

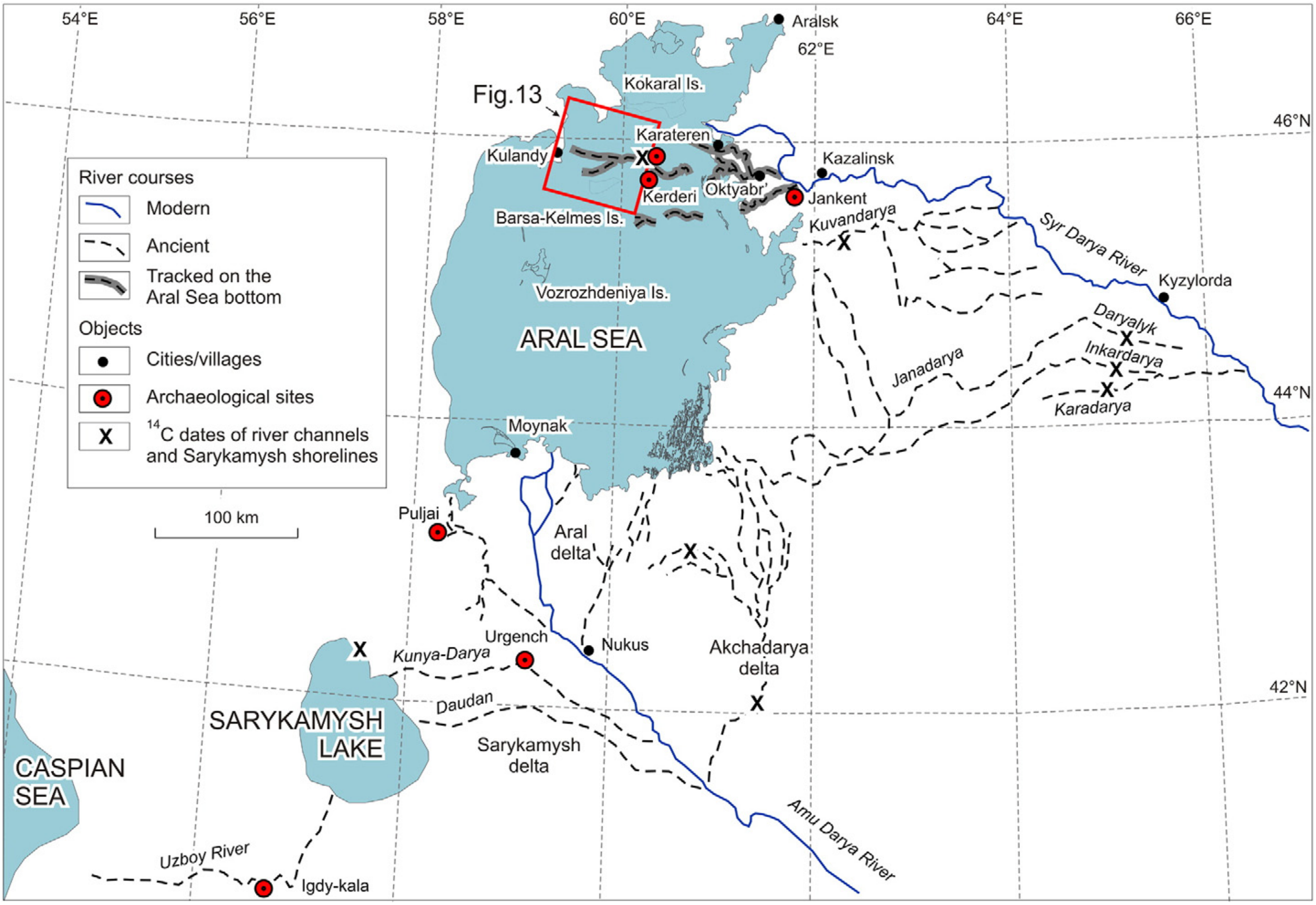

Fig. 12. Modern and ancient river courses of the Amu Darya and Syr Darya deltas, and location of important archeological sites and ^{14}C-dated localities mentioned in the text. The Aral Sea coast is shown as of AD 1960.

Bekovich-Cherkasskii in AD 1715 (Shafranovskii and Knyazhetskaya, 1952).

The actual dimensions of the Aral Sea were geodetically measured by Russian topographers under the leadership of A. Butakov in AD 1848–1849 (Butakoff, 1853). On the map compiled by Butakov, the areal extent of the Aral Sea looks similar to its size in the 1960s or even a bit larger, as the map shows the Aibughir Bay extending about 100 km to the south (Fig. 1).

Berg (1908) summarized the data on the changes of Aral Sea lake level since AD 1790, and subsequent work documents changes up until the present (e.g., Shermatov et al., 2004). These studies show that the lake level fluctuated within a range of 3–3.5 m (Fig. 3), indicating a metastable transgressive state for the Aral Sea during the last 170 years.

7. Channels and deltas of the Syr Darya River on the dry bottom of the Aral Sea

Nikolaev (1991) firstly identified paleochannels of the Syr Darya River on the Aral Sea bottom, north of Barsa-Kelmes Island and in the middle part of the lake, and attributed these features to a 1.6 ka BP drop in Aral Sea lake level (1.5–1.4 ka cal BP in this paper). Krivonogov (2009) mapped the channels with the help of satellite imagery where ancient river beds and side channels of Syr Darya River are clearly seen for a distance of more than 100 km. There are two braids, to the north and to the south of Barsa-Kelmes Island (Fig. 12).

The northern braid starts near Oktyabr' Village where the present Syr Darya River turns sharply to the north. To the west of the Oktyabr', the ancient river furcates into three channels. The northern channel reaches the Akkol Bay south of Karateren Village, follows the dry bottom of the Aral Sea for a distance of about 40 km, and then forms a delta. The middle channel reaches Karashokhat Cape and terminates with a small delta, corresponding to a maximum water level of about 53 m a.s.l. The southern channel continues far to the west, and the Kerderi site cluster is situated near this riverbed. There are many minor water passes in-between which represent broad springtime floods over the dried floor of the Aral Sea.

The delta of the southern channel covers an area of 22 by 22 km north of the Barsa-Kelmes Island (Fig. 13). The western edge of the delta touches the opposite side of the Aral Sea, namely the Kulandy Peninsula. The edge of the delta has an elevation of ca. 29 m a.s.l. which marks the level of the Aral Sea in Medieval times.

The delta system of the northern channel is less extensive than the southern delta, and its surface is complicated by a smaller delta, reflecting a transgressive event. This gives grounds to suggest that the northern channel is younger than the southern one, whereas the middle channel may represent high stands that occurred before or after the Kerderi low stand.

The Kerderi archeological site cluster indicates a late Medieval age for the longest channel, dated to ca. 0.8–0.4 ka cal BP. In order to confirm this conclusion we drilled channel sediments near the Kerderi-1 mausoleum (K-2009-1 borehole, Fig. 10C). This 40 m wide channel is, however, not a main stream of the Medieval Syr Darya River. The main channel is ca. 120 m wide and is situated 2 km to the south of it (Fig. 13).

The 12 m long core contained 1.9 m of river sediments underlain by Aral Sea deposits (Fig. 14). Sedimentological analyses describe the

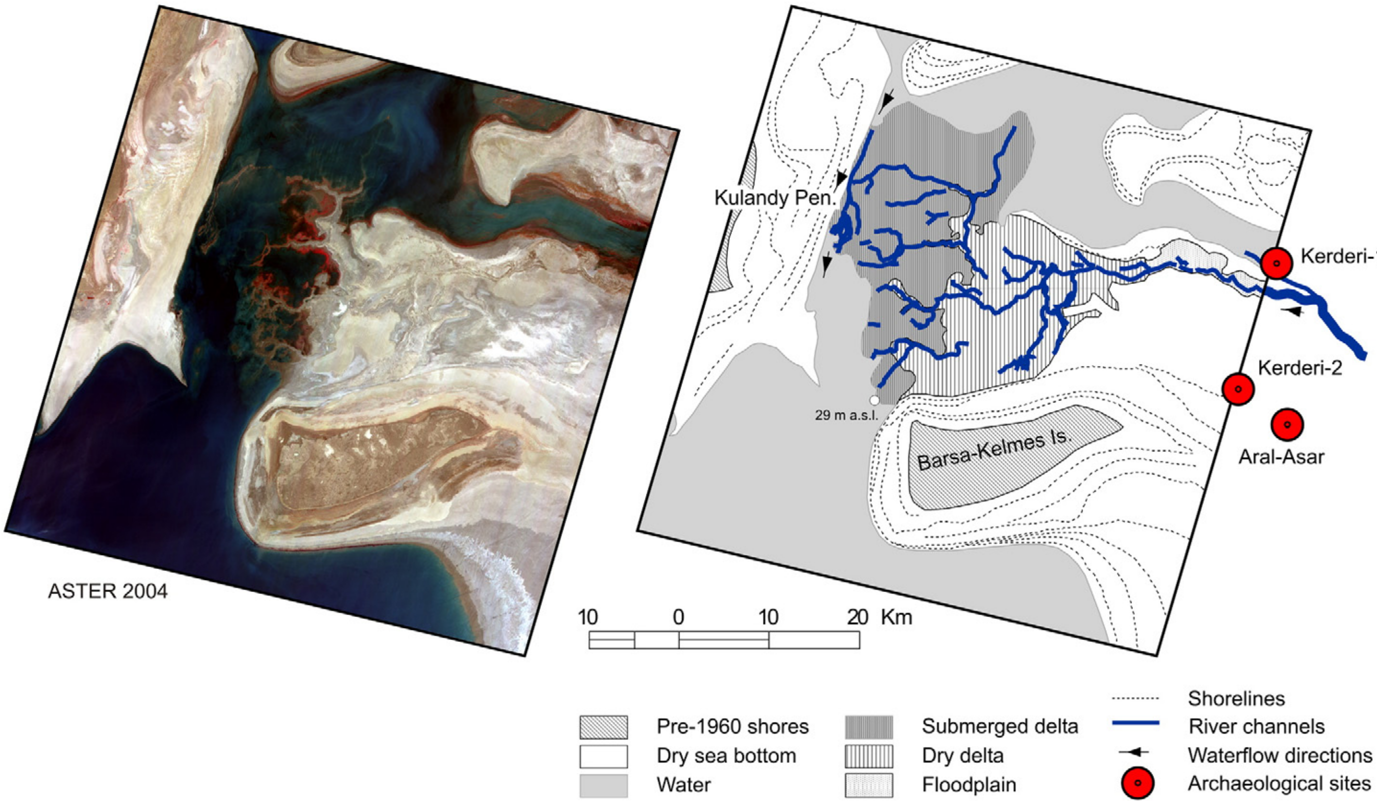

Fig. 13. The 2004 ASTER satellite image (left panel) showing a part of the Aral Sea bottom between the Kulandy Peninsula and Barsa-Kelmes Island, and its interpretation (right panel) showing the Medieval delta of the Syr Darya River (after Krivonogov, 2009). For georeference, see Fig. 12.

sediment structure and origin. Water soluble components (mainly chlorides) tend to increase from the bottom to top of the core, which may reflect pervasive salinization of the basin through time. Carbonates correspond to lithological variations in the sediments. They average 20% in the silty to sandy layers and constitute 10–12% of the clayey layers. Those layers, which contain mollusk shells, increase in carbonate content to 30 and 40%. Organic matter shows a low correlation with lithology and changes in its concentration depend on the origin of the sediments. Deep-water lacustrine clays are depleted in carbonates and chlorides. These probably formed in fresh-to-brackish-water conditions and are rich in organic matter, ca. 15%. Lacustrine silts and sands have low organic matter concentrations, less than 5%. Riverine silts are floodplain facies that contain abundant plant remains, and show organic matter concentrations similar to the lacustrine clays. The lower sand layer, which represents a channel facies, is poor in organic matter.

Abundant plant remains in the river beds, mainly roots and stems of *Phragmites*, are dated to ca. 0.3–0.6 ka cal BP (Table 3). Roots probably contaminate the substrata to a depth of about 1 m below the river bed, where some younger ages are observed in the same level as much older ones. The top of the lacustrine sequence is dated to ca. 4.2–4.7 ka cal BP.

A similar braid, situated to the south of Barsa-Kelmes Island, has not been studied yet. It furcates from the Syr Darya River near the Urkendeu Village where the ruins of the ancient capital city Jankent are located (Fig. 12). The age of this braid can be estimated from the archeological history of the Jankent region. The city of Jankent appeared in the tenth century AD, and existed as a major political and economic center up to the twelfth century AD (Tolstov, 1962; Levina, 1998). Data from new excavations narrow this range considerably, to the ninth–tenth centuries AD (Arzhantseva and Ruzanova, 2010).

We ^{14}C-dated bones collected by archeologists during new excavations of the Jankent. The samples consisted of many small bone fragments and yielded an "averaged" radiocarbon age of 1150 ± 45 BP (SOAN-8177), i.e., 960–1180 cal BP. This age coincides with the archeological estimate.

Researchers suggest that settling of the Syr Darya River delta strongly depended on the nature of its braiding, along with political, economic, and social factors (e.g., Tolstov, 1947; Andrianov, 1969). According to our data, Jankent City appeared near the Medieval Jankent braid of the Syr Darya River, and developed intensively until the river turned to the north. As the new channel was situated only 5 km from Jankent, this change was important but not critical for the existence of the city.

All this information allows us to conclude that the Jankent channel was active at the same time as Jankent City flourished, i.e., about

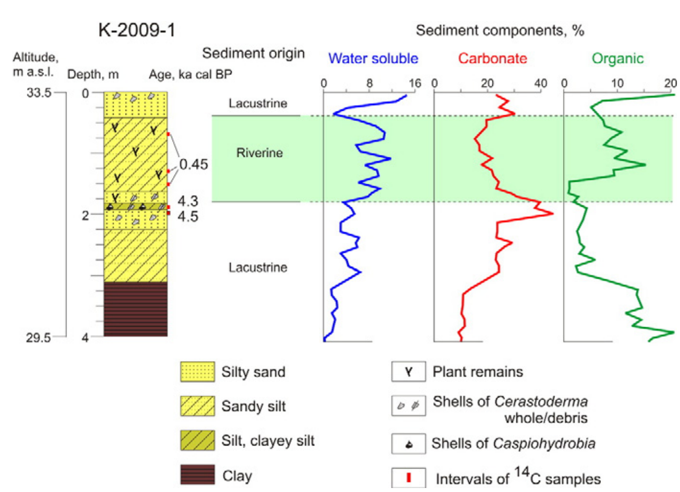

Fig. 14. Sediment core K-2009-1: recognition of river and lacustrine beds.

Table 3
Radiocarbon dates from the K-2009-01 sediment core, upper part.

Depth, cm	Material	Lab code AA-	$\delta^{13}C$, ‰	^{14}C age, BP	Calibrated age, BP
78	Plant remains	90634	−27.6	510 ± 45	500–560
134	Plant remains (root?)	90635	−25.6	410 ± 45	420–520
179	Plant remains	90636	−24.6	310 ± 40	300–480
189	Shells of *Caspiohydrobia*	90637	2.9	4150 ± 35	4200–4570
200	Shell of *Cerastoderma* (bivalve in situ)	90638	0.9	4230 ± 55	4300–4740

1 ka cal BP. The channel probably extended to the dry bottom of the Aral Sea at the beginning of the Kerderi regression.

8. Development of the Syr Darya and Amu Darya deltas

Although the Syr Darya and Amu Darya rivers originated in the Pliocene, their current deltas are much younger. The rivers made their way through a series of basins of the Turan Plain, and reached the Aral Basin in the Late Pleistocene. Archeological data suggest a presumably Holocene age for the deltas (e.g., Tolstov, 1962; Kes', 1983, 1991; Pinkhasov, 2003; Boroffka, 2010). In the Holocene, formation of deltas followed a long-term trend, shifting northward for both the Syr Darya and Amu Darya rivers.

As these rivers are the main feeders of the Aral Sea, its water budget relies on them. Prograding deltas naturally regulate water courses, and water feeding the Aral Sea was redirected in the past, between the Aral Sea and other basins in the region including the Sarykamysh and the Caspian Sea. In addition, redirections flushed water to the surrounding deserts where it evaporated. The natural mechanism of these changes is river sedimentation which provides convex shaped deltas, and rivers could occasionally turn to either side of a given delta. Geographers prefer explanations of changes of the Syr Darya and Amu Darya courses by natural forces (Mamedov, 1991b), while archeologists suggest a predominance of political and socio-economic causes (Tolstov, 1962; Andrianov, 1969). Archeologists have shown that irrigation activities pursued by local populations in certain periods in antiquity[5] and the Middle Ages were as important as in modern times.

The extensive, ca. 400 km long, delta of the Syr Darya River possesses several prominent ancient river courses with well-preserved channels, including: the Karadarya, Inkardarya, Janadarya, and Kuvandarya (Fig. 12). These probably functioned in different periods of the Holocene; however, exactly when they were active is not well-known. The distribution of archeological sites (Tolstov, 1962; Tajekeev, 2010) shows that the Inkardarya Channel was the main river course in the late Neolithic and the Bronze Age, the end of third–beginning of the first millennia BC, i.e., at ca. 4–3 ka cal BP; however, later on it functioned as a part of the Janadarya Channel. The Janadarya Channel formed at 2.7–2.5 ka cal BP. The Kuvandarya Channel appeared more or less simultaneously with the Janadarya Channel, and both channels episodically functioned until the eighteenth–nineteenth centuries AD. Inhabitants abandoned settlements along the emptied Janadarya Channel at ca. 2.3 ka cal BP, whereas the Kuvandarya Channel was full-flowing and became a center of local civilization. The lower reaches of the Janadarya and Inkardarya channels had water at ca. 1.1–0.9 ka cal BP. The Janadarya Channel contained abundant water at 0.9–0.7 ka cal BP. In addition, the Jankent and Kerderi braids of the Syr Darya River, which functioned at 1.0 and 0.8–0.4 ka cal BP, respectively, suggest simultaneous activity of the northern and southern courses of the Syr Darya River, with a primary northern course.

The delta of the Amu Darya River consists of three separate sub-deltas (Fig. 12). Early investigators considered their sequential formation as follows: eastern Akchadarya; western Sarykamysh; and middle Aral (Tolstov and Kes, 1960; Tolstov, 1962; Kes, 1983; Yagodin, 1986). Other researchers suggest that they were formed simultaneously (e.g., Mamedov, 1991b). Archeological sites along the Akchadarya sub-delta indicate its long activity, from the end of the fourth to the beginning of the first millennia BC, i.e., at ca. 5–3 ka cal BP, judging from the presence of sites belonging to the Kelteminar Culture of the Neolithic, and Tazabagab and Suyargan cultures of the Bronze Age. Archeologists suggest an absence of natural flow of the Akchadarya at ca. 2.8–1.4 ka cal BP. They suggest that it was artificially watered with an extensive irrigation system (Tolstov and Kes, 1960; Tolstov, 1962).

The Sarykamysh sub-delta includes two major channels, the Daudan and Kunya-Darya (Darialyk). The Daudan Channel was very active in antiquity, whereas the Kunya-Darya Channel was a primary water course in the late Middle Ages and a subordinate stream in antiquity. The Medieval reactivation of the Sarykamysh sub-delta was to a large degree artificial. It resulted from the destruction of irrigation systems (dams) of Urgench City after devastating wars waged by Genghis Khan (AD 1221) and Tamerlane (AD 1388). The direction of the Amu Darya River to the Sarykamysh Basin continued until AD 1573 when the river turned to the Aral Sea (Bartold, 1902).

The Aral sub-delta of the Amu Darya River has been dated using archeological data from antiquity to the present. The sub-delta was significantly canalized and braided from its eastern to western edges, both naturally and artificially (Yagodin, 1986). The eastern channels were naturally active from the second–fourth to seventh–eighth centuries AD, i.e., at 1.9–1.2 ka cal BP. The Kerder Canal was constructed in the tenth century AD, probably to compensate for water losses that resulted from the migrated course of the Amu Darya River. The western channels were active in the tenth–fourteenth centuries AD, i.e., 1.1–0.6 ka cal BP (see evidence of the Puljai settlement, Section 5).

The final destination of the Aral sub-delta's channels was the Aral Sea, while researchers reconstructed a number of inland deltas for some channels which did not reach the Aral Sea (Yagodin, 1986). The water supply of the Aral sub-delta fluctuated through time. It was minimal or even ceased in the fifth–sixth centuries AD, i.e., 1.6–1.4 ka cal BP when the Sarykamysh sub-delta received a major part of the Amu Darya waters (Tolstov and Kes, 1960).

In order to better understand the flow patterns of the Syr Darya and Amu Darya rivers, we ^{14}C-dated the main ancient river courses (Fig. 12). We assume that sediments that currently fill dry channel beds were deposited during the most recent periods of activity. We drilled the beds, and tried to find remains of aquatic plants and shells which could ensure a reliable chronostratigraphy for the sediments. Dating of plant fragments alone could produce unreliable ^{14}C dates, since desert plant roots can penetrate deeply into the ground. This may account for some results from the Inkardarya Channel where wood fragments returned very young ages (Table 4). In most cases, this did not appear to be a problem, and material from other channels gave reasonable ages (Tables 3 and 4).

In the delta of the Syr Darya River, the Kerderi Channel (Fig. 12) was the primary river course in late Medieval times, whereas the Kuvandarya Channel was probably active earlier. It is probable that the river courses south of the Kuvandarya Channel functioned in the middle–early Holocene, as the ^{14}C dates from Karadarya and Daryalyk

[5] The term "antiquity" is used here to indicate the time period for early civilizations in the Aral Sea region following the terminology of previous investigators (e.g., Tolstov). It does not mean more distant past, Bronze and Early Iron ages and prior to that.

Table 4
Radiocarbon dates from riverbeds ([a]) and floodplains ([b]) of the Syr Darya and Amu Darya deltas.

Site	Coordinates	Depth, cm	Material	Lab code AA-	Date	$\delta^{13}C$, ‰	Calibrated age, BP
Delta of Syr Darya							
Kuvandarya[a]	N 45.2783 E 62.1718	90–110	Shell debris	93680	1900 ± 40	−9.1	1730–1930
Inkardarya[a]	N 44.4899 E 65.0931	100–110	Wood	93682	20 ± 35	−12.4	Rejected
Inkardarya[a]	N 44.4746 E 65.1628	130–150	Wood	93683	240 ± 40	−13.2	Rejected
Karadarya[a]	N 44.2879 E 65.1042	70	Fruit of *Potamogeton pectinatus* L.	93684	5380 ± 45	−15.7	6170–6290
Daryalyk[b]	N 44.6117 E 65.2103	100	Pelecypod shells	93681	9630 ± 60	−4.9	10,770–11,190
Delta of Amu Darya							
Akchadarya[a]	N 43.1407 E 60.6118	450–460	Shell of gastropod and oogonium of *Chara*	59336	910 ± 40	−3.8	740–920
Akchadarya[a]	N 43.1407 E 60.6118	790–800	Shell of gastropod and oogonium of *Chara*	59337	1090 ± 45	−5.0	930–1090
Akchadarya[b]	N 42.0637 E 61.4575	500	Gastropod shells	59334	5880 ± 90	−0.2	6490–6940

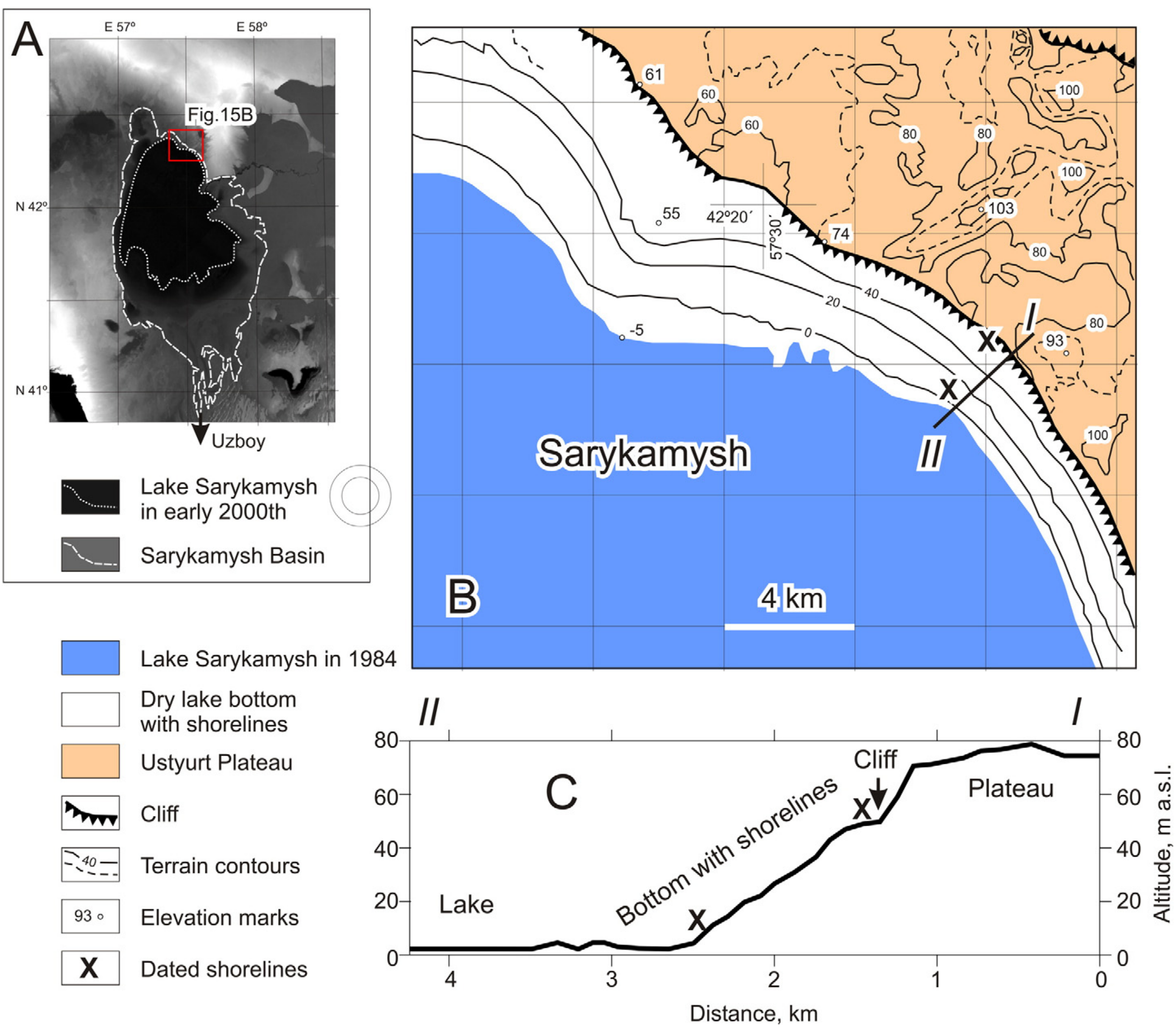

Fig. 15. The Sarykamysh Basin and Lake Sarykamysh: A — general SRTM DEM-based view; B — 1:200,000 scale map of the investigated area; and C — altitudinal profile along lines I–II.

Table 5
Radiocarbon dates from shells of Lake Sarykamysh shore bars.

Coordinates, dd	Elevation, m a.s.l	Lab code AA-	Date	$\delta^{13}C$, ‰	Calibrated age, BP
N 42.30148 E 57.57339	54	59345	1575 ± 30	−0.3	1410–1540
N 42.28557 E 57.56728	13	59346	1625 ± 30	+1.2	1430–1590

channels show (Table 4). Therefore, the ^{14}C dates support the idea of a gradual south to north shift of the Syr Darya deltaic channels.

In the delta of the Amu Darya River, the Akchadarya Channel functioned at least since the middle Holocene. The ^{14}C dates from the western part of the Akchadarya sub-delta suggest that it was active until ca. 0.7–1.1 ka cal BP. The ^{14}C dates (Table 4) highlight the activity of the Sarykamysh sub-delta, as discussed in the following section.

9. Lake Sarykamysh and Uzboy River

In contrast to the Akchadarya and Aral sub-deltas of the Amu Darya River which belong to the Aral Basin, the Sarykamysh sub-delta emptied into a separate basin of Lake Sarykamysh (Figs. 1 and 12). Therefore, discharge of the Amu Darya River into this basin implies significant loss of water for the Aral Sea. The peak water level of the Sarykamysh Basin is limited to an elevation of ca. 54 m a.s.l.,[6] which marks the level of a spillway to the Caspian Sea via the currently dry Uzboy River. As mentioned in ancient chronicles, the Uzboy used to be a navigable river (e.g., Bartold, 1902; Berg, 1908); and was of special interest to investigators from the times of Peter the Great (expedition of A. Bekovich-Cherkassky in AD 1716) to the present (e.g., Tolstov and Kes, 1960; Tolstov, 1962; Andrianov, 1969; Kes and Klyukanova, 1999). Morphometrics of the Uzboy River, Sarykamysh Basin, and their feeding Daudan and Kunya-Darya channels have been used to make water balance calculations that account for the partitioning of the Amu Darya waters. Létolle et al. (2007) concluded that ca. 10 km^3 of water per year flowed through the Uzboy out of the Sarykamysh Basin and that its inflow was in the range of 20–30 km^3 per year. This implies that the Amu Darya River with an annual runoff of 30–70 km^3 (56 km^3 on average) was never completely diverted into the Uzboy and at least part of its waters continuously fed the Aral Sea.

The Sarykamysh Basin has dimensions of 125 × 90 km, with a range in elevation from −38 to +58 m a.s.l. It can store about 250 km^3 of water,[7] i.e., 25% of the total capacity of the Aral Sea at its maximum level of 54 m a.s.l. Nowadays, Lake Sarykamysh collects agricultural runoff, ultimately from the Amu Darya River. Its artificial rise started in the early 1960s. In 1985 the lake reached level of −2.2 m a.s.l., an area of 3200 km^2, and a volume of 26.4 km^3 (Kes', 1991), and it continued to rise. Previously, the basin was dry. There were several saline lakes with a total volume of ca. 1 km^3 mapped in 1872–1876.[8] As for earlier times, researchers do not agree on evidence from European travelers of the sixteenth–seventeenth centuries AD because it is not certain that they crossed either the Aral Sea or Sarykamysh Lake on their way to Khorezm (e.g., Berg, 1908). The Amu Darya River evidently flowed to the Sarykamysh Basin from the early fifteenth century AD to AD 1573 (see Section 5). Water also reached the Sarykamysh Basin after the destructive wars of Genghis Khan (AD 1221) and Tamerlane (AD 1388). An unresolved question is whether Lake Sarykamysh rose to its maximum level in those times, or it remained at a low or intermediate level. Tolstov (1962) presented archeological evidence that determined the lower levels of Lake Sarykamysh in the Middle Ages, but some scholars speculate that the flow of the Amu Darya River was diverted from the Aral Sea to the Caspian Sea via Lake Sarykamysh and Uzboy as a result of military catastrophes (due to the destruction of dams which kept the river flowing into the Aral Sea).

Archeologists found that Lake Sarykamysh was full at ca. 5–4 ka cal BP because the upper reaches of the Uzboy were densely settled by ancient humans of the Neolithic Kelteminar Culture. Archeological data suggest that water flow in the Uzboy decreased during the following Bronze and Early Iron ages, at ca. 4–3 ka cal BP, and became insignificant in early antiquity (Tolstov, 1962). Since then, settlements of the Uzboy area relied on wells and not on the river. An exception was a short period in the fourth–fifth centuries AD when the river reappeared, and the Igdy-kala fortress (Fig. 12) was constructed, in order to control the water pass.

We visited the northeastern shore of Lake Sarykamysh in 2003, and found its level at an elevation of ca. 9 m a.s.l.[9] Our measured altitude of the basement of the Ustyurt Plateau cliff is 54 m a.s.l. Below the cliff, a more-or-less gentle slope, 2 km long, descends toward the lake with an overall height difference of ca. 45 m. There are more than 100 lake-shore bars on this slope that probably formed during the last retreat of the lake from its maximum level (Fig. 15). The 0.5–0.8 m high shore bars contain many shells of *Dreissena polymorpha* Pall., which allowed us to ^{14}C-date the bars. The samples were collected from the uppermost shore bar and one of the lowermost shore bars. The ^{14}C dates are almost identical (Table 5), and indicate that the last maximum level of Lake Sarykamysh finished at ca. 1.4–1.6 ka cal BP, i.e., fifth to sixth centuries AD. Therefore, our data support the conclusion of archeologists suggesting a probable discharge of the Amu Darya River waters via the Uzboy during the fifth century AD, and indicate a considerable drop of Lake Sarykamysh at the turn of the century. Later on, the lake level never rose above 9 m a.s.l., and its water never discharged to the Caspian Sea.

10. Conclusion: integrated reconstruction of the Aral Sea lake level changes

In this study, we used multiple lines of evidence to reconstruct the patterns of geological history of the Aral Sea as a model of possible future natural and human-induced ecological disasters in Central Asia and other arid regions on Earth. For this purpose, we combined data from geological (including geomorphological, sedimentological, paleontological, and radiocarbon methods), archeological, and historical sources. These data update our preliminary interpretation of Aral Sea lake level changes (Krivonogov et al., 2010b).

Fig. 16 summarizes all available data about the Aral Sea lake level changes during the last two millennia; brown blocks show low levels, and blue blocks show high levels. Gray bars indicate substantial lake level drops, and white spaces represent transgressions. These intervals are compiled from different datasets and are not identical, and gaps or inconsistencies can occur due to incomplete sedimentary records, obstacles in radiocarbon dating, and different responses of specific Aral Sea ecosystems to environmental changes. The data from sediment cores which provide consistent evidence for low levels tend to expand these intervals. The data from the Kerderi archeological cluster and its ^{14}C ages, historical records, data from outcrops and the Amu Darya River courses narrow these intervals. The narrowed intervals described by the data from the Kerderi sites obviously represent the lowest stand of the Aral Sea during the corresponding (late Middle Ages) regression, whereas the widened intervals inferred from the sedimentological data may more-or-less represent the whole regression. Moreover, we cannot

6 There are different estimates of the threshold for the Sarykamysh Basin. Berg (1908) used a value of 54 m a.s.l.; similarly, Saparov and Golubchenko (2001) measured it as 53 m a.s.l. Other scholars suggest a maximum water capacity of the basin in the past at the level of 58 m a.s.l. (Kes', 1991; Létolle et al., 2007).

7 Estimated with a help of the USGS SRTM DEM (digital elevation model).

8 The maps are available from the Cartographic Division of the Russian State Library, Moscow.

9 Our measurements of altitudes were made barometrically with the help of a Garmin GPS calibrated on the nearest topographic mark of 93 m a.s.l. (Fig. 15). We suggest ±1 m errors due to the precision of the device and instabilities in atmospheric pressure.

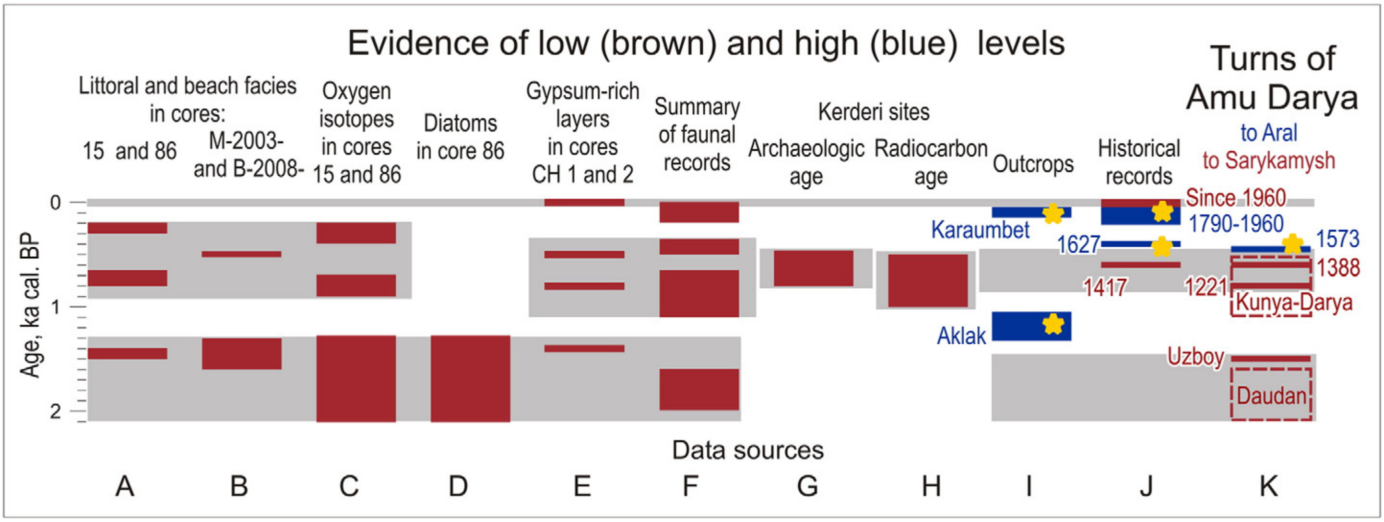

Fig. 16. Summary of available data related to Aral Sea lake level changes during the last 2000 years. Data sources: A — Maev et al. (1983), Sevastyanov et al. (1991), Maev and Karpychev (1999), and Ferronskii et al. (2003); B — Krivonogov et al. (2010a,b); C — Nikolaev (1991); D — Aleshinskaya (1991); E — Sorrel et al. (2006, 2007) and Austin et al. (2007); F — Boomer et al. (2009); G — Smagulov (2002), Boroffka et al. (2005a, 2006), Catalogue of monuments of the Kazakhstan Republic history (2007), Boomer et al. (2009), Sorokin and Fofonov (2009); H — Krivonogov et al. (2010a,b) and this paper; I — Reinhardt et al. (2008) and Krivonogov et al. (2010a,b); J — Bartold (1902) and Berg (1908); K — Tolstov and Kes (1960), Tolstov (1962), and this paper.

explain why the sedimentary and faunal records indicate dual low stands, and the other data suggests a single one during the late Middle Ages.

Therefore, the temporal limits for the regressions and transgressions remain inconclusive, and further studies are necessary. However, there are several dated levels in our discussed datasets which can be used to delimit these events (labeled by stars on Fig. 16). The outcrops at the Aral Sea shores clearly indicate two high stands at ca. 1.3–1.1 ka cal BP (Aklak) and 0.15–0 ka cal BP (Karaumbet). An onset of the last transgression is historically recorded: the turn of the Amu Darya River to the Aral Sea in AD 1573, the expansive Aral Sea in AD 1627, its high level in AD 1790–1960, and the modern drop since AD 1960.

These facts allow us to recognize the following Aral Sea lake level changes during the last two millennia. There were two deep regressions followed by the modern artificial regression since ca. 0.05 ka cal BP, and two intermediate transgressions. The regressions occurred at ca. 2.1–1.3 and 1.1–0.35 ka cal BP according to the sedimentary and faunal data, and 2.1–1.45 and 1.0 (0.85)–0.45 ka cal BP according to the other data. All these regressions were very deep. The Aral Sea level dropped to ca. 29 m a.s.l. in late Middle Ages similar to present conditions, and levels may have reached 10 m a.s.l. from late antiquity to the early Middle Ages. Intermediate transgressions are established with an inferred Aral Sea lake level of ca. 52 m a.s.l. for the middle Middle Ages, and an elevation of ca. 53 m for the sixteenth–twentieth centuries. The highest level of the last transgression could be as high as 54 m a.s.l., as the flooded ruins of the Puljai settlement indicate. According to currently available data, the duration of regressions is unclear. They could be longer than the transgressions or of equal duration. Reasons for past Aral Sea lake level changes proposed by previous investigators include both natural and human-related causes, as the region features more than 2000 years of agricultural activity. In any case, it is evident that during the last 2000 years the Aral Sea experienced several desiccations and related ecosystem impacts, and it subsequently recovered naturally through time.

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