ENVIRONMENTAL CHANGES OF THE ARAL SEA (CENTRAL ASIA) IN THE HOLOCENE: MAJOR TRENDS

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ABSTRACT. Changes of the Aral Sea level have been observed in 3 sediment boreholes, 2 outcrops, and associated archaeological sites. The obtained results are supported by 25 radiocarbon dates. Major trends of lake-level changes have been reconstructed in some detail for the last 2000 yr, and additional data provide an outline of fluctuations throughout the Holocene. Several distinct changes are shown to precede the modern, human-induced regression of the Aral Sea. These include: 1) the latest maximum in the 16th–20th centuries AD (53 m asl); 2) a Medieval "Kerderi" minimum of the 12th–15th centuries AD (29 m asl); 3) the early Medieval maximum of the 4th–11th centuries AD (52 m asl); and 4) a near BC/AD lowstand, whose level is not well established. Since then, events are only inferred from sparse data. The studied cores contain several sandy layers representing the lowering of the lake level within the Holocene, including the buried shore-bar of ~4500 cal BP (38 m asl), and shallow-water sediments of ~5600 cal BP (44 m asl), 7200 cal BP (28 m asl), and 8000 cal BP (26.5 m asl).

INTRODUCTION

The Aral Sea in Central Asia (Figure 1) was a large brackish water reservoir 50 yr ago, with abundant biota. Since the early 1960s, its level began to drop. In 2000, the area of the lake had decreased by a factor of 4, and the water volume declined to 10 times less than in the 1960s. The AD 2008 level is less than 30 m above the mean Baltic Sea level (hereafter asl). The Aral Sea is now broken into 3 shallow basins (Figure 1, shaded), and its southeastern part is about to disappear. This disastrous situation is usually attributed to the extensive use of water from the 2 major rivers that feed the lake, Amu Dar'ya and Syr Dar'ya, for irrigation (e.g. Middleton 2002). But did such environmental catastrophes occur previously or is this a unique phenomenon from our industrial era? In order to find the answer, a detailed study of past lake levels is required.

The fact that the Aral Sea is a notably changeable body of water became clear after the pioneering study by Berg (1908). He drew the first curve of the level fluctuations from the early 1900s to AD 1780, based on historical evidence and instrumental data. Later, this curve was extended to the early 2000s (Shermatov et al. 2004). According to these data, the range of lake-level changes throughout the last 200 yr (up to AD 1970 when the fast drop of the level began) was ~3 m. This shows the natural variability of the Aral Sea level during its transgressive phase, over the last 2 centuries, and before the 1960s.

Until the early 2000s, the main ideas about the development of the Aral Sea environment and changes in lake level were based primarily on geomorphologic, geological, biostratigraphic, and archaeological evidence (e.g. Veinbergs and Stelle 1980; Kes 1983; Shnitnikov 1983; Rubanov et al. 1987) that lacked geochronological control. In the 1970s, about 100 short cores (up to 4.5 m long) were taken from the Aral Sea bottom for lithological, paleontological, and ^{14}C studies. About 30 ^{14}C dates were obtained, mainly on bulk carbonates and organics (see Appendix). However, these results

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Proceedings of the 20th International Radiocarbon Conference, edited by A J T Jull
RADIOCARBON, Vol 52, Nr 2–3, 2010, p 555–568

https://doi.org/10.1017/S0033822200045598 Published online by Cambridge University Press

were unsuitable for paleoenvironmental purposes (e.g. Rubanov et al. 1987), and only data from sediment cores 15 (Maev et al. 1983) and 86 (Maev and Karpychev 1999) (see Figure 1) were used to understand the history of the Aral Sea (e.g. Ferronskii et al. 2003). Some data were obtained in the 2000s (e.g. Nourgaliev et al. 2003; Sorrel et al. 2006, 2007; see Appendix) and a consensus view of Holocene lake level was established (Tarasov et al. 1996:108–14; Boomer et al. 2000, 2009).

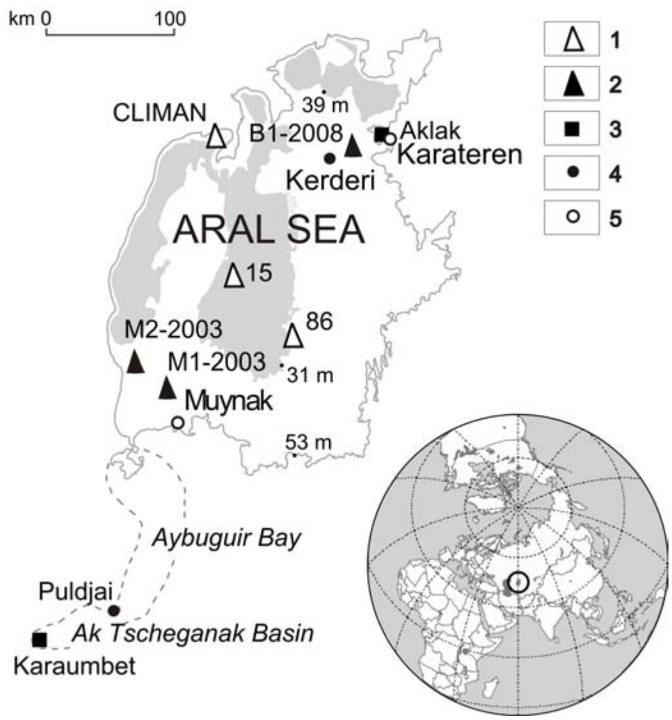

Figure 1 Location of the studied sites: 1-boreholes of previous investigators; 2-boreholes used in this study; 3-outcrops; 4-archaeological sites; 5-towns. Dots with numbers indicate former and recent (AD 2008) lake levels.

Analysis of previous research shows that the chronological framework of the Aral Sea environmental changes in the Holocene is unsatisfactory by modern standards (e.g. van de Plassche 1986). Our research addresses the need to establish a firm chronology for the Aral Sea lake level, which reflects the ecosystem's response to natural and anthropogenic factors, and identifies significant paleoenvironmental events such as transgressions and regressions.

MATERIAL AND METHODS

Basic data about the Aral Sea changes used in this study come from boreholes drilled on the dry bottom of the lake, outcrops on the former shore, and archaeological sites (Figure 1). Three boreholes were obtained in the northern and southern parts of the basin (Table 1). The sediments are of lacustrine origin, and the entire length of the core contains mollusk shells, foraminifers, and ostracods. The facies structure of deposits is quite complicated, and it reflects the sedimentation conditions determined mainly by lake-level fluctuations. Both transgressive and regressive facies are well recognized in the cores (e.g. Svitoch 2009): the transgressive sediments consist of monotonous silts, and the regressive ones of silty sands and sands. Sandy layers were accumulated in shallow water nearshore conditions and in some cases represent beach-ridges.

Table 1 Cores of the Aral Sea bottom sediments used in this study.

Core ID	Latitude (N), longitude (E)	Altitude (m asl)	Core length (m)	Suggested ^{14}C age of bottom of core (yr BP)	Source
B1-2008	45°53′N, 60°43′E	39.0	11.0	20,000[a]	Krivonogov, this study
M1-2003	43°55′N, 58°41′E	50.0	8.2	6000	Krivonogov, CLIMAN Project
M2-2003	44°17′N, 58°19′E	36.0	20.0	9000	
86[b]	44°25′N, 59°59′E	30.0	4.08	6000	Maev et al. 1983; Maev and Maeva 1991
15[b]	~75 km NNW of Core 86	27.0	3.7	12,000	
CH1 and CH2	45°58′N, 59°14′E	7.2	11.04 (CH1), 6.0 (CH2)	1600	Austin et al. 2007; Sorrel et al. 2007
Ar7, Ar8, and Ar9	45°58′N; 59°14′E (approximately)	8.8 (Ar7); 6.3 (Ar8); 6.5 (Ar9)	~6.0	1200	Nourgaliev et al. 2003

[a]Bottom of the lacustrine sediments at 7 m depth.
[b]Data from Tarasov et al. (1996).

Using these sedimentological criteria, we determined Aral Sea levels as higher than the hypsometric position of sediments (clays and silts) or proximal to the elevation of nearshore deposits (sands). The low levels of the lake should be reflected as stratigraphic hiatuses, although we cannot visually identify them in the studied cores. The elevation of each core was determined using standard GPS equipment, using a digital model of the Aral Sea bottom topography inferred from a navigational map (scale 1:200,000). We employed a simple model for the filling of the Aral Sea depression with sediments, without taking into account possible tectonic movements. The AD 1960 level of the Aral Sea (~53 m asl) served as a reference elevation.

In Core M1-2003, 4 layers were determined: 2 transgressive and 2 regressive stages (Figure 2). In Core M2-2003, sand layers are found only in the middle part of the 20-m sequence, at depths of 7.2 and 8.5–9.4 m (Figure 2). Core B1-2008 has a complex structure, with 6 sand layers of different thickness (Figure 2). In the regression layers, the mollusk shells are usually plentiful, and this allows us to use them for accelerator mass spectrometry (AMS) ^{14}C dating. Mainly, the shells of *Cerastoderma glaucum* Poiret (formerly *Cardium edule* L.) were ^{14}C dated. Some samples were represented by gastropod *Caspiohydrobia* Starobogatov shells and ostracods collected after paleontological study of the core with special care to prevent their contamination by modern organics. Dating of shells follows a routine AMS protocol for carbonates (e.g. Kuzmin et al. 2007). Samples were analyzed at the NSF-Arizona AMS Laboratory (University of Arizona, Tucson, Arizona, USA; lab code AA). The ^{14}C dating of wood and animal bones from archaeological sites was performed at the Institute of Geology & Mineralogy (Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia; lab code SOAN). Bone samples underwent standard collagen extraction procedures, and wood samples were subjected to acid-base-acid pretreatment. Dates were then obtained by liquid scintillation counting (e.g. Kuzmin and Orlova 2004). Calibration of the raw ^{14}C values was done with the help of the CALIB 6.0 program (www.calib.org) using the IntCal09 calibration data (Reimer et al. 2009), with a reservoir age correction of $\Delta R = -128 \pm 53$ yr for mollusk shells (Kuzmin et al. 2007:465). All calibrated values are $\pm 2\ \sigma$ and rounded to the next 10 yr (Tables 2–3).

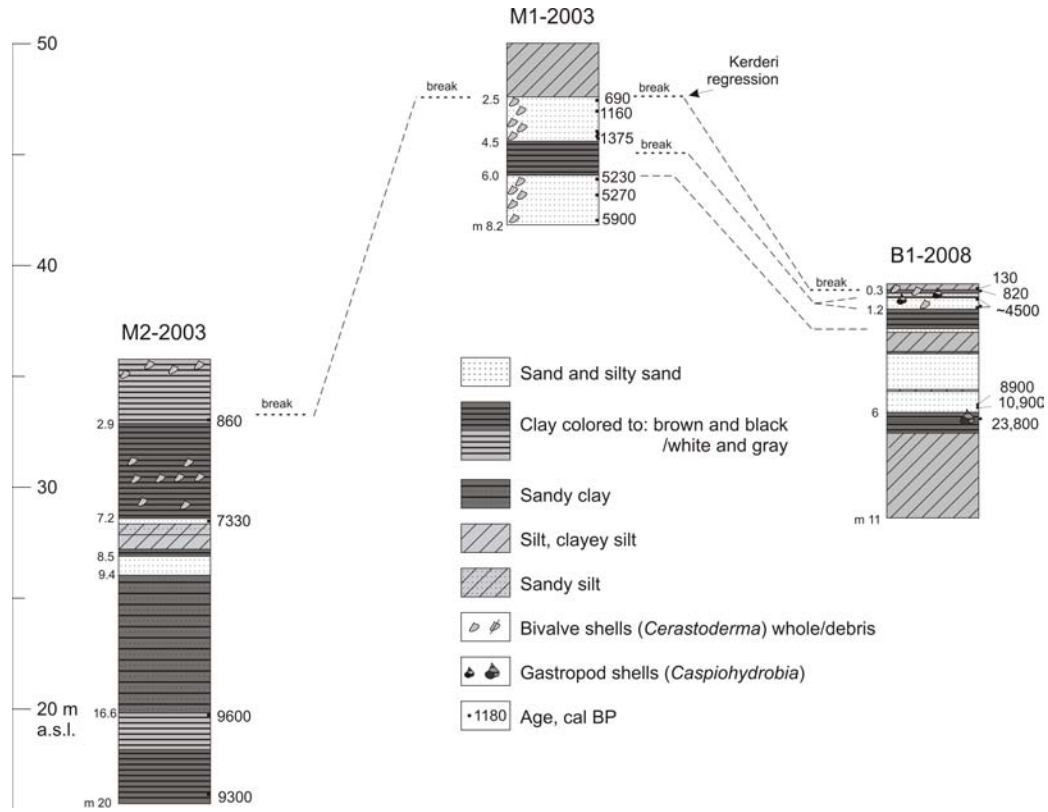

Figure 2 Boreholes used in the study (lithology and age) (see Tables 1–2). Ages are given as average values of the calibrated time intervals.

The evidence for lake highstands was studied in coastal outcrops (Figure 1). The Karaumbet section (43°07′N; 58°15′E) is 150 km from the AD 1960 Aral Sea shoreline, in the southern part of its former bay, recorded by Butakoff (1853) as Aybuguir or Laudan and now referred to as Ak Tscheganak. Here, salt deposits occur at an elevation of about 38–40 m asl; a well-preserved shoreline marks the maximal transgression at ~54 m asl. This 3-m-thick section of lake deposits is visible in the wall of a small creek. The elevation of the top of the Karaumbet section is ~45 m asl. Two layers with abundant *Cerastoderma glaucum* shells, at depths of 0.5 and 2 m (elevations of ~44.5 and ~43 m asl, respectively) were observed. These sediments are separated by both lacustrine and nearshore deposits (Reinhardt et al. 2008). Another locality with transgressive deposits is on the bank of the Syr Dar'ya River ~15 km upstream from the AD 1960 mouth (46°01′N; 61°03′E). Here, the Aklak Dyke is being built (Figure 1). Due to the artificial lowering of the Sur Dar'ya level to ~50.5 m asl, deltaic and underlying lacustrine sediments were exposed. The top of the lacustrine stratum shows that the level was ~52 m asl.

The pre-modern regression is detected by archaeological sites on today's dry bottom of the Aral Sea. Archaeologists have discovered 2 sites, Kerderi I and Kerderi II (Smagulov 2001, 2002), located east of the former Barsa-Kel'mes Island (Figure 1). These sites are located ~60 km from the AD 1960 shoreline at an elevation of ~34 m asl. During the last transgression, they were covered by ~20 m of water. The Kerderi II site includes a settlement and mausoleum (or *mazar* in local terminology), spaced 4.5 km apart. The archaeological age determination of these sites varies: the end of the 13th–14th centuries AD (Smagulov 2002); 15th–16th centuries AD (Boroffka et al. 2005); 14th–

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Table 2 ^{14}C dates for the boreholes and outcrops of the Aral Sea region used in this study.

Depth (cm)	Material	Lab nr (AA-)	Uncalib-rated date (yr BP)	δ^{13}C (‰)	Calibrated age (cal yr BP)	Water level (m asl)	Trend of the level change
Core M1-2003 (50 m asl)							
260–270	Shell of *Dreissena*	59339	1010 ± 30	+1.0	560–820	47.4	Regressive
310–320	Shell of *Cerastoderma*	59340	1485 ± 30	+1.1	1030–1290	>46.9	Transgressive
400–410	Shell of *Cerastoderma*	61833	1330 ± 40	+1.1	880–1180	>46	Transgressive
420–430	Shell of *Cerastoderma*	61834	1580 ± 40	+0.9	1110–1400	>45.8	Transgressive
430–440	Shell of *Cerastoderma*	61835	1675 ± 40	+0.2	1240–1510	>45.7	Transgressive
620–630	Shell of *Cerastoderma*	59342	4790 ± 40	–0.9	5030–5430	>43.8	Transgressive
690–700	Shell of *Cerastoderma*	59343	4840 ± 40	+0.3	5070–5470	>43.1	Transgressive
800–810	Shell of *Cerastoderma*	59344	5385 ± 40	+0.6	5720–6080	>42	Transgressive?
Core M2-2003 (36 m asl)							
280–292	Shells of ostracods, gastropods	83691	1190 ± 60	+0.9	690–1030	>33.2	Regressive
720–752	Shells of ostracods	83690	6690 ± 80	–2.7	7150–7510	28.8	Unclear
1660–1672	Shells of ostracods	83689	8740 ± 95	–3.3	9300–9870	>>19.4	Unclear
1880–1892	Shells of ostracods, gastropods	83688	8545 ± 95	–3.2	9050–9530	>>17.2	Unclear
Core B1-2008 (39 m asl)							
25–27	Shell of *Cerastoderma*	83393	385 ± 35	+2.7	0–260	>38.75	Transgressive
31–32	Shells of *Caspiahydrobia*	83394	1155 ± 35	+1.0	690–950	38.7	Regressive
69	Shell of *Cerastoderma*	83396	4240 ± 45	+1.5	4340–4770	38	Unclear (distinct beach-ridge)
100–110	Shells of *Cerastoderma*	83397	4225 ± 35	+1.5	4300–4710		
118	Shells of *Cerastoderma*	83398	4200 ± 40	+0.5	4260–4680		
560–570	Terrestrial plant remains	86200	8030 ± 130	–25.4	8560–9290	34	About stable
570–580	Terrestrial plant remains	86199	9590 ± 120	–25.8	10,590–11,220		
634	Shell of a gastropod (broken)	83399	19,900 ± 140	–1.6	23,370–24,240	>>33.6	Deep water
Karaumbet outcrop (45 m asl)							
45–50	Shells of *Cerastoderma*[a]	Poz-?	300 ± 30	—	0–150	44.5	Regressive
201–210	Shells of *Cerastoderma*[a]	Poz-?	1805 ± 30	—	1330–1640	43	Transgressive
210	Shells of *Cerastoderma*	59338	1715 ± 30	–0.3	1270–1520	43	Transgressive
Aklak outcrop (54.5 m asl)							
250	Shell of *Cerastoderma*	83390	1510 ± 35	+1.1	1050–1310	52	About the highest level

[a]Dates produced at the Poznań Radiocarbon Laboratory, Poland (Reinhardt et al. 2008); δ^{13}C values not given.

Table 3 ^{14}C dates from the Kerderi II archaeological sites.

Site	Material	^{14}C date (yr BP)	Lab nr (SOAN-)	Calibrated age (cal AD)	Calibrated age (cal BP)
Mausoleum Kerderi II	Thin wood stick	600 ± 65	7688	1280–1430	670–520
Mausoleum Kerderi II	Thick wooden plank	820 ± 55	7687	1150–1280	800–670
Settlement Kerderi II	Domestic animal bones	910 ± 80	7686	990–1260	960–690

early 15th centuries AD (Boroffka et al. 2006); and 13th–14th centuries AD (Boomer et al. 2009). We ^{14}C dated bones of domestic animals (cow, horse, and sheep/goat) from the Kerderi II settlement and pieces of wood from the Kerderi II mausoleum.

RESULTS

Changes of the Aral Sea Level According to the Data from Boreholes

The results of AMS ^{14}C dating of samples from 3 cores are given in Table 2. The correlation of sediments based on these data is shown on Figure 2. For Core M1-2003, 2 events of relatively stable

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lake level are detected at ~690–1380 cal BP (47 m asl; depth in core 2.5–4.5 m) and ~5200–5900 cal BP (44 m asl; depth in core 6.0–8.1 m); each of them persisted for ~700 yr. The clays between these 2 layers reflect relatively high lake levels that lasted for approximately 4000 yr. The uppermost silt layer is younger than ~700 cal BP and corresponds to the latest transgression.

In Core B1-2008, the upper layer (0.0–0.3 m depth) accumulated since ~130 cal BP. In the interval of 0.3–0.7 m dated to about 800–4500 cal BP, 2 highstands are recognized; they are separated by shallow water events with lake levels of ~38.5 m asl, unfortunately not constrained with ^{14}C dates. Below the depth of 0.7 m, there is layer 0.5 m thick with shells of *Cerastoderma glaucum*, and the ^{14}C values are very uniform throughout it. This can be interpreted as an ancient beach-ridge that was deposited instantaneously in a geological sense. In this case, it shows that the lake level ~4500 cal BP was at ~38 m asl. This ridge provides evidence that the deep-water sediments in Core M1-2003 dated to about 1380–5200 cal BP do not belong to a single transgressive phase with a level above 50 m asl but are separated by at least 1 regression at ~4500 cal BP. However, it is impossible to detect this event in the monotonous sequence of the core, and the hiatus is thus obscured.

An age of about 8900–10,900 cal BP was determined from plant remains in the interval 5.6–5.8 m in the core B1-2008. The value of ~19,900 BP is generated on a thin-walled shell of a large (1.5 cm diameter) gastropod unexpectedly cut by knife in the process of the core splitting, which did not allow to identify its species. The gastropod was placed vertically, probably in living position, in the brown clays, which possibly correspond to the transgressive phase, and were accumulated during the Last Glacial Maximum. Below are dense clays and silts of brownish and bluish colors with scattered gypsum crystals, and this is suggested to be a basal layer of non-lacustrine origin.

Core M2-2003 is taken at the lowest modern elevation among the studied boreholes (Figure 1; Table 1). Clay sediments prevail in this core and show that 20 m of deposits were accumulated in deep-water conditions. However, 2 sandy layers at depths of 7.2–7.33 and 8.5–9.4 m reflect deep regressions down to levels of ~28 and ~26 m asl, respectively. The upper sandy layer is ^{14}C dated to ~7300 cal BP. The base of this core is ^{14}C dated to ~9500 cal BP.

The High Aral Sea Levels as Seen from Data on the Outcrops

In the Karaumbet section, the lower layer with mollusk shells dates to about 1300–1600 cal BP (Table 2). This coincides with the highstand of the lake level recorded in Core M1-2003 dated to ~1400 cal BP. The upper layer with shells has a date of 0–150 cal BP, and this is evidence of the latest transgression. However, in the southernmost part of the Aral Sea basin the situation was different from the rest of the lake. The Puldjai settlement (elevation ~53–51 m asl) east of Karaumbet is dated to the 13th–14th centuries AD (Boroffka et al. 2006; Reinhardt et al. 2008). It was flooded by the Aral Sea during the last transgression, and the Aybuguir Bay appeared. Later on, it was separated from the main body of the Aral Sea and turned into a shallow freshwater basin with many reeds; the source of water was the Amu Dar'ya River. This description is known from early sources (Berg 1908). It seems that later the Ak Tscheganak Basin parted from the Aybuguir Bay and became an isolated saltwater body. According to the geological mapping done in AD 1917 (Arkhangelski and Churakov 1930), the level of Ak Tscheganak Basin was ~48 m asl. The remote sensing data of AD 1962 show that it was completely dry (Reinhardt et al. 2008). Therefore, the upper layer with shells in the Karaumbet section corresponds to a time of shrinking of the Ak Tscheganak Basin in the first part of the 20th century.

In the Aklak section (northern Aral Sea), evidence of the transgression above the level of 52 m asl is found, and its age is about 1100–1300 cal BP (Table 2), roughly corresponding to the final part of the first highstand in the Karaumbet section. In Core B1-2008, this event is expressed as deep-water sediments below a depth of 0.3 m. The top of these deposits has an age of 690–950 cal BP (Figure 2). This event is also detected in Core M2-2003. Some discrepancy exists in Core M1-2003, where the transgression of about 1100–1300 cal BP falls within a layer of shallow-water sands dated to 690–1375 cal BP (Figure 2), and the level for this period is estimated as close to 47 m asl. Perhaps such a level was more common for this time interval, but this does not exclude the possibility of a higher level, at 52 m asl.

Summing up the data from outcrops, we can determine a transgressive event at about 1100–1600 cal BP, and it was as high as the latest one. Although we do not see evidence of the latest ("historic") transgression in the studied outcrops, except for the uppermost layer in the Karaumbet section, historical data summarized by Bartold (1902) and Berg (1908) show that it lasted from the end of the 16th century AD to the middle of the 20th century AD, with a peak in the 16th–17th centuries AD.

The Kerderi Regression and Its Age

^{14}C dating of the Kerderi II settlement and mausoleum (Table 3) gave ages that are older than archaeological estimates (see above). Pieces of wood overlying the sarcophagus in the burial chamber of the mausoleum were ^{14}C dated. A thin wooden stick dates to the 13th–15th centuries AD, while a thicker plank is older, within the 12th–13th centuries AD. The difference could be either due to inherited age of the thicker wood fragment or the repeated use of older wood for construction in the treeless region. The age of animal bones from the Kerderi II settlement is even older, in the 10th–13th centuries AD (Table 3). However, all ages nearly overlap. The possibility remains that the settlement is about a century older than the mausoleum. Therefore, this very deep regression (deeper than 34 m asl) is dated to the early Middle Ages, 10th–15th centuries AD. The beginning of the Kerderi regression may be estimated using data from the B1-2008 and M1-2003 cores where the end of the preceding transgressive phase is dated to 690–950 and 560–820 cal BP, respectively.

The scale of the Kerderi regression is equal to the modern stage of the lake degradation (Boomer et al. 2009). The latest data show that people could settle the dry bottom of the Aral Sea because the Syr Dar'ya River was flowing nearby. It developed a new channel, in excess of 100 km, and an extensive delta that has extended to the western side of the Aral Sea bottom (Krivonogov 2009). According to the position of this ancient delta, the level could be as low as 29 m asl. The existence of a large delta is also consistent with the relative longevity of the Aral Sea lowstand in the Middle Ages. Therefore, we can assume that the Kerderi regression persisted for 200–300 yr, most probably in the 12th–15th centuries AD.

DISCUSSION

Resume of Previous Studies of the Aral Sea History

Modern progress in research aimed at understanding the Holocene history of the Aral Sea began in the late 1960s to early 1970s and resulted in a series of summary papers (e.g. Tarasov et al. 1996; Boomer et al. 2000, 2009). A number of ^{14}C dates were generated from coastal outcrops and boreholes (see Appendix). These results allowed general conclusions to be drawn indicating that the modern Aral Sea existed since at least ~7000 BP (e.g. Maev et al. 1983; Maev and Karpychev 1999; Ferronskii et al. 2003) and experienced significant variations in water level. However, these findings did not provide much information about environmental change during the Holocene. The number of mollusk ^{14}C dates substantiating the age model for cores 15 and 86 (Maev et al. 1983; Maev and Karpychev 1999) is small, and hence the reliability of the reconstructions based on it is therefore low, providing only qualitative information (see Tarasov et al. 1996).

The most important result of previous investigations for our purposes is the establishment of lowstands of the Aral Sea level. For example, Maev et al. (1983) dated an *in situ* saxaul tree stump to ~970 BP (Appendix), which shows that the lake level was lower than in AD 1980. A similar specimen was obtained at the Butakov Bay and dated to ~280 BP, indicating a level below ~40 m asl (Appendix). Some highstands of the Aral Sea level were also suggested (e.g. Maev et al. 1983; Tarasov et al. 1996:108–14; Boomer et al. 2000, 2009).

^{14}C dating of bulk carbonates and dispersed organic matter from cores gives unreliable results (Kuptsov 1985; Kuptsov et al. 1982; Maev and Karpychev 1999; see Appendix). This is especially clear for relatively big samples needed for liquid scintillation counting, which yield ^{14}C dates with large uncertainties. These values were later rejected (Ferronskii et al. 2003). It was concluded that the most reliable material for ^{14}C dating in sediment cores are mollusk shells, mainly *Cerastoderma glaucum* (e.g. Ferronskii et al. 2003).

One of the latest research campaigns took place in the early 2000s under the CLIMAN Project funded by the INTAS Foundation (European Union), which focused on Holocene climatic variability and the evolution of human settlements in the Aral Sea basin. New data reflecting environmental changes in the Aral Sea region over the last 2000 yr were obtained (Nourgaliev et al. 2003; Boroffka et al. 2005, 2006; Sorrel et al. 2006, 2007; Oberhähsli et al. 2007; Reinhardt et al. 2008). However, ^{14}C results from these studies were inconsistent (Sorrel et al. 2006:308).

The Aral Sea level curves obtained by different authors are shown in Figure 3. The general correspondence of results from Tarasov et al. (1996) and Boomer et al. (2000) may be explained by their use of the same original sources. They are different, however, from the curves of Boomer et al.

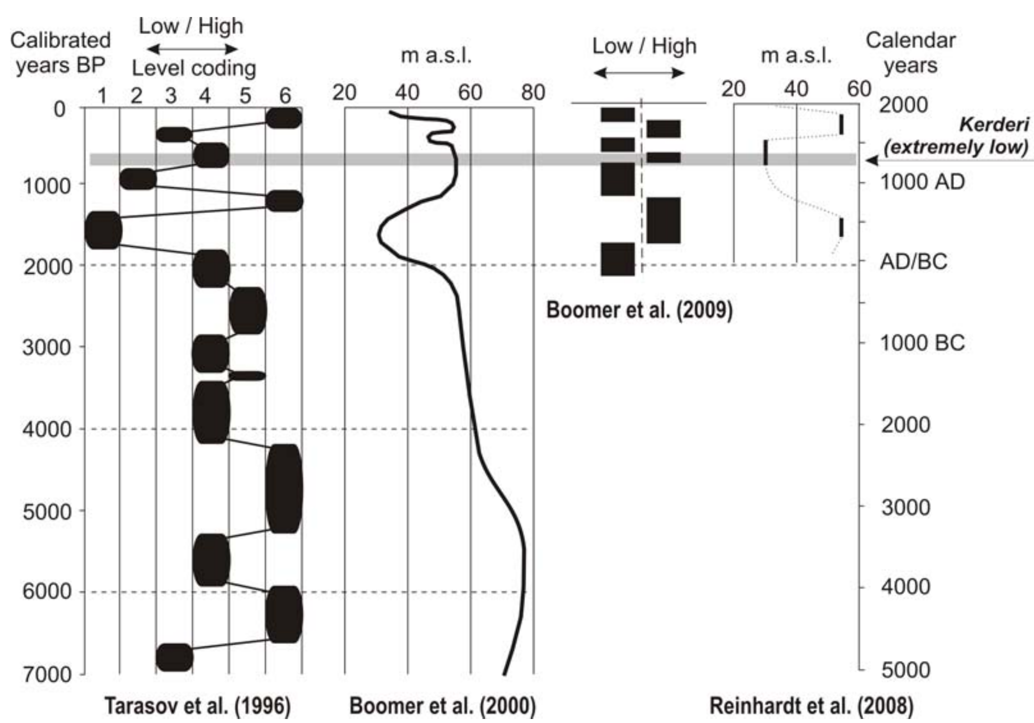

Figure 3 Fluctuations of Aral Sea level in the Holocene (according to different authors)

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(2009) and Reinhardt et al. (2008) based on more recent materials. Nevertheless, the newer data remain inconsistent, and the differences are likely due to the methodologies employed. Boomer et al. (2009) applied mainly paleontological techniques, while Reinhardt et al. (2008) used geomorphological and sedimentological approaches.

Current Problems in the Study of the Holocene History of Aral Sea

Our tentative knowledge about the fluctuations of the Aral Sea level is summarized in Figure 4. There are a number of problems that hamper precise conclusions. The degree of reliability is not high enough; only the curve for the last 2000 yr is based on good quality data with a high sampling density. It is very similar to the results obtained by Reinhardt et al. (2008) (Figure 3). Going further into the past (from about BC/AD onwards), we have records of some events that are securely established, but they do not yet constitute a unified framework. There is some resemblance with the curve by Tarasov et al. (1996) (Figure 3), but the chronologies of all of the major events are shifted significantly.

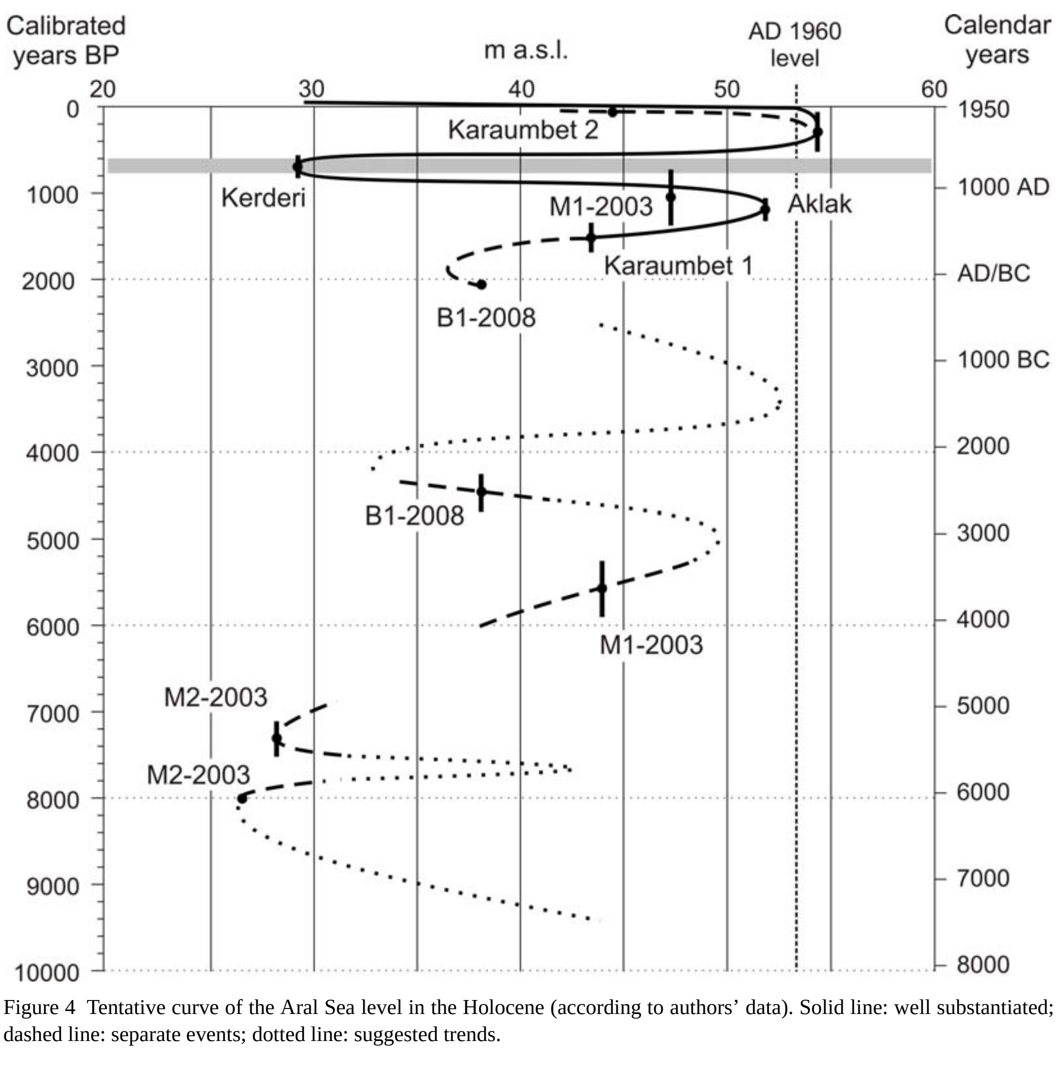

Figure 4 Tentative curve of the Aral Sea level in the Holocene (according to authors' data). Solid line: well substantiated; dashed line: separate events; dotted line: suggested trends.

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The core results demonstrate the utility of the approach for identifying and dating transgressive events. It is very hard to detect regressive phases as they produce hiatuses in the sediment cores. Still, it is possible to infer their existence and place boundaries on their timing. Although the study of deep regressions remains a serious problem, the Kerderi regression (e.g. Krivonogov 2009) is an exception.

The complexity of sedimentation processes in such a changeable reservoir as the Aral Sea is reflected in the numerous facies changes that are impossible to correlate by the study of a few individual cores. Also, layer counting for correlation is not possible due to incomplete sequences, especially where regression events and shifting layer boundaries obscure evidence for a particular facies. This is quite significant for the centennial timescale that we are trying to establish. Increasing the number of reliable ^{14}C dates is perhaps the best tool to reconstruct spatial changes of the Aral Sea level through time.

CONCLUSION

The understanding of Holocene fluctuations of the Aral Sea is far from complete. We can reliably reconstruct events for the last 2 millennia, including 2 transgressive and 2 regressive phases. Transgressions occurred in the 6th–12th and the 16th–20th centuries AD; the regressions can be dated to the 13th–14th centuries AD (Kerderi) and since the mid-20th century AD. Further into the past, we can only detect broad changes, including a lake level below 40 m asl at ~2000 and 4500 cal BP; and below 30 m asl at ~7500 and 8000 cal BP. For the time interval of ~4500–20,000 cal BP, there was no less than 4 regressive episodes down to 20–36 m asl, but the timings of these events are not yet firmly established.

The discrepancy between our data and results of previous research may well be related to the insecure methods of dating in the past and a lack of calibrated ^{14}C dates using an appropriate δ^{13}C and reservoir age correction factors. In order to obtain reliable data, drilling of the dry bottom of the Aral Sea and its extensive ^{14}C dating are necessary. This will allow us to compile geological profiles and to recognize facies structures of the lake deposits.

ACKNOWLEDGMENTS

We are grateful to the staff of the Arizona AMS Laboratory for assistance with AMS ^{14}C dating of the shell samples. We are also thankful to Dr S K Vasiliev (Institute of Archaeology & Ethnography, Siberian Branch of the Russian Academy of Sciences, Novosibirsk) for identification of the animal bones from the Kerderi II site; Dr L A Orlova (Institute of Geology & Mineralogy, Siberian Branch of the Russian Academy of Sciences, Novosibirsk) for ^{14}C dating of the Kerderi II specimens; and the staff of the Barsa-Kel'mes Natural Reserve for logistic support. Prof S Stine (California State University, Hayward, California, USA) provided information for one of the ^{14}C dates. This study is supported by the CRDF–RFBR Project "Environmental history of the Aral Sea in the last 10,000 years: natural and anthropogenic components" (RUG1-2921-NO-07 and 08-05-91105), Programs of the Russian Academy of Sciences (nos. 15, 17), and by the US NSF (0010835000 and EAR06-22305).

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Appendix ^{14}C dates from the Aral Sea region obtained prior to 2008.

Locality	^{14}C date (BP)[a]	Lab nr	Material dated	Source[b]
Kulandy Spit	920 ± 120	LG-?	Mollusk shells[c]	[1]
Core 281	3700 ± 600[1,d]	IOAN-125	Total carbonates	[2]
	1160 ± 290[1]	IOAN-139	Total organics	
	7980 ± 100[2]	IOAN-110	Total carbonates	
	6040 ± 330[2]	IOAN-119	Total organics	
	6300 ± 330[2]	IOAN-118	Wood	
Core 280	4740 ± 120[3]	IOAN-116	Total carbonates	[2]
	2950 ± 180[3]	IOAN-137	Total organics	
	5100 ± 200[4]	IOAN-113	Total carbonates	
	5560 ± 460[4]	IOAN-134	Total organics	
	10900 ± 130	IOAN-111	Total carbonates	
Core 293	2130 ± 280	IOAN-123	Total organics	[2]
	1770 ± 130[5]	IOAN-115	Total carbonates	
	1870 ± 160[5]	IOAN-135	Total organics	
Core 292	210 ± 270	IOAN-124	Total organics	[2]
	6900 ± 90[6]	IOAN-112	Total carbonates	
	2740 ± 110[6]	IOAN-122	Total organics	
Core 15	1590 ± 140	MGU-778	Mollusk shells[c]	[3]

Appendix ^{14}C dates from the Aral Sea region obtained prior to 2008. *(Continued)*

Locality	^{14}C date (BP)[a]	Lab nr	Material dated	Source[b]
	3610 ± 140	MGU-742	Mollusk shells[c]	
	4846 ± 90	MGU-741	Mollusk shells[c]	
	4956 ± 100	MGU-740	Mollusk shells[c]	
Lazarev Island[e]	970 ± 140	MGU-734	Wood	[3]
Core 75	4970 ± 110	IOAN-1784	Total organics	[4]
Core 110	18,340 ± 310	IOAN-1781	Total carbonates	[4]
Core 47	2870 ± 80	IOAN-1785	Total carbonates	[4]
	5570 ± 110[7]	IOAN-1782	Total carbonates	
	4930 ± 180[7]	IOAN-1783	Total organics	
Core 49	2030 ± 100[8]	IOAN-1375	Total carbonates	[4]
	0 ± 175[8]	IOAN-1738	Total organics	
	5690 ± 220[9]	IOAN-1376	Total carbonates	
Core 39	4930 ± 180	IOAN-1783	Total organics	[4]
Core 76	12,250 ± 1100	IOAN-1786	Total carbonates	[4]
Syr Dar'ya River mouth[f]	12,580 ± 370	IOAN-1839	Total carbonates	[4]
Amu Dar'ya River mouth[f]	12,820 ± 210	IOAN-1840	Total carbonates	[4]
Core 93	1200 ± 200	MGU-876	Mollusk shells	[5]
Section Kulandy	730 ± 80	Ri-?	Mollusk shells[c]	[6]
	745 ± 80	Ri-?	Mollusk shells[c]	
Kulandy Spit	2860 ± 80	Ri-?	Mollusk shells[c]	[6]
Core 86	4760 ± 220	IVP-262	Mollusk shells[c]	[7]
	740 ± 120[10]	IVP-246	Total carbonates	[8]
	340 ± 160[10]	IVP-281	Total organics	
	3760 ± 100	IVP-247	Total carbonates	
	1435 ± 100	IVP-280	Total organics	
	2760 ± 100[11]	IVP-248	Total carbonates	
	720 ± 120[11]	IVP-286	Total organics	
	3480 ± 120	IVP-249	Total carbonates	
	3280 ± 100[12]	IVP-250	Total carbonates	
	1760 ± 300[12]	IVP-292	Total organics	
	3160 ± 120[13]	IVP-251	Total carbonates	
	1240 ± 250[13]	IVP-295	Total organics	
	2130 ± 180	IVP-294	Total organics	
	1480 ± 150	IVP-285	Plant organics	
	2480 ± 100	IVP-252	Total carbonates	
	3200 ± 120[14]	IVP-253	Total carbonates	
	1810 ± 250[14]	IVP-293	Total organics	
	3500 ± 100	IVP-254	Total carbonates	
	4540 ± 100	IVP-258	Total carbonates	
	3080 ± 80	IVP-273	Plant organics	
	6760 ± 180	IVP-255	Total carbonates	
	5480 ± 80	IVP-259	Total carbonates	
	8000 ± 150[15]	IVP-261	Total carbonates	
	4080 ± 180[15]	IVP-260	Mollusk shells[c]	
	7330 ± 220[16]	IVP-256	Total carbonates	
	4280 ± 250[16]	IVP-296	Total organics	

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Appendix ^{14}C dates from the Aral Sea region obtained prior to 2008. *(Continued)*

Locality	^{14}C date (BP)[a]	Lab nr	Material dated	Source[b]
	5940 ± 150[17]	IVP-257	Total carbonates	
	4910 ± 250[17]	IVP-297	Total organics	
	4760 ± 220	IVP-268	Mollusk shells[c]	
	7290 ± 100[18]	IVP-270	Total carbonates	
	7070 ± 120[18]	IVP-271	Total organics	
	6680 ± 150[19]	IVP-259	Total carbonates	
	5190 ± 150[19]	IVP-258	Mollusk shells[c]	
	7170 ± 100[20]	IVP-272	Total carbonates	
	6040 ± 390[20]	IVP-287	Total organics	
	6620 ± 100[21]	IVP-382	Total carbonates	
	5700 ± 390[21]	IVP-289	Total organics	
Core 45	4230 ± 80	IVP-275	Total carbonates	[8]
	9500 ± 300	IVP-277	Total carbonates	
	5450 ± 150[22]	IVP-283	Total carbonates	
	1570 ± 100[22]	IVP-285	Total organics	
Core Ar-8	450 ± 100	ETH-?	Macrofossils	[9]
	480 ± 120	ETH-?	Macrofossils	
	655 ± 65	ETH-?	Macrofossils	
	1095 ± 125	ETH-?	Macrofossils	
	1145 ± 35	ETH-?	Macrofossils	
	1495 ± 125	ETH-?	Macrofossils	
	1470 ± 110	ETH-?	Macrofossils	
Core Ar-9	1145 ± 135	ETH-?	Macrofossils	[9]
	1310 ± 90	ETH-?	Macrofossils	
South part of Butakov Bay[g]	287 ± 5[h]	?	Wood	[10]
Core CH2/1	4860 ± 80[i]	Poz-4760	Green algae	[11]
	1540 ± 30[i]	Poz-4756/59	Green algae	
	730 ± 30[i]	Poz-1351	Total organics	
	1395 ± 30	Poz-4762	Green algae	[11–12]
	1480 ± 30	Poz-9662	Mollusk shells	
	1521 ± 40[i]	Poz-4764	Green algae	[11]
	1515 ± 25	Poz-4760	Green algae	[11–12]
Core 82	685 ± 33	KIA-18247	Water plants	[13]
	705 ± 38	KIA-18248	Water plants	
Core in Butakov Bay	380 ± 40	?	Plant macrofossils	[14]
Core AR01-3	4421 ± 55	?	Mollusk shells[c]	[14]

[a]In sediment cores, the ^{14}C ages are given according to depth (from top to bottom).

[b]Original sources indicated by numbers: [1]–Gorodetskaya (1978); [2]–Kuptsov et al. (1982); [3]–Maev et al. (1983); [4]–Kuptsov (1985); [5]–Parunin et al. (1985); [6]–Veinbergs (1986); [7]–Tarasov et al. (1996); [8]–Maev and Karpychev (1999); [9]–Nourgaliev et al. (2003); [10]–Boroffka et al. (2005); [11]–Sorrel et al. (2006); [12]–Sorrel et al. (2007); [13]–Filippov and Riedel (2009); [14]–Boomer et al. (2009).

[c]*Cerastoderma glaucum* (formerly *Cardium edule*) shells.

[d]These pairs of samples (1 through 22) are taken from the same depth.

[e]This saxaul (*Haloxylon* sp.) stump was found *in situ* buried in shallow-water sediments on the island's coast.

[f]Samples were collected from the surface of lake sediments indicating apparent ^{14}C age of the carbonate matter discharged to the reservoir.

[g]This saxaul stump was found *in situ* on the dry bottom of the lake, elevation of ~40 m asl (former depth of ~14–15 m).

[h]This value is 280 ± 70 BP (CAMS-2504) (sample ID 12-10-91-1) (S Stine, personal communication, 2009).

[i]These are calibrated dates; original ^{14}C values are not given (Sorrel et al. 2006).

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