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Advances in understanding the late Holocene history of the Aral Sea region

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Abstract

Until recently, little attention has been devoted to palaeoclimate records in western Central Asia although the potential for improving our understanding of the connections between local and regional climate changes in this region is high. The location of the Aral Sea in the heart of western Central Asia offers a unique opportunity to scrutinise palaeoenvironmental changes during the Holocene, and particularly over the last few thousand years, in a region that is dominated by a continental climate regime and is relatively isolated from the monsoons to the south and southeast. Aral Sea sediments provide an excellent opportunity for high-resolution studies of past climatic and hydrological changes in the catchment area. We review recent palaeoenvironmental work in the region and focus on recent investigations on core material from the Aral Sea that details marked 'sea level' oscillations over the past ca. 2000 years as the Aral responded to local climate forcing. Furthermore, archaeological and digital terrain modelling reveal that the previously proposed mid-Holocene highstand of the Aral Sea at 72–73 m a.s.l. cannot have been achieved, a revised Holocene highstand is set at about 54–55 m a.s.l.

1. Introduction

The Aral Sea basin comprises much of the western boundary of Central Asia and, sitting as it does in the pathway of the major westerly air-stream, it experiences little direct influence by monsoon systems (Fig. 1). In this paper, we review recent advances in our understanding of environmental change over the last few thousand years in the Aral basin proper as well as summarising evidence for environmental change from other archives, including tree-rings and ice and lakes cores, from adjacent areas.

The history of the Aral Sea continues to be a focus of research for a number of reasons, particularly in the fields of water management and regional palaeoclimatology. Since the publication of two review articles on the history of the Aral Sea by Boomer et al. (2000) and Létolle and Mainguet (1997), there has been much further interest in examining the sedimentary, palaeontological, geomorphological and archaeological evidence from the Aral Sea basin with a view to reconstructing a detailed palaeoclimatic history for the basin and the wider region. The complex bathymetry and hydrology of the Aral Sea makes it difficult to interpret palaeoenvironmental records from sea-bed cores. The main body of the Aral Sea has a shallow, gently sloping eastern shelf whereas the western area comprises a number of distinct, and relatively deep sub-basins. The northern Small Aral is separated from the main Aral during lowstands by a shallow sill; the northern Aral also has its own complex bathymetry. As sea levels fall progressively within the Aral basin, sub-basins become progressively and hydrologically isolated. This must be borne in mind when interpreting core material from different parts of the Aral basin.

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Fig. 1. Regional location map with key lake and cave sites referred to in the text.

It has become clear that Aral Sea sedimentary records from the last few millennia have been influenced both by natural climatic variability and anthropogenic efforts to control water courses in the region. We begin by reviewing palaeoclimate evidence from the wider region (Aral catchment and beyond), then focus on recent studies from the Aral Sea and its immediate coastal fringes. In this paper, Aral Sea levels are given in metres above sea level, for this purpose 'sea level' is usually taken as modern mean sea level in the Baltic Sea.

Aral Sea level fluctuations result from variations in evaporation, precipitation and basin drainage linked to climate change and abstraction. Aspects of atmospheric circulation, which control interactions between different climate systems (e.g., the subpolar westerly jet stream, the Siberian High pressure cell and the North Atlantic Oscillation), are therefore crucial for understanding the climatic teleconnections that exist between the Aral Sea basin and neighbouring regions. The Siberian High is the dominant spring feature controlling temperature gradients and wind dynamics in western Central Asia, influencing the intensity of detrital input blown into the basin by storms (Sorrel et al., 2007b). The Aral Sea basin's hydrological budget is essentially regulated by the westerly trajectories and the Eastern Mediterranean cyclonic system. While the latter provides the moisture which falls as rain over Central Asia during late winter and early spring, the westerlies are the main source of humidity to the montane regions (Tien Shan and Pamir) where, during the spring and early summer, melting glaciers and snowfields feed the Amu Darya and the Syr Darya which account for ca. 80% of the Aral's hydrological input. Hence, due to the strong dependence of the Aral Sea to hydrological inputs from its tributaries, the regressions and associated salinity increases may be linked to fluctuations in meltwater discharges. In turn, the amplitude of the contribution in glacial meltwater inputs into the Aral Sea is largely controlled by temperature contrasts between the seasons in these montane regions, and thus has a primary impact on Aral levels.

A recent study by Shibuo et al. (2007) has also highlighted the possibility that the 20th century increase in irrigation within the Aral Sea drainage basin, which ultimately led to the most recent fall in the level of the Aral Sea, may initiate local climate change. This arises from the greater flux of evapo-transpired water vapour to the atmosphere in irrigated areas, thus producing an enhanced cooling effect and possibly local increases in precipitation.

2. Climate proxy records from the wider region

2.1. Tien Shan mountains

Although some 1500 km to the east of the Aral Sea, the Tien Shan mountains fall partly within the Aral catchment, as the Syr Darya river rises within the western part of the Tien Shan mountains of Kyrgyzstan and China. Changes in moisture supply and in the balance between snow/ice accumulation and ablation in the region impact the Aral Sea, the smaller Lake Issyk Kul, a deep-water, brackish lake and Lake Bosten, both of which lie within the Tien Shan range.

Lake Issyk Kul, in northern Kyrgyzstan (Fig. 1), is a relatively deep lake (>650 m) with a surface area of more than 6000 km^2 (Ricketts et al., 2001). The climate at Issyk Kul is strongly influenced by the Siberian High and the southwest Indian Low with much of the moisture sourced from a westerly direction (Aizen et al., 1995). Ricketts et al. (2001) described an approximately 8 ka record of hydrological change within Lake Issyk Kul based on sedimentary, faunal and geochemical evidence from two piston cores. They identified an early Holocene period of enhanced freshwater input, possibly associated with meltwater supply, between about 8.7 and 8.3 ka BP; and until

6.9 ka BP, an open, well-mixed, freshwater lake was established. Subsequently, between 6.9 and 4.9 ka BP the lake switched to become a poorly mixed, closed basin with higher salinity, a situation that continued throughout much of the late Holocene.

Ricketts et al. (2001) attributed the early Holocene period of high moisture availability to strengthening Asian and Indian summer monsoons that subsequently weakened in the late Holocene resulting in more arid conditions. Whether the strengthening influence of the monsoon increased westerly moisture supply or permitted direct monsoonal influence is unclear. Nevertheless, the Issyk Kul record provides an important long-term record linking the main Aral basin in the west and the Central Asian plateau to the east.

The Holocene lake history of Lake Bosten at the south-eastern margin of the Tien Shan has recently been reconstructed by Wünnemann et al. (2006) and Mischke and Wünnemann (2006). Since Lake Bosten's headwater area is located in the same mountain range as that of the Syr Darya, variability in meltwater contribution as well as climate-controlled moisture availability in the region should have had a similar impact on both hydrological systems. With respect to climate-induced hydrological changes of Lake Bosten, the major results show a generally positive water balance and thus warm–wet climate conditions starting after the dry 8.2 ka event which remained relatively stable during mid Holocene time. However, short-term fluctuations with a general trend towards a drier climate encompass the time between 3.9 and 0.9 ka BP. A negative water balance and thus reduced water availability is observed in the period 50–1000 AD, while during a later Medieval Warm Period (or at least contemporary with it), lake level rise could be recognised. A short-term regression is apparent at around 1650 AD.

To the north of the Tien Shan lies Lake Balkhash a relatively large but very shallow (<30 m) water body that is weakly brackish today. As yet no palaeoenvironmental investigations have been undertaken into the Holocene history of this water body although it must retain an archive of environmental change in the area to the north of the Tien Shan.

Although much interest in the palaeoclimatic record from ice-cores focuses on polar regions, there is also a significant body of research involving lower latitude, high-altitude settings including the Tien Shan. Aizen et al. (2004) investigated the oxygen-isotope and major-ionic composition of the accumulated firn–ice in a relatively short (14 m) ice-core from the South Inilchek Glacier, central Tien Shan, to identify the trajectories and origins of moisture. Although the ice-core only covered a period of about one decade, a comparison between composition and meteorological data enabled the authors to identify two major moisture sources. The dominant mode of moisture supply is by westerlies, with marine-derived precipitation sourced from the Atlantic Ocean, Mediterranean and Black Seas. During low-precipitation seasons (autumn, winter), the moisture reaching the central Tien Shan included a significant contribution from the more arid and semi-arid regions of Central Asia (Caspian and Aral regions). As yet the palaeoclimatic evidence from the Tien Shan ice-cores does not rival the long-term polar records, there is surely further potential in this region's glacial archive.

Tree-rings afford the possibility to recover high-resolution (annual) palaeoclimate records. Li et al. (2006) reconstructed more than 300 years of 'regional drought variability' from spruce trees (*Picea schrenkiana*) in the Tien Shan. Their evidence showed that both precipitation and temperature were recorded in the tree-rings, and that both low- and high-frequency cycles could be seen in the drought patterns. More significantly, Esper et al. (2002) established a 1300-year climate history record based on high-elevation tree-ring records of juniper (*Juniperus turkestanica, Juniperus seravchanica, Juniperus semiglobosa*), spruce (*P. smithiana*) and pine (*P. wallichiana*) trees including a number of sites in the southern Tien Shan. Their study involved tree-ring width (TRW) analysis from 20 sites in the main area of interest. They identified inter-annual, decadal and centennial-scale variability within the data and produced a climate history for western Central Asia since AD 618.

Their research indicated above average growth rates for the period AD 618–AD 1139 (a possible 'Medieval Warm Period') followed by growth rates below the long-term average from AD 1140 (a 'Little Ice Age'). The data also suggest subsequent elevated growth rates since the mid 17th century. They ascribe the observed centennial variability to temperature variability with the warmest decades between AD 800 and AD 1000 with the coolest decades in the first half of the 17th century.

2.2. *Lake Van, Lake Zeribar and Soreq Cave*

To the south and west of the Aral basin, a number of water bodies and cave sites have yielded important palaeoclimatic archives for the region that includes the direct path of westerly sourced moisture from the Atlantic Ocean and the Mediterranean Sea. Lake Van, in eastern Turkey, contains an annually laminated sedimentary sequence that has revealed a high-resolution climate history for the catchment over the last 13,000 years (Landmann et al., 1996; Wick et al., 2003). However, details of the last 2000 years is poorly resolved although Lake Van continues to be the focus of ongoing research.

Stevens et al. (2001) described changing climatic conditions through the late glacial and Holocene sediments of Lake Zeribar, in north-west Iran (south-east of Lake Van) but the records do not yet provide high-resolution proxies for the latest Holocene. Further to the west at Soreq Cave (Israel), speleothem records provide an indication of changing moisture and temperature conditions in the eastern Mediterranean throughout the Holocene (Bar-Matthews et al., 1998, 1999). A comparison between Soreq Cave speleothems and eastern

Mediterranean planktonic foraminiferal oxygen-isotope records (Schilman et al., 2002) have shown there to be a strong link between marine and land hydrology during the late Holocene with three humid events dated to around BC 1250, AD 650 and AD 1250 with three distinct dry events at BC 150, AD 1050 and AD 1650. The latter event of each type has been taken to represent the Medieval Warm Period and the Little Ice Age, respectively.

3. Aral Sea cores (Butakov Bay and Southern Aral Sea)

Although the retreating shoreline has made it virtually impossible to collect cores today from large ships in the Aral Sea, a number of cores have been recovered in recent years from smaller vessels and directly from the newly exposed sea-bed. Maev and Maeva (1983a, b), summarised in Maev and Maeva (1991), described the lithological changes in the uppermost sediments of the Aral Sea from a series of piston cores taken across a large part of the main Aral Sea, although these cores lack a detailed integrated chronostratigraphical framework, they clearly illustrated the potential for sedimentological and biological evidence to reconstruct past hydrological changes in the Aral basin. Similarly, Rubanov (1991) outlined the evidence for past fluctuations in the level of the Aral Sea based on the occurrence of evaporite deposits.

Two short cores (<2 m) collected from the northern Small Aral, and one of its embayments (Butakov Bay; Fig. 2) during 1994, were described by Boomer et al. (2003). The faunal and geochemical records from these cores, based largely upon ostracod shells, identified periods of hydrological change in this northern part of the Aral Sea over recent centuries. The core evidence in the main part of the northern basin suggests that sometime between the late 15th to early 17th centuries, the main part of the northern basin, the 'Small Aral', became desiccated for a short time, with a fall in sea level of approximately 30 m compared to the 1960 level. The environmental change is reflected in the ostracods, sediments and the occurrence of what appear to be in situ plant macrofossils dated to 380 ± 40 RC years (AD 1440–1640). A similar, but undated short core from Butakov Bay shows the same pattern of environmental change but without evidence of severe desiccation suggesting that Butakov Bay may have become hydraulically isolated but with enough inflow to support some level of water.

Similarly, the value of ostracods in studying the Aral Sea has been demonstrated in two further short cores containing mostly laminated sediments (<3 m covering about the last 2000 years) obtained from Tschebas Bay (Fig. 2), a small embayment in the NW part of the main Aral Sea (Keyser, personal communication). Changes in the ostracods over this period (based on the identification of three salinity-controlled ostracod assemblages) indicated five hydrological stages, two periods of highstand, one of lowstand and two intermediate.

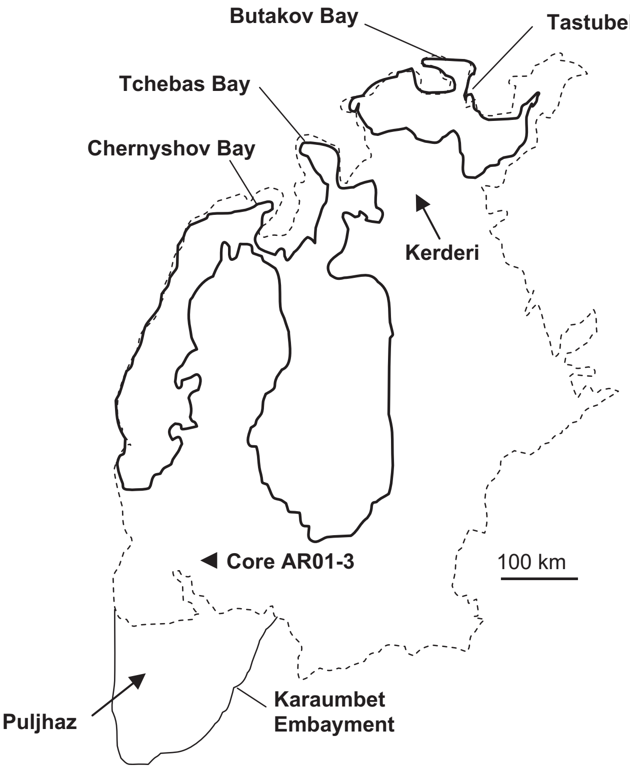

Fig. 2. Detailed location map of sites within and around the Aral Sea referred to in the text, shorelines shown as of 1960 (dotted) and 2002 (solid).

One of the longest sequences so far investigated from the Aral Sea was recovered from the now-exposed former sea-bed in the south-west area of the former Aral Sea. Core AR01-3 at almost 18 m deep (44°00.906′N, 59°05.494′E, Fig. 2), was drilled under a French–Uzbek cooperative research programme by the CNRS (France), Uzbekistan's Ministry of Agriculture and Water Management and the French IFEAC Agency in Tashkent. The core was sampled for ostracods and a preliminary comparison of the faunal change through the core with those from other parts of the Aral Sea suggests that it represents up to 5000–6000 years of accumulation (Boomer, unpublished). A single radiocarbon date from a *Cerastoderma* shell taken at a depth of 54–60 cm returned a RC age of 4421 ± 55 years suggesting very low sediment accumulation rates. The possibility exists that this may, however, be a reworked specimen. Work continues on this core as a potentially important source of palaeoclimatic information from the early–mid Holocene to the present.

4. Aral Sea cores (Chernyshov Bay)

Detailed palaeoenvironmental proxy records have been investigated from cores CH1 and CH2/1, retrieved from Chernyshov Bay (Fig. 2) during the CLIMAN field campaign in July/August 2002 (http://climan.gfz-potsdam.de/). These two cores, undisturbed by turbidites, provide a long and continuous record of palaeoenvironmental changes spanning approximately the last 2000 years. A summary of the data from these cores and palaeoenvironmental interpretation is given in Fig. 3. The dinoflagellate cyst record of Sorrel et al. (2006a, b), the diatom-inferred palaeoconductivity record of Austin et al. (2007) and the relative Ca content, a proxy for gypsum deposition (Boroffka et al., 2006, Sorrel et al., 2007b), are used to assess evidence of large palaeosalinity variations in the Aral Sea during the last ca. 2000 years. The pollen-based palaeoclimate record of Sorrel et al. (2007a) is also included, documenting significant changes in temperature and moisture conditions in western Central Asia.

The principal objective of the CLIMAN project is to identify prominent shifts in environmental conditions as inferred from integrated aquatic and terrestrial proxy data in the Aral Sea basin. The timing of these events is then compared with evidence for climate change and human activity across the region in an effort to determine the extent to which anthropogenic and natural climatic factors have been the primary driving factors controlling water level changes over the last ca. 2000 years. Sections 4.1–4.4 summarise four periods of low water level based on a range of palaeoenvironmental proxy data. Four regressions are recognised at (i) ca. AD 0–400, (ii) ca. AD 900–1350, (iii) ca. AD 1500–1650, and (iv) the present-day regression (Fig. 3). For further details of these cores see Boroffka et al. (2006) and Sorrel et al. (2006a).

4.1. Low Aral levels during ca. AD 0–400

The first of these four low sea level stands is believed to have been initiated at some time between ca. AD 0 and AD 400. At Chernyshov Bay (Fig. 2), a major regression recorded in both the dinoflagellate cyst assemblages and the diatom flora, is very likely associated with a severe decline of meltwater run-off from the tributaries to the Aral Sea. During this period, it is believed that discharge from the Amu Darya was limited with much of the flow being diverted along old river beds and irrigation channels towards Lake Sarykamysh (Létolle, 2002; Tsvetsinskaya et al., 2002). This regression is also indicated by high Ca contents and the occurrence of gypsum in sediments from Chernyshov Bay, which may be contemporaneous with the deposition of mirabilite in the western basin (Maev and Karpychev., 1999), which probably existed as a series of shallow hypersaline lakes (Aleshinskaya et al., 1996) during a prolonged period of cold, arid conditions in the Aral Sea region. During this low-level stand, the pollen-based climate reconstruction suggests that the climate in western Central Asia was characterised by cold winter temperatures, relatively cool summers and arid conditions (mean annual rainfall <300 mm) (Fig. 3). Similar conditions were reported from Syria with reduced winter/spring rains

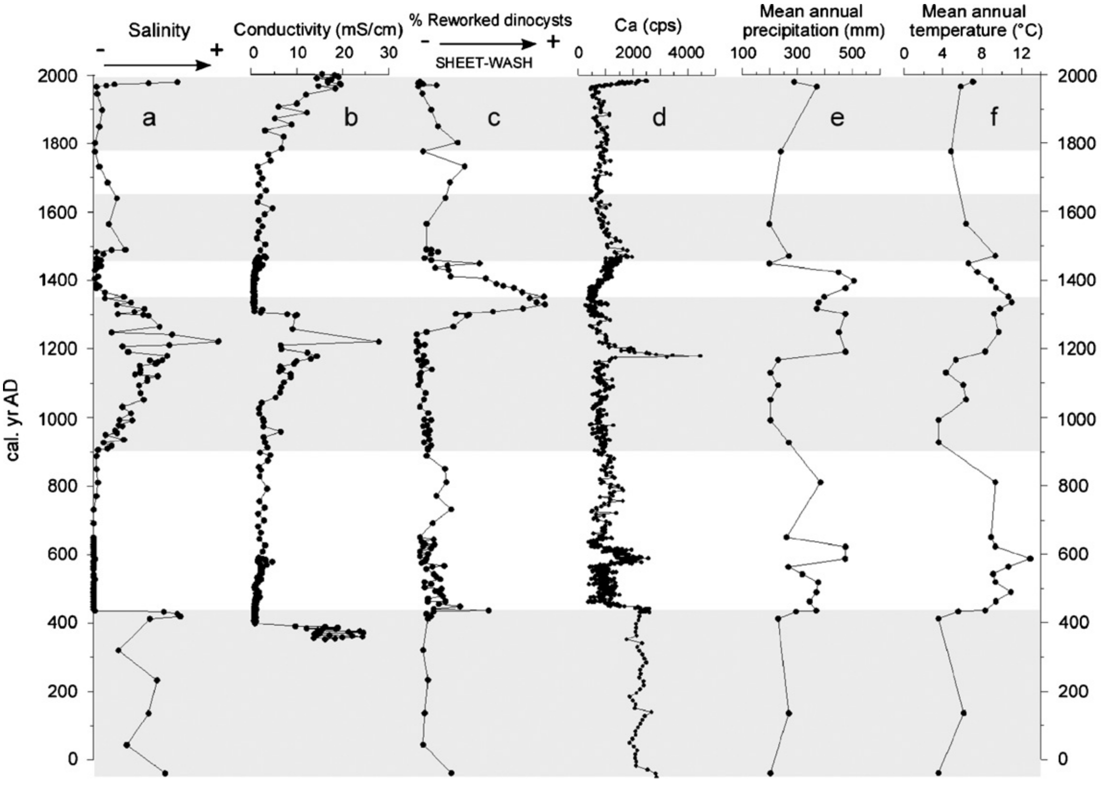

Fig. 3. Palaeoenvironmental and palaeoclimatic proxy data from Chernyshov Bay (northwest Aral Sea) during the last 2000 years (project CLIMAN; http://climan.gfz-potsdam.de): (a) the palaeosalinity reconstruction of Sorrel et al. (2006a, b) based on the relative abundance of *Lingulodinium machaeroforum* in section CH2/1; (b) the diatom inferred palaeoconductivity record of Austin et al. (2007) in Core CH1; (c) the sheet-wash index record of Sorrel et al. (2006a, b) based on the abundance of reworked Tertiary dinoflagellate cysts in section CH2/1; (d) high-resolution Ca content (X-ray fluorescence data) within Core CH1 (Boroffka et al., 2006; Sorrel et al., 2007b); (e) pollen-based reconstruction of mean annual precipitation (mm) in the Aral Sea basin (section CH2/1; Sorrel et al., 2007a); (f) pollen-based reconstruction of mean annual temperature (°C) in the Aral Sea basin (section CH2/1; Sorrel et al., 2007a). Shaded areas correspond to the four severe regressions recorded in the Aral Sea during the last 2000 years.

(Bryson, 1996), while a pronounced decrease in humidity and lake levels occurred in Lake Van (Turkey) between ca. BC 1500 and AD 0 (Landmann et al., 1996, Lemcke and Sturm, 1996).

In Soreq Cave (Israel), the time span AD 0–400 is characterised by negative precipitation anomalies (Schilman et al., 2002), implying reduced cyclogenesis in the Eastern Mediterranean region. Since the latter is the main source of overall moisture availability to the middle east and west Central Asia (Aizen et al., 2001; Lioubimtseva, 2002; Roberts and Wright, 1993), the cold and arid climate that persisted during ca. AD 0–400 most probably originated from the failure of depressions to penetrate into those continental regions of Central Asia which are reliant upon the westerly transport of cyclones, and/or the shift of storm tracks farther north (as happens during the positive NAO phase). This is also concurrent with low frequencies of reworked dinoflagellate cysts that indicate reduced on-land sheet-wash linked to weaker late winter/early spring rains (Sorrel et al., 2006a). The extensive irrigation systems initiated by the Persians in the 7th–5th centuries BC along the Amu Darya and the Syr Darya (Andrianov, 1969; Tolstov, 1962) date, at least in part, to this period and culminated around 300–400 AD. Reports from Greek sources (Barthold, 1910) also indicate that the Amu Darya was flowing to the west, through the Uzboj channel, into the Caspian Sea, so that the regression was most probably triggered by natural climate conditions although its severity may have been enhanced by human activity.

Shortly above the basal gypsum deposit in Chernyshov Bay, the presence of freshwater algae *Botryococcus braunii* type and *Pediastrum* spp., with nutrient-dependent (protoperidiniacean) dinoflagellate cysts and freshwater diatom species capable of withstanding brackish conditions indicates mesosaline conditions but probably persistently low water levels. After AD 450, the dinoflagellate cyst and diatom assemblages indicate that the Aral Sea was characterised by high water levels and dilute conditions, and that surface water salinity was below 15‰ or most probably around 10‰ (Fig. 3). Because of the low topography of the shorelines around the Aral, even a small rise in water level will have a substantial effect on the position of the shoreline. Reconstructions based on pollen data indicate that the climate was characterised by an increase in temperature and moisture conditions between ca. AD 450 and AD 900, with annual precipitation in this region almost twice that of the present day (Sorrel et al., 2007a). This corresponds with elevated temperatures and favourable conditions for the growth of trees in Israel (Lipschitz et al., 1981), which is linked to increased rainfall over the Eastern Mediterranean (Bar-Matthews et al., 1998; Schilman et al., 2002). The causes driving water level lowering during the 6th–7th centuries AD as suggested from higher Ca content, though moderate, still remain uncertain. Indeed, a contemporaneous increase in salinity levels is not supported by other palaeoenvironmental proxies (diatoms, dinoflagellate cysts) and neither significant climate change (at the time-resolution available), nor time-equivalent archaeological events are recorded in the region during this period. This phase, however, corresponds to a milder period (cool winters, warm summers) favourable for the development of some arboreal vegetation in the less dry edaphic areas and the replacement of sub-desertic herbs by steppe vegetation.

4.2. Low Aral levels during ca. AD 900–1350

The diatom flora and the dinoflagellate cyst assemblages indicate a second severe regression from ca. AD 1100 to 1300 but with salinity levels probably increasing from as early as ca. AD 900 (Fig. 3). This is concurrent with a gypsum horizon at ca. AD 1200 corresponding with a maximum of the Ca content within the sediments. However, much higher salinity (and lower water levels) is indicated at ca. AD 1220 and is characterised by the presence of halite within the sediments (Sorrel, unpublished data) and contemporaneous peaks in both the dinoflagellate cyst and diatom assemblages. This interpretation is strengthened by the discovery of new archaeological sites from the Middle Ages around the Aral Sea; at Pulzhaj (SW Aral Sea, Fig. 2), the atypical stone foundations of houses, indicating prosperity, are dated to the 13th to early 14th centuries AD (Boroffka et al., 2006). In the northern part of the main Aral Sea, a mazar (Islamic mausoleum) has been identified next to a settlement, named Kerderi, at an altitude of 32 m a.s.l. Both are dated to the 13th–14th centuries AD (Boroffka et al., 2005). While the mazar lies on an artificial mound and is exposed today, at least during the summer season, the adjacent settlement is still mostly submerged, indicating that the water level must have been below 31 m a.s.l. during the Middle Ages (Boroffka et al., 2006). This regression has already been described as resulting in water levels of 44–45 m a.s.l. (Aladin and Plotnikov, 1995; Boomer et al., 2000); however, it now appears to have been considerably more severe than at first suggested. The forces driving the progressive phase of this regression during ca. AD 900–1220 are very likely climatically controlled, although some anthropogenic activity, indicated by the inception of new irrigation laws in the region is also likely (Blanchard, 2002). The salinity increase and regression reported from Chernyshov Bay is also recorded in Tschebas Bay in the northern Aral basin, and reflects long-term declining discharges from the Syr Darya and the Amu Darya rivers. This is highly concurrent with the TRW records of Esper et al. (2002) and Mukhamedshin (1977), who report a general decrease in TRW from 800 AD to ca. 1230 AD, corresponding to a colder phase in the Tien Shan and Pamir-Alay mountains, respectively, which correlates with higher salinity levels in the Aral Sea (see Sorrel et al., 2006a). This is also consistent with pollen-based climate reconstructions that infer the climate switched back to cooler conditions during ca. AD 900–1200, with cold winters, cool summers and enhanced aridity ($<250\,\mathrm{mm\,a^{-1}}$). We attribute this increase in aridity to reduced humidity transported from the Eastern Mediterranean to western Central Asia during a period of lowered rainfall in winter and early spring in Israel (Issar et al., 1991), as inferred by higher $\delta^{18}O$ values in Soreq Cave carbonate deposits (Schilman et al., 2002).

In common with the earlier regression at ca. AD 0–400, cyclonic activity may have been reduced in the Eastern Mediterranean, with a significant drop in moisture reaching western Central Asia, a common occurrence during a negative phase of the NAO (Cullen et al., 2002; Mann, 2002). This period is characterised by low abundances of reworked dinoflagellate cysts (Fig. 3), suggesting reduced sheet-wash from the shore. However, as for the previous regression, human intervention in the flow of the Amu Darya is also likely. According to ancient documents (Barthold, 1910), the Amu Darya discharged into the Aral Sea until the devastating Mongol invasion in AD 1221, during which Genghis Khan's army destroyed hydraulic installations along the Amu Darya (Boroffka et al., 2005; Létolle and Mainguet, 1997). It is possible that this event is recorded by the peaks in both dinoflagellate cysts and diatoms and the presence of halite within the sediment. However, historical records also indicate the occurrence of a major earthquake around AD 1220 in western Central Asia. We cannot therefore exclude the possibility that river bed geometry in the flat delta area has been modified by tectonic activity, contributing to deviations in the flow direction of the Amu Darya, although, we know that climate had already changed some decades previously, thereby contributing to the triggering of this regression.

After AD 1220, both dinoflagellate cyst assemblages and the diatom flora indicate that water levels were raised within a short period of time (Fig. 3). This period coincides with the abandonment of the lower site at Pulzhaj (after the early 14th century AD) because of flooding, leading to a newly formed bay (Boroffka et al., 2006). This rise in the water level was evidently caused by rapid freshwater inflow into the Aral as shown by abundant freshwater algae at that time (Sorrel et al., 2006a), concurring with the opinion that the preservation of evaporate deposits in the western basin was made possible by rapid fluvial input with a heavy sediment load thereby preventing dissolution. Higher water levels and decreasing salinity correlate consistently with higher temperatures in the high catchment area (Esper et al., 2002), thereby increasing the flow of meltwater runoff in the Aral Sea during late spring and early summer (Sorrel et al., 2006a). In turn, the high frequency of reworked dinoflagellate cysts indicates intensified erosion of shore sediments during extreme sheet-wash events which coincide with the onset of moister conditions in western Central Asia with higher humidity ($370–500\,\mathrm{mm\,a^{-1}}$) and increased warmth (mean annual temperature: 7–11 °C). These conditions were maintained until the beginning of the 15th century AD (possibly analogous to the Medieval Warm Period) and probably favoured the establishment of steppe vegetation and the regression of both steppe herbs and shrubs. At the onset of more humid conditions in the Aral Sea basin, the climate signal from the Eastern Mediterranean unequivocally indicates a conspicuous decline in terrestrial $\delta^{18}O$ values from Soreq Cave (Schilman et al., 2002). This is interpreted as strong positive rainfall anomalies in Israel, reflecting enhanced cyclogenesis in the Eastern Mediterranean during winter and early spring. It also coincides with high levels of the Dead Sea (Issar et al., 1991) and the Sea of Galilee (Frumkin et al., 1991) also implying elevated moisture supply.

4.3. Low Aral levels during ca. AD 1500–1650

While the diatom-inferred conductivity indicates that fresh and oligosaline conditions and high water levels persisted until ca. AD 1780, the dinoflagellate cyst assemblages together with higher Ca content in the sediments suggests that the Aral Sea experienced a third but important regression around AD 1500–1650 (Fig. 3). This is also reflected in the $\delta^{13}C_{org}$ record ($C{:}N<10$ and therefore indicative of algae) from the Aral Sea (Austin et al., in review) which fluctuates in a similar fashion to the diatom-inferred conductivity where low lake levels and increased salinity are accompanied by shifts to higher, less negative, $\delta^{13}C$ values. This is not an uncommon process (e.g., Benson et al., 1991) and may reflect several processes working together, including: (i) increased algal productivity (this is known to have occurred during the present regression and may be a result of the increased input of nutrients from the former sea-bed during dust storms), (ii) increased conductivity and subsequently less isotopic discrimination by algae under physiological stress, and (iii) increased lake water residence time during regressive phases and elevated $\delta^{13}C$ values of the total dissolved organic carbon within the lake water. This regression is consistent with results obtained from Butakov Bay (Boomer et al., 2003) where sometime between the late 15th and early 17th centuries (AD 1440–1640) ostracods indicate that the main part of the northern basin (the Small Aral) became at least partly desiccated for a short period suggesting that a significant regression affected the entire Aral Sea.

According to a report by Khan Abulghazi (Barthold, 1910 and Boroffka et al., 2006), it is not until AD 1573 that the Amu Darya changed its course and discharged again into the Aral Sea. Similarly, the low-level stand occurring at ca. AD 1650 in the dinoflagellate cyst record match well with the presence of drowned *Saxaul* stands, which have been dated to 287 ± 5 ^{14}C years BP (307 cal. years BP, AD 1643) (Boomer et al., 2000, p. 1266). Both low level stands correspond to reduced temperatures in the Tien Shan mountains (Esper et al., 2002 and Sorrel et al., 2006a), resulting in lower meltwater discharges into the Aral Sea. Between ca. AD 1450 and AD 1550, the Aral Sea region underwent a switch towards a brief aridification with cooler mean annual temperatures (6–9 °C) and reduced aridity ($<250\,\mathrm{mm\,a^{-1}}$). This cooler interval has been identified in other regions within Eurasia (e.g., Mackay et al. 2005; Naurzbaev and Vaganov, 2000), and are considered to correspond to the Little Ice Age recorded in both aquatic and terrestrial proxies. In the Eastern Mediterranean region, it is contemporaneous with higher δ^{18}O values from the foraminiferan *G. ruber* (Schilman et al., 2001) from carbonate deposits in Israel (Bar-Matthews et al., 1998; Schilman et al., 2002), indicating lowered moisture transported to western Central Asia. Hence, as with the regression reported during the 13th–14th centuries AD, these regressions are most probably climatically driven through the onset of colder and drier conditions in the region. Moreover, there is no evidence of any significant human activity which could have enhanced the negative water balance for this time period.

4.4. Low Aral levels from ca. AD 1800 to the present day

The present-day severe regression is widely illustrated in our proxy data with a pronounced increase in salinity levels recorded in the dinoflagellate cyst assemblages, the diatom flora and higher Ca content (Fig. 3). However, while the dinoflagellate cysts and geochemical data indicate dilute conditions and rather high water levels during the 19th century (55 m a.s.l. in AD 1850), concurring with documentary and historical evidence (Arrowsmith, 1875; Barthold, 1910; Berg, 1908; Butakoff, 1853), the diatom assemblages suggest an increasing trend in conductivity starting at ca. AD 1780. This discrepancy can, however, be explained by the presence of diatom species, which in the transfer function used (EDDI, http://craticula.ncl.ac.uk/Eddi/jsp/index.jsp) have a high conductivity optima which drives the reconstruction to higher conductivity i.e., the increased abundance of *Cyclotella choctawhatcheeana* (the main driver of inferred conductivity in the Aral) which is concordant with a 3 m decline in lake levels which commenced in AD 1790 (Shermatov et al., 2004). A decline of this magnitude results in a significant loss of the lake's littoral zone and as lake levels fell, the extensive habitat for benthic flora provided by the shallow eastern basin was dramatically reduced. This resulted in the lake gradually becoming confined to the deep, steeper sided, western basin from where the core for the CLIMAN project was obtained (Austin et al., 2007; Fig. 1) in which, as one would expect, planktonic species (e.g., *C. choctawhatcheeana*) dominate. A further similar regression commenced in AD 1840 (Shermatov et al., 2004) and the abundance of *C. choctawhatcheeana* was maintained throughout these minor fluctuations and into the current regression. Nevertheless, all proxy records indicate a rapid, prominent regression starting during the early 1960s due to large-scale diversion of upstream waters from the Amu Darya for cultivation purposes. The pollen-based climate reconstruction from AD 1550 indicates a progressive warming of the climate and corroborates evidence of enhanced aridity and higher temperatures during recent decades. Similarly, meteorological data show a steady increase of annual temperatures over the region during the 20th century (Lioubimtseva et al., 2005).

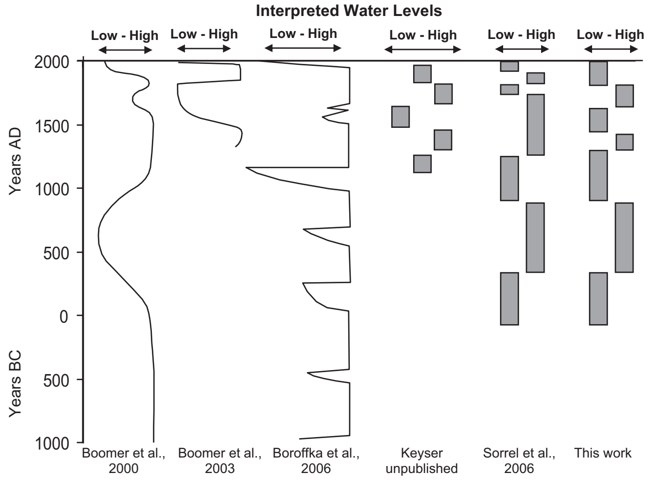

Fig. 4. Composite water level records for the Aral Sea over the last 3000 years interpreted from recent publications (Boomer et al., 2000 curve revised in light of evidence from Reinhardt et al., 2007).

The changing Aral levels described above are graphically compared to those from other recent publications in Fig. 4. While these records do not all necessarily agree in magnitude or timing, it is clear that all studies have shown the Aral Sea to have been a dynamic and fluctuating system over the last few thousand years, responding to both natural and anthropogenic forces.

5. Archaeological and geomorphological evidence around the Aral Sea

Boroffka et al. (2005, 2006) presented archaeological and geomorphological evidence from the immediate area around the Aral Sea. Their work highlights a number of important observations relating to the patterns of settlement activity and previous models of Aral Sea level change during the late Holocene. The archaeological evidence indicates clear responses to water level shifts as settlements moved with the migrating shoreline, especially during the last 2000 years. Furthermore, they observed that the evidence for 'Terrace I' of Boomer et al. (2000), first proposed by Epifanov (1961), a water level highstand of about 72–73 m a.s.l. around approximately 5000 years ago, cannot be supported. Man-made artefacts dating to about 35,000 years ago were found in what was considered to be an undisturbed context on a cliff top near Tastubek on the northern Aral coast at an altitude of 65 m a.s.l. Had the 72–73 m a.s.l. water level been attained after that time, these remains would at least have been disturbed if not overlain by sediments.

Reinhardt et al. (2007) undertook detailed field and differential-GPS surveys of two areas in the northern and southern parts of the Aral basin to establish what evidence existed for some of the terrace levels described in previous literature, including the 72–73 m terrace. They produced a series of digital elevation models (DEMs, Figs. 5 and 6) that permit high-resolution reconstructions of past Aral shorelines based on particular 'sea levels'.

Reinhardt et al. (2007) confirm the work of Kes (1995) who doubted that a high level at 72–73 m a.s.l. could be attained. Kes (1995) assumed that a water level above 70 m a.s.l. would trigger overflow into the Caspian Sea. The SRTM-3 digital elevation model (Fig. 5A) indicates that a critical value of only 64–65 m a.s.l. is required to initiate overflow (Fig. 5B), which in turn prevents the further water level rise. This, together with the archaeological evidence all but excludes the possibility of a 72–73 m a.s.l. terrace. The previous hypotheses are thought to have been based on observations of geomorphological surfaces and features that are genetically un-connected with Aral Sea processes.

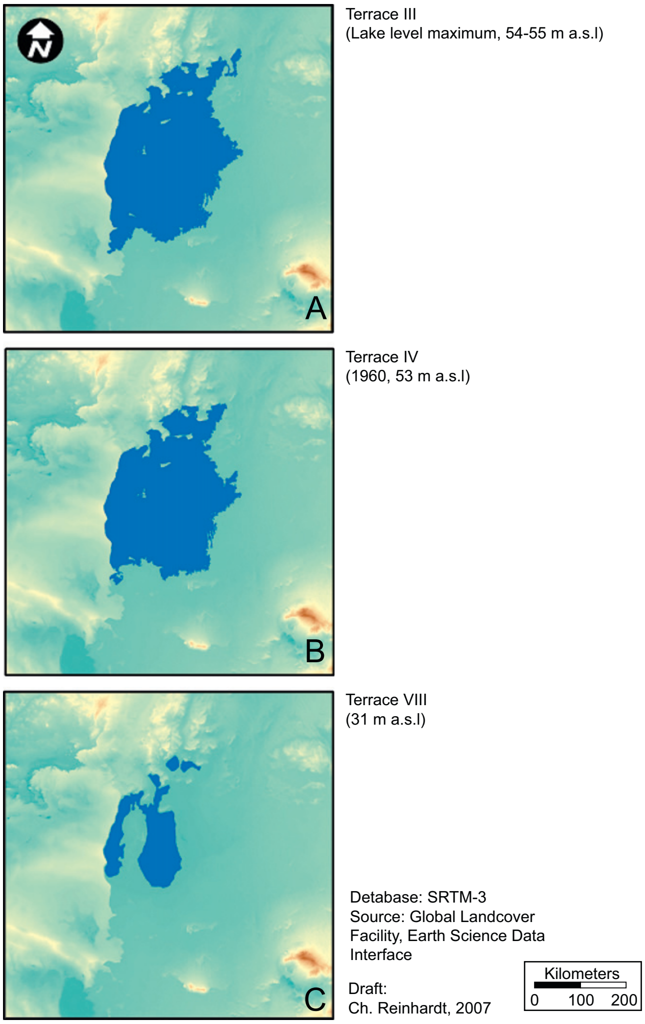

Fig. 5. SRTM-3 DEM images, showing the state of Aral Sea levels: (A) Aral level maximum at 54–55 m a.s.l., according to terrace III (sensu Boomer et al., 2000); (B) Aral highstand at 53 m a.s.l. prior to the 'Aral Sea crisis' at around 1960, according to terrace IV (sensu Boomer et al., 2000); (C) Aral lowstand (c. 31 m a.s.l.) at modern times and during the Kerderi regression (14th–15th century, Boroffka et al., 2006), according to terrace VIII (sensu Boomer et al., 2000).

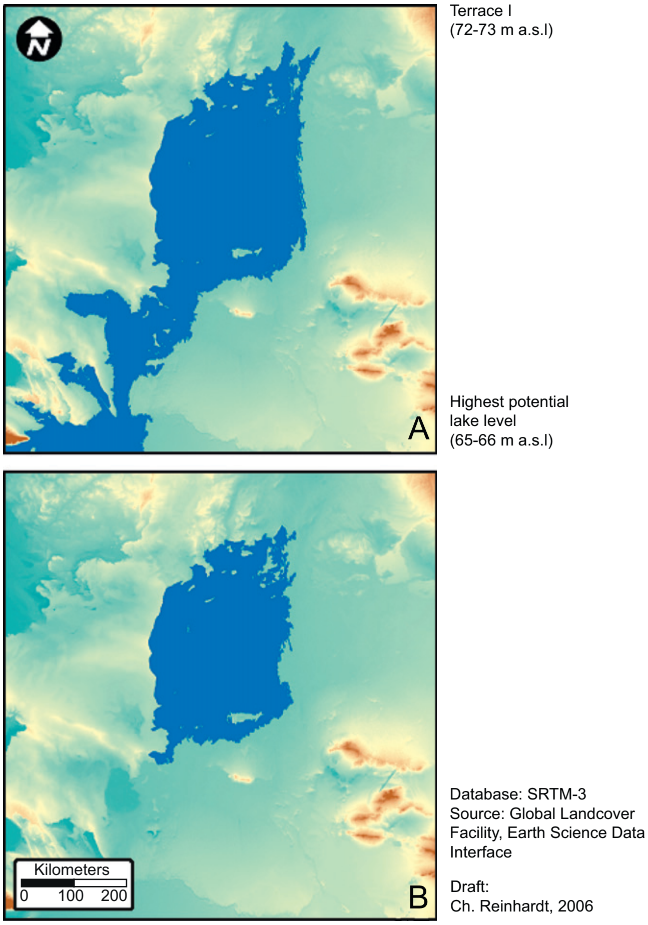

Fig. 6. SRTM-3 DEM images, showing two critical stages of Aral Sea level highstands, assuming negligible tectonic influence. (A) Aral level at 72–73 m a.s.l. (terrace I, Aral Boomer et al., 2000) would lead to an overflow via the Usboy channel towards the Caspian Sea. This level is assumed not to have existed during the Holocene. (B) Highest potential level at 65–66 m a.s.l. before the water would overflow, thus preventing the Aral from further rise.

Based on geomorphological investigations at several sites along the northern small Aral Sea (Tastubek, Tchebas and Chernyshov bays, Fig. 2), and the eastern and south-western border of the large Aral Sea, it seems most likely that the highest Holocene Aral sea level never exceeded 54–55 m a.s.l., since neither shoreline features nor related sediments have been found above this elevation. This maximum level is confirmed by the highest shoreline at Karaumbet Bay (south-western part of the Aral; Fig. 2) and reveals a total surface water area of about 72,400 km^2 (Fig. 6A; Reinhardt et al., 2007), some 6400 km^2 larger than the level of the early 1960s (Fig. 6B).

During the last 2000 years, this high level was first established at about AD 200 ± 60, when transgression of the Aral reached Karaumbet Bay, as evidenced by lacustrine sediments dated by Reinhardt et al. (2007). This observation contradicts the evidence for an Aral lowstand between AD 0-400. The confusion may arise over difficulties with the chronology and it may be that the 'Karaumbet' transgression equates to the 'post-AD 450' transgression referred in Section 4.1.

A further transgression began some time after AD 1570 ± 47, i.e., from the mid-16th century onwards (taking the dating uncertainty into consideration this chronology is consistent with historical records, cf. Boomer et al., 2000), documenting the Amu Darya's change of course towards the Aral Sea in 1573 and the related rapid filling of the main basin after the 14th–15th century Kerderi regression (Boroffka et al., 2006) and it probably remained at about this level for several hundred years. Historical maps (e.g., Butakoff, 1853) show that this level existed until at least about AD 1850. Fig. 6C shows the Aral level at 31 m, a lowstand that, according to Boroffka et al. (2006), had already occurred during the 14th and 15th century Kerderi regression. The Aral lowstand during the 15th–16th (and possibly 17th) century regression, again possibly related to the Little Ice Age, is also seen in the sedimentary record from Chernyshov Bay as outlined in Section 4.3.

6. Summary

The use of detailed multi-proxy analysis of core material from the Aral Sea has provided an important insight into the late Holocene, hydrological history for the western margin of Central Asia. Four major regressive phases have been recognised over the past 2000 years correlative with climate signals deduced from lake and tree-ring records in adjacent areas occurring at approximately: AD 0–400, AD 900–1350, AD 1500–1650 and AD 1800 to today.

It is now apparent from digital elevation modelling and archaeological evidence that the previously proposed maximum highstand of the Aral Sea at 72–73 m a.s.l. cannot have been attained and that the revised maximum elevation is almost 10 m lower at 64–65 m a.s.l. with a Holocene maximum at only 54–55 m a.s.l.

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