Available online at www.sciencedirect.com
ScienceDirect
Quaternary Research 67 (2007) 383 – 393
QUATERNARY RESEARCH
www.elsevier.com/locate/yqres

# A high-resolution diatom-inferred palaeoconductivity and lake level record of the Aral Sea for the last 1600 yr

Patrick Austin [a,*], Anson Mackay [a], Olga Palagushkina [b], Melanie Leng [c,d]

[a] Environmental Change Research Centre, Department of Geography, University College London, Pearson Building, Gower Street, London, WC1E 6BT, UK
[b] Laboratory of Water Ecosystems, Department of Ecology, Kazan State University, 18 Kremlin street, Kazan, Tatarstan Republic, 420008, Russia
[c] NERC Isotope Geosciences Laboratory, British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK
[d] School of Geography, University of Nottingham, Nottingham, NG7 2RD, UK

Received 17 January 2006
Available online 7 March 2007

**Abstract**

Formerly the world's fourth largest lake by area, the Aral Sea is presently undergoing extreme desiccation due to large-scale irrigation strategies implemented in the Soviet era. As part of the INTAS-funded CLIMAN project into Holocene climatic variability and the evolution of human settlement in the Aral Sea basin, fossil diatom assemblages contained within a sediment core obtained from the Aral Sea have been applied to a diatom-based inference model of conductivity ($r^2$=0.767, RMSEP=0.469 $\log_{10}$ μS $cm^{-1}$). This has provided a high-resolution record of conductivity and lake level change over the last ca. 1600 yr. Three severe episodes of lake level regression are indicated at ca. AD 400, AD 1195–1355 and ca. AD 1780 to the present day. The first two regressions may be linked to the natural diversion of the Amu Darya away from the Aral Sea and the failure of cyclones formed in the Mediterranean to penetrate more continental regions. Human activity, however, and in particular the destruction of irrigation facilities are synchronous with these early regressions and contributed to the severity of the observed low stands.


*Keywords:* Aral Sea; Diatoms; Transfer Function; Late Holocene; Anthropogenic activity; Natural climate variability

## Introduction

The last 2000 yr are a particularly important time frame during which anthropogenic activity has radically altered the physical environment. Such changes may be a consequence of increased population growth and the need to further exploit natural resources, or a response to climatic fluctuations, notably that of moisture availability. This is particularly important in arid and semi-arid regions where the establishment and development of civilizations and societies are dependent upon the successful management of freshwater resources. The Aral Sea basin, where early human occupation is known from the Palaeolithic (Boroffka et al., 2005), provides an excellent location from which to increase knowledge of the interactions between human activity, climate and environmental processes, currently a major focus of the IGBP-PAGES programme (Dearing et al., 2006).

Closed or terminal lakes in arid and semi-arid regions, such as the Aral Sea, provide excellent archives of detailed palaeoenvironmental data due to their rapid response to changing hydrological inputs caused by natural climatic variability and/or anthropogenic activity. Responses are primarily in the form of changes in water level and chemistry, particularly ionic concentration or conductivity, and ionic composition which may impact upon the species composition of the lake's biota. Diatoms are especially sensitive to changes in lake water chemistry and in particular conductivity, which varies inversely with depth. When preserved in lake sediments, diatoms may then provide quantitative information on former salinity through the development of transfer functions that enable a record of lake-level fluctuations to be established. These have been developed on a regional scale for Africa (Gasse et al., 1995), North America (e.g., Fritz et al., 1993; Wilson et al., 1996), Spain (Reed, 1998) and South America (Servant-Vildary and Roux, 1990), while the

* Corresponding author. Fax: +44 20 7679 0565.
*E-mail address:* patrick.austin@ucl.ac.uk (P. Austin).

0033-5894/$ - see front matter © 2007 University of Washington. All rights reserved.
doi:10.1016/j.yqres.2007.01.009

European Diatom Database Initiative (EDDI) has combined a range of data sets from Europe, Africa and Asia in order to reconstruct former chemical parameters including conductivity (Battarbee et al., 2000).

Evidence for climatic change over the past ca. 2000 yr in regions bordering the Aral Sea basin has been derived from the Tien Shan (Savoskul and Solomina, 1996; Esper et al., 2002, 2003) and the Pamir (Zech et al., 2000) (these, as well as records from the Aral Sea itself, are dealt with in the discussion). The aim of this paper is to establish, for the first time, a high-resolution palaeoconductivity record of the Aral Sea from which lake-level fluctuations may be inferred. The timing of these events is compared with evidence for climate change and human activity across the region to determine whether anthropogenic or natural factors have been the primary driving force of diatom-inferred lake-level changes over the last ca. 1600 yr.

### *Study site*

The Aral Sea (43°24′–46°56′N and 58°12′–61°59′E) is a large saline terminal lake situated in the arid and semi-arid Turanian Depression of Central Asia. Mean precipitation in the region, ca. 100–140 mm/yr (Zavialov, 2005), is primarily a result of the transport into Central Asia of depressions formed over the eastern Mediterranean by the westerly jet stream (Lioubimtseva et al., 2005).

The Aral Sea was once the world's fourth largest lake by area and has undergone a well-documented regression as a consequence of large-scale irrigation strategies implemented by the former Soviet Union (fSU) and the subsequent diversion of water from the Amu Darya and Syr Darya river inflow. This activity has led not only to the severe desiccation witnessed today but also to an acute ecological catastrophe, resulting in the loss of an estimated 216 species of phytoplankton, 38 species of zooplankton and 57 species of zoobenthos, while only two out of 20 species of fish remain (Mirabdullayev et al., 2004).

Since 1960, the surface area of the lake has decreased from ca. 66,000 km$^2$ to ca. 20,000 km$^2$ and volume from ca. 1100 km$^3$ to just 130 km$^3$ (Zavialov, 2005). From 1901 to 1961 the level of the Aral Sea was stable at 53 m a.s.l. By 1989, however, water levels had fallen to 39 m a.s.l. resulting in the formation of two separate waterbodies, the southern Large Aral and the northern Small Aral. The Small Aral (currently fed directly by the Syr Darya) has since shown signs of recovery with water levels presently at 41 m a.s.l. The Large Aral, however, has continued to undergo desiccation with lake levels currently 29 m a.s.l. As levels have declined, so salinity has increased. The average salinity of the Aral Sea from 1911 to 1960 was ca. 10 g l$^{-1}$ (Glazovsky, 1995); at the time of division this had reached 29 g l$^{-1}$. The stabilisation of the Small Aral has since seen salinity decline to ca. 17 g l$^{-1}$ (Friedrich and Oberhaensli, 2004). That of the Large Aral, however, continues to increase with surface waters of the western basin measuring ca. 82 g l$^{-1}$ and bottom waters in excess of 100 g l$^{-1}$ (Friedrich and Oberhaensli, 2004; Zavialov, 2005). Estimates for the more shallow eastern basin suggest salinities of ca. 150 g l$^{-1}$ (Mirabdullayev et al., 2004).

## Methods

### *Sampling*

Coring was undertaken in Chernyshov Bay in the western basin of the Large Aral during August 2002 (Fig. 1), details of which are given in Sorrel et al. (2007). However, where their CH1/2 is a composite of two cores, this investigation is limited to CH1 alone, which has a length of 11.12 m. This, together with different calibration methods (IntCal04) used by Sorrel et al. (2007), accounts for the minor differences observed between the age models expressed. Subsampling for diatom analysis was undertaken every 4–8 cm.

### *Chronology and sediment accumulation rates*

In order to establish a secure chronology for the core, AMS radiocarbon dates were obtained from filamentous algae (*Vaucheria* spp.) and molluscs (Table 1). $^{14}$C ages were transformed into calendar ages using OxCal v. 3.10 (Bronk Ramsy, 2005). Heim (2005) details a peak in $^{137}$Cs at 46 cm representing the 1963 fallout maximum from atomic weapons testing. This date, combined with similar trends in the $\delta^{13}$C of organic material (Austin, 2006) from a further radiometrically dated short core (Heim, 2005), suggest that the uppermost sample of CH1 contains modern-day sediments. Two dates, 480 cal yr BP at 152 cm and 655 cal yr BP at 480 cm (Table 1), were obtained by correlating the magnetic susceptibility record of CH1 with material recovered by Kazan State University (for a full description, see Nourgaliev et al., 2003).

A linear extrapolation from the lowermost radiocarbon date of 1475±95 cal yr BP at 860 cm provides a date of 1558 cal yr BP at 1028 cm, at which point an abrupt transition in the diatom flora and magnetic susceptibility (Sorrel, 2006) indicates a hiatus within the material. High lake levels of the Aral Sea are indicated at ca. AD 300 (Nik Borrofka, personal communication, 8 November 2006) and a gypsum layer at the base of the core correlates with a severe regression of the lake at ca. 1600 $^{14}$C yr BP (Boomer et al., 2000). Peat deposited in the lake's eastern basin has been dated to 1590±140 $^{14}$C yr BP (1600±300 cal yr BP) and is believed to correspond with mirabilite deposition in the western basin (Letolle and Mainguet, 1997). On this basis, a date of ca. 1600 cal yr BP, thought to reflect the maximum regression of this period (Boomer et al., 2000), is ascribed to the base of the core at 1112 cm.

The sediment accumulation rates ranged between 0.21 and 2.01 cm yr$^{-1}$, based upon linear interpolation between points (Fig. 2). This would suggest that a second gypsum horizon at 501 cm is dated to ca. 750 cal yr BP and as such correlates with a known regression of the Aral Sea initiated in AD 1221 due to the destruction of irrigation systems along the upper reaches of the Amu Darya by the Mongols (Letolle and Mainguet, 1997). The dates 4320±80 cal yr BP, 1650±30 cal yr BP, 1655±30 cal yr BP and 1600±40 cal yr BP (Table 1) are believed to reflect the reworking of older material from the shoreline and are confirmed by the large number of reworked dinoflagellate cysts found in the sediments (Sorrel et al., 2006). These dates are consequently rejected.

*Sediment analysis and lithology*

Percentage dry weight calculations were initially carried out at 4-cm resolution in order to determine diatom concentrations. Carbonate material was removed from wet sediment samples by treatment with 5% HCl. These were then analysed for total organic carbon (TOC) at 4-cm resolution during combustion in a Carlo Ebra 1500 on-line to a VG Triple Trap and dual-inlet mass spectrometer. Total organic carbon (TOC) fluctuates between 1% and 3% for the majority of the core. Values reach 10% at 494 and 498 cm and in the uppermost sample (Fig. 3).

From 0 to 479 cm, the sediments are composed of dark grey and black silt to sandy clay interspersed with organic mud horizons. From 479 to 501 cm, there is initially a 11-cm-thick dark brown section of finely laminated sediments; underlying these is a further 11 cm of finely laminated yellowish-brown sediments. At the base of this zone is a 0.5-cm horizon of

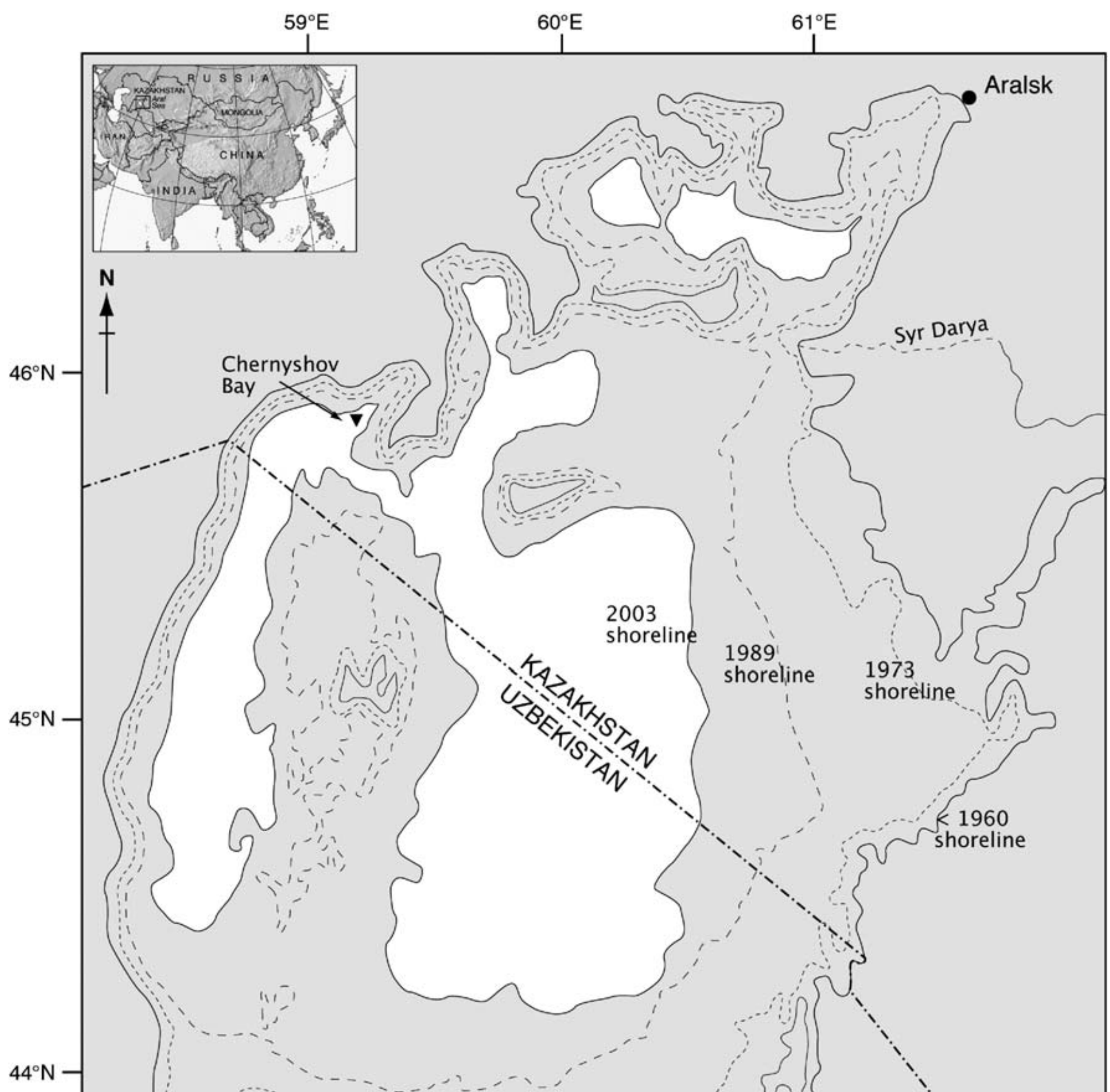


Figure 1. Map showing the present status of the lake compared with the shoreline in 1960 and intervening years. The location of the coring site at Chernyshov Bay can be seen in the western basin of the southern Aral Sea.

Table 1
Radiocarbon dates from Chernyshov Bay

| Laboratory code | Core | Depth | Material | Age, $^{14}C$ yr BP | ±(1 sigma) | Age, cal yr BP | ±(2 sigma) |
|---|---|---|---|---|---|---|---|
| KSU 1 | k-Ar-8 | 100 cm | Algae | 340 | 50 | 450 | 100 |
| KSU 2 | k-Ar-8 | 152 cm | Algae | 435 | 50 | 480 | 120 |
| KSU 3 | k-Ar-8 | 480 cm | Algae | 640 | 45 | 655 | 55 |
| POZ 4753 | Ar-21 | 55 cm | Algae | 108.6 | 0.3 | Modern | |
| POZ 4750 | Ar-22 | 124 cm | Algae | 4320 | 80 | 5000 | 350 |
| POZ 4756 | Ar-23 | 593 cm | Algae | 1650 | 30 | 1600 | 140 |
| POZ 4758 | Ar-23 | 604 cm | Algae | 1225 | 30 | 1215 | 105 |
| POZ 4759 | Ar-27 | 617 cm | Algae | 1655 | 30 | 1600 | 140 |
| POZ 4762 | Ar-27 | 720 cm | Algae | 1395 | 30 | 1360 | 35 |
| POZ 4764 | Ar-28 | 763 cm | Algae | 1600 | 40 | 1535 | 90 |
| POZ 9962 | Ar-28 | 788 cm | Mollusc | 1480 | 30 | 1410 | 55 |
| POZ 4760 | Ar-28 | 860 cm | Algae | 1515 | 25 | 1475 | 95 |

Radiocarbon dates were calibrated using OxCal version 3.10 (Bronk Ramsy, 2005).

gypsum, interspersed with a narrow layer of grey silty clay. From 502 to 1028 cm, the sediments are characterised by dark brown silt and sand, the material being interspersed with the remains of filamentous algae. In the lowermost zone from 1028 to 1112 cm (after the hiatus), the sediment consists of laminated grey silty clays. At the base of this zone is a 10-cm section of material characterised by a gypsum horizon interspersed with narrow bands of grey silty clay.

*Diatom analysis*

Samples at 4- and 8-cm resolution were processed in 30% $H_2O_2$ in a water bath at 70 °C in order to destroy organic matter. After 48 h, these were rinsed with distilled water and between 0.1 and 2 g of microspheres (mean concentration $6.18 \times 10^6$ g $l^{-1}$) were added to each sample in order to calculate diatom concentration. Samples were then settled on to coverslips and allowed to air-dry overnight before being mounted on slides using Naphrax™. Diatom species identification was carried out using a ×1200 Leitz Ortholux oil-immersion light microscope with phase contrast. A total of 300 valves were counted per slide, except in those samples where diatom concentration was low or preservation was such that there were insufficient diatom numbers. The main taxonomic sources were Krammer and Lange-Bertalot (1986–1991), Snoeijs (1993–1996), Witkowski (1994), Witkowski et al. (2000) and others, referred to in the

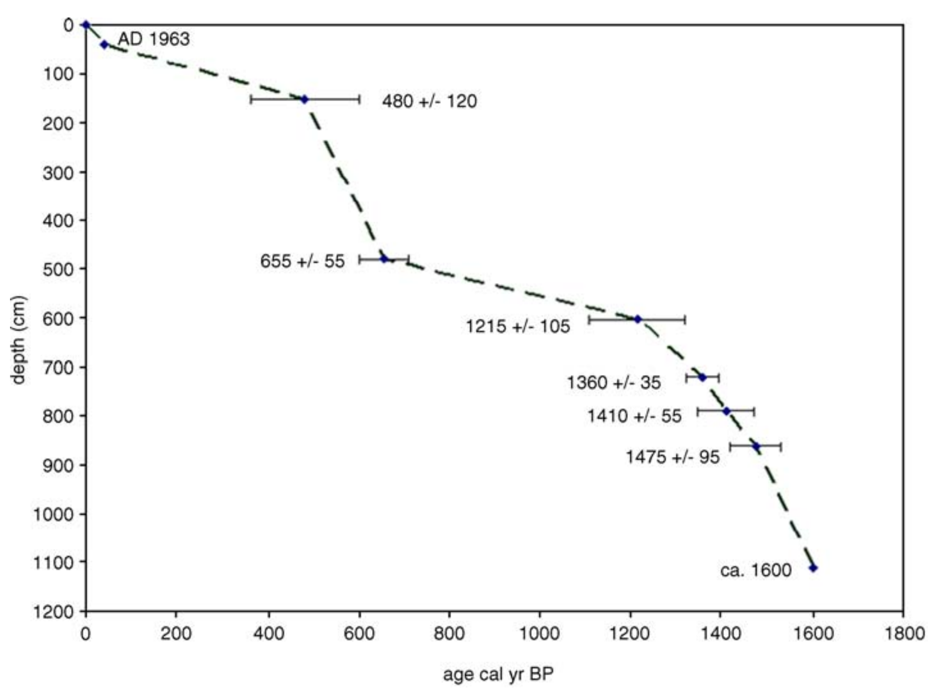


Figure 2. Age depth model for CH1 from Chernyshov Bay. The error bars represent the 95.4% probability distribution for the calibrated radiocarbon dates. The $^{137}Cs$ peak of 1963 is also shown (see text for details).

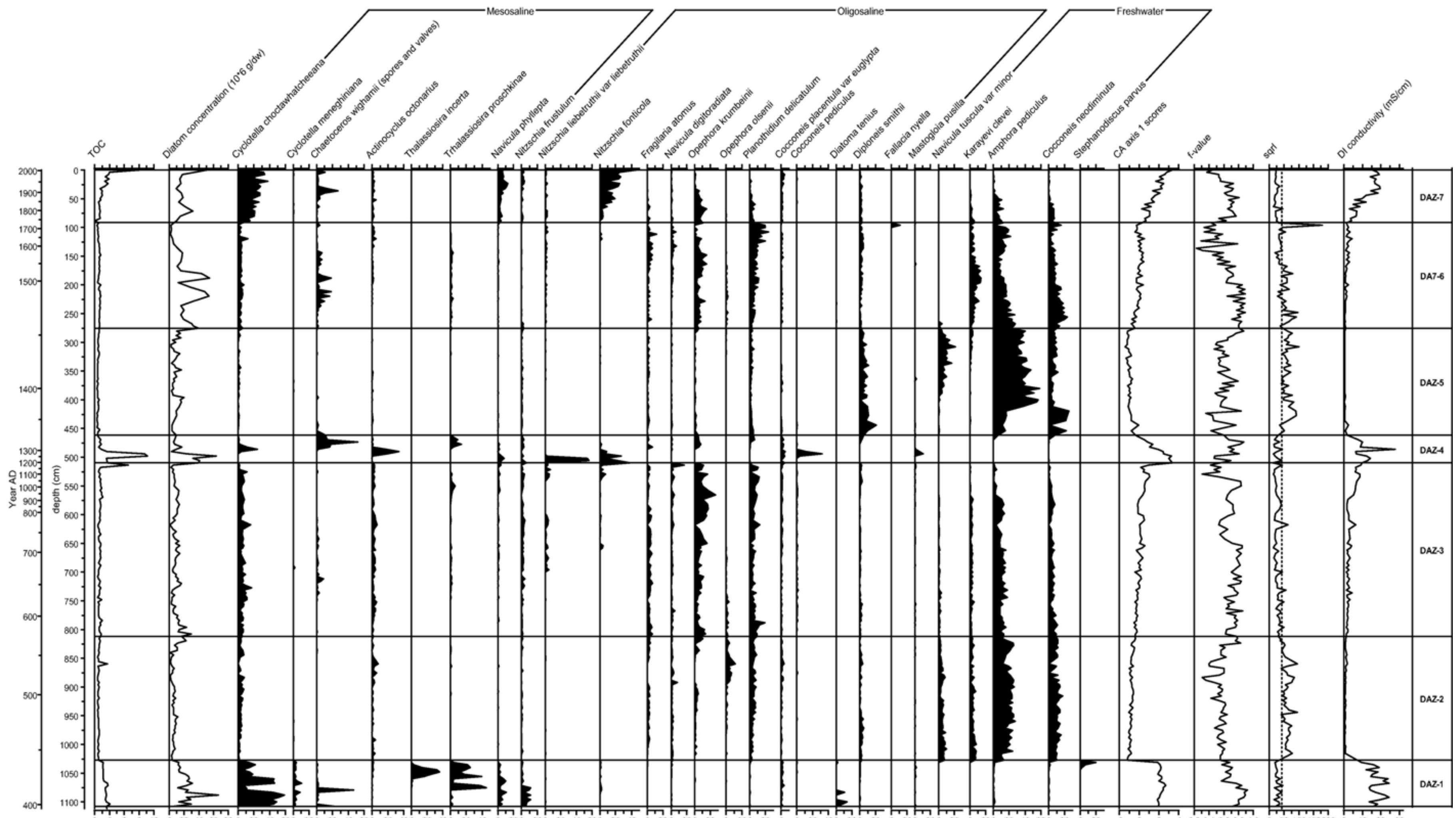


Figure 3. Summary of the diatom stratigraphy of Chernyshov Bay, Aral Sea. Species shown are those that appear with an abundance of >10% on one occasion or more. Also shown are the CA axis 1 scores, the F-index of diatom dissolution, the SqRL (see text for details) and diatom-inferred conductivity.

discussion. Diatom assemblages were zoned using stratigraphically constrained cluster analysis with the programme CONISS (Grimm, 1987).

### Statistical analyses

To provide a summary of the major changes in the diatom assemblages over the last ca. 1600 yr, taxa were initially analysed using detrended correspondence analysis (DCA) with CANOCO v. 4.5 (ter Braak and Šmilauer, 2002). This also established whether species responses were linear or unimodal. Data were square-root transformed in order to stabilise the variance and rare species were downweighted. A gradient length of 2.35 indicated a unimodal species response. Consequently, the main gradients of floristic variation within the core were analysed using correspondence analysis (CA) (no arch was apparent in the data) in which species were square root transformed and rare taxa downweighted. The CA axis 1 scores are plotted stratigraphically in Figure 3.

### Transfer function/salinity reconstruction

Salinity, in the form of conductivity ($\log_{10}$ μS $cm^{-1}$), was reconstructed using the EDDI Combined Salinity training set (http://craticula.ncl.ac.uk/Eddi/jsp/index.jsp), a composite of those established for Spain, North and East Africa, and the Caspian region. This data set consists of 604 species from 387 lakes ranging from freshwater to hypersaline conditions (Battarbee et al., 2000). The mean bootstrap estimates of salinity (from 1000 cycles) correlate well ($r$=0.76, RMSEP=0.469) with weighted average (inverse deshrinking) salinity estimates. In this study, results are back transformed into mS $cm^{-1}$ and classification follows that of Reed (1995), where fresh water is indicated by values <0.5, oligosaline 0.5–7.5, mesosaline 7.5–25 and polysaline 25–40.

Canonical correspondence analysis (CCA) is used to evaluate the reliability of the reconstructed conductivity by fitting fossil samples passively on to the first axis of the environmental variable being reconstructed (i.e., conductivity) and calculating the residual distance (square residual length, SqRL) of samples from that axis. This provides a 'goodness of fit' measure; fossil samples with a low SqRL from the environmental variable axis are deemed as having a good fit to that variable. Conversely, samples in the extreme 10% of the modern calibration samples are regarded as having a poor fit to the environmental variable under investigation (Birks, 1998).

## Results

### Diatom stratigraphy

Figure 3 shows the percentage diatom abundance for species occurring at >10% in any one sample. The flora was diverse with a total of 335 species identified, the majority of which are benthic and characteristic of the littoral zone. The differential preservation of diatom valves in highly saline and alkaline waters may bias conductivity reconstructions towards those species more resistant to dissolution (e.g., Ryves et al., 2001). This was assessed by using a simple index of preservation (*F* index, Fig. 3), in which valves with no indication of dissolution are expressed as a ratio of all valves counted (0=all valves partly dissolved, 1=all valves pristine). Valve preservation was generally good throughout the core, possibly due to the high sedimentation rate and their subsequent rapid removal from the water column. Between 96–136 cm and 840–892 cm, it was not possible to count 300 valves, although this is thought to reflect low concentration within the sediment rather than extreme dissolution due to a lack of dissolution features on diatom valves. Diatoms were absent in the basal sample at 1112 cm. Table 2 illustrates the dominant and subdominant species in the respective diatom assemblage zones.

### Statistical analysis

CA axes 1 (14%) and 2 (7%) account for 21% of the total variance in species data. Axis 1 (Fig. 3) would appear to reflect conductivity, with species such as *Chaetoceros wighamii*, *Navicula phyllepta*, *Nitzschia fonticola* and *Nitzschia liebetruthii* var. *liebetruthii* having high positive axis 1 scores, while those indicative of dilute conditions, such as *Navicula tuscula* var. *minor* and *Cocconeis neodiminuta*, have negative axis 1 scores. Axis 2 scores (not shown) are strongly influenced by species present in the lowermost samples below the hiatus. In particular, *Diatoma tenius*, *Stephanodiscus parvus* and *Thalassiosira*

Table 2
Dominant and subdominant diatom taxa in zones DAZ-1 to DAZ-7

| Zone | Core depth (cm) | Age (year AD) | Dominant taxa | Subdominant taxa |
|---|---|---|---|---|
| DAZ-7 | 0–88 | 1780–present day | *C. choctawhatcheeana*, *N. fonticola* | *N. phyllepta* |
| DAZ-6 | 92–272 | 1460–1765 | *Karayeva clevei*, *A. pediculus*, *C. neodiminuta* | *O. krumbeinii* |
| DAZ-5 | 276–458 | 1360–1455 | *A. pediculus* | *D. smithii*, *N. tuscula* var. *minor* |
| DAZ-4 | 462–512 | 1195–1355 | *A. octonarius*, *C. wighamii*, *C. choctawhatcheeana*, *N. fonticola*, *N. liebetruthii* var. *liebtruthii*, *Cocconeis pediculus* | *Cocconeis placentula* var. *euglypta*, *C. choctawhatcheeana* |
| DAZ-3 | 516–808 | 575–1175 | *A. pediculus* | *C. neodiminuta*, *C. choctawhatcheeana* *O. krumbeinii*, *P. delicatulum* |
| DAZ-2 | 812–1028 | 445–570 | *A. pediculus, C. neodiminuta* | *N. tuscula* var. *minor*, *P. delicatulum.* |
| DAZ-1 | 1032–1112 | 400–440 | *C. choctawhatcheeana, T. incerta, Thalassiosira proschkinae* | *C. wighamii*, *D. tenius*, *N. phyllepta*, *Nitzschia frustulum*, *S. parvus* |

*incerta* all have positive axis 2 scores, while *N. fonticola* and *N. liebetruthii* have negative scores along axis 2.

### *Diatom-inferred conductivity and environmental reconstruction*

Overall, just 113 out of 335 taxa recorded in the fossil samples were found in the modern calibration set. The diatom-inferred conductivity is shown in Figure 3. The SqRL of fossil samples resulted in 137 having a poor fit to the reconstructed conductivity (SqRL > 42). This is largely due to these having no strong analogues in terms of similar relative diatom abundances in the training set. The distribution throughout the core of those samples regarded as having a good fit to conductivity are found in the uppermost 92 cm, from 462 to 510 cm, and 1032 to 1108 cm, all concordant with elevated periods of conductivity. During these intervals, samples are dominated by *Cyclotella choctawhatcheeana* and/or *N. fonticola* and *N. liebetruthii* var. *liebetruthii*. Conversely, samples where reconstructions are deemed unreliable are those indicative of dilute conditions and high lake level phases, with species such as *Fragilaria atomus*, *Opephora krumbeinii* and *N. tuscula* var. *minor* that are absent from the training set, or fossil assemblages containing species that are rare in the training set such as *C. neodiminuta*, *Diploneis smithii*, *Karayevi clevei* and *Planothidium delicatulum*. The highest inferred conductivity values correspond with and subsequently confirm geochemical, biological and historical evidence of severe regressions of the Aral Sea since ca. AD 400 (Letolle and Mainguet, 1997; Le Callonnec et al., 2005; Sorrel et al., 2006).

Low lake levels and high conductivity are inferred by the gypsum horizon at the base of the core. This is supported by the diatom-inferred conductivity values (9.64–16.12 mS $cm^{-1}$) reflecting mesosaline conditions in zone DAZ-1 between 1108 and 1032 cm (ca. AD 400–440). There is a rapid decline in diatom-inferred conductivity to 0.60 mS $cm^{-1}$ at the start of the overlying zone DAZ-2, 1028–812 cm (ca. AD 450–570); however, it is impossible to state whether this is a true reflection of events due to the sediment hiatus at this point. Conductivity fluctuates between 1.94 and 0.57 mS $cm^{-1}$, with these lower values reflecting oligosaline conditions and higher lake levels.

In zone DAZ-3 from 808 to 516 cm (ca. AD 575–1175), diatom-inferred conductivity values are slightly higher than in the underlying zone fluctuating between 1.29 and 9.82 mS $cm^{-1}$. This zone is characterised by initial oligosaline values reflecting high lake levels. There is, however, a gradual shift to mesosaline conditions and declining lake levels by ca. AD 1000. Between 512 and 462 cm (ca. AD 1195–1355) in zone DAZ-4, a second episode of severely reduced lake levels occurs with conductivity values reaching 27.86 mS $cm^{-1}$ at ca. AD 1300. In zone DAZ-5 from 458 to 276 cm (ca. AD 1360–1455), a return to high lake levels and fluctuating fresh and oligosaline (0.41–2.40 mS $cm^{-1}$) conditions are inferred. The training set indicates that the dilute conditions persist throughout the overlying zone DAZ-6 from 272 to 92 cm (AD 1460–1765), with values ranging from 0.50 to 4.61 mS $cm^{-1}$, the higher values towards the top of this zone. An increase in conductivity (1.39–19.60 mS $cm^{-1}$) is highlighted in the uppermost zone, DAZ-7, between 88 and 0 cm (AD 1780 to the present day). Initially, conductivity fluctuates around oligosaline and mesosaline values; however, by ca. AD 1850 values are at the high end of the mesosaline range.

## Discussion

The diatom-inferred conductivity reconstruction of the Aral Sea highlights three distinct phases of severe lake level regression: (i) ca. AD 400, (ii) ca. AD 1195–1355 and (iii) ca. AD 1780 to the present. To understand why these regressions may have occurred, knowledge of the controls on the hydrological balance of the lake must first be summarised.

Inflow from the Amu Darya and Syr Darya accounts for ca. 80% of the hydrological inputs to the Aral Sea. From AD 1911 to 1960, the mean river discharge to the lake totalled 56 $km^3$ $yr^{-1}$, compared with 9 $km^3$ $yr^{-1}$ and 0–5 $km^3$ $yr^{-1}$ from precipitation and groundwater, respectively. The mean annual evaporation rate during this period was 66 $km^3$ (Zavialov, 2005). Such dependence on river discharge for hydrological inputs means that any regressions are inextricably linked to fluctuations in their flow, in particular that of the Amu Darya which accounts for ~80% of the total fluvial input.

A close correlation has been shown to exist between the discharge rate of the Amu Darya and solar activity, leading to several regressions of the Aral Sea of around 3 m during the last ~200 yr (Shermatov et al., 2005). However, when trying to ascertain a climatic connection to more severe regressions, it is necessary to look at events in two distinct geographical regions where increased aridity may have contributed to low lake level stands. Isotope data from GNIP stations indicate that the Indian Monsoon has little or no influence on precipitation in Central Asia (Kreutz et al., 2003); consequently, the majority of moisture is derived from the Eastern Mediterranean (EM) where depressions form and are transported across Central Asia by the westerly jet stream to the Pamir and Tien Shan mountains, where moisture condenses and falls as snow. Conditions in the montane regions themselves must also be considered, where climatic conditions control the rate at which melting glaciers and snowfields feed the Amu Darya and Syr Darya. Importantly, severe regressions may not only be linked to overall moisture availability across the region and the subsequent flow rate of the Amu Darya but also to the river's direction of flow, which since the late Pleistocene has altered (Kes, 1995; Boomer et al., 2000) due, in the main, to two possible factors: (i) the natural build-up of sediment within its bed, which may alternately divert the river away from and towards the Aral Sea and (ii) human activity, particularly irrigation and military conflicts that have previously diverted discharge away from the lake (Letolle and Mainguet, 1997; Letolle, 2002).

### *Low lake levels ca. AD 400*

Lacustrine sediments indicative of high levels of the Aral Sea are dated to ca. AD 300 (Nik Boroffka, personal communication, 8 November 2006) and correspond with increased moisture availability and lower temperatures across much of the EM. This is reflected by increased precipitation in the Levant, (Yakir et al., 1994; Schilman et al., 2002) and high levels of the Dead Sea between ca. AD 0 and 450 (Frumkin et al., 1991; Heim et al., 1997; Klinger et al., 2003; Bookman et al., 2004). In the Pamir and Tien Shan, humid conditions are also indicated by expanding glaciers (Savoskul and Solomina, 1996; Zech et al., 2000) and high levels of Lake Issyk-Kul (Aleshinskaya et al., 1996). The increased moisture availability across the region also allowed a stable water supply to the Prisarykamysh, an area lying between the Aral Sea and Lake Sarykamysh, ca. 100 km to the southwest, through which water occasionally flowed to the Caspian Sea via the presently dry Uzboi Channel (Tsvetsinskaya et al., 2002). During wet episodes, it has been suggested that the Amu Darya is diverted away from the Aral Sea towards Lake Sarykamysh or that it may form several deltas discharging into both lakes (Shnitnikov, 1969, cited in Boomer et al., 2000). This latter explanation would account for the stable water supply in the Prisarykamysh and high lake levels of the Aral Sea at around AD 300. Another likely cause was the development of extensive and sophisticated irrigation systems in the region, which may have allowed discharge of the Amu Darya to both lakes (Boomer et al., 2000).

The initial regression in our core is considered to have commenced at any time between ca. AD 300 and 400. During this low lake level stand, discharge of the Amu Darya to the Aral Sea was limited, with much of the flow being diverted along old river beds and irrigation channels towards Lake Sarykamysh (Letolle, 2002; Tsvetsinskaya et al., 2002). This is considered to have resulted in the deposition of mirabilite in the western basin, a process requiring a salinity of 150 g $l^{-1}$. This equates to a lake level of around 23 m a.s.l. (Letolle et al., 2004), making this regression more severe than the current low stand. At this time the Syr Darya is believed to have maintained a shallow freshwater body in the eastern basin, resulting in the deposition of as much as 10,000 $km^2$ of peat-like sediments (Letolle and Mainguet, 1997) and a diatom flora indicative of a shallow freshwater environment (Aleshinskaya et al., 1996). In the EM, levels of the Dead Sea are believed to have been in decline from ca. AD 300 (Heim et al., 1997; Frumkin et al., 1991) to as late as ca. AD 450 (Bookman et al., 2004). This range of dates corresponds with the potential timing of the low levels of the Aral Sea at 1600 ± 300 cal yr BP. Enzel et al. (2003) suggest that dry episodes and low lake levels of the Dead Sea are characterised by the failure of cyclones to penetrate into the EM and/or the displacement of storm tracks farther north. This would similarly have the effect of reducing overall moisture availability in those continental regions of Central Asia that are reliant upon the westerly transport of these cyclones.

As the Syr Darya was able to maintain some discharge into the lake's eastern basin, increased aridity may not be the sole cause of this regression. This period coincides with the westwards expansion and destruction of settlements along the Amu Darya by the Ephphalites (White Huns) in the early 5th century AD, one consequence being the diversion of the Amu Darya towards Lake Sarykamysh (e.g., Letolle and Mainguet, 1997; Tsvetsinskaya et al., 2002). Thus, differentiating between the two forcing factors is difficult. It is likely, however, that an episode of increased aridity across the region may have been responsible for the onset of a low lake level stand, the severity of which was ultimately enhanced by human activity.

Immediately overlying the gypsum deposit, the diatom-inferred conductivity indicates mesosaline conditions and low lake levels. Planktonic lifeforms dominate, particularly *C. choctawhatcheeana*. Although generally considered to favour mesosaline conditions (e.g., Prasad and Nienow, 2006), *C. choctawhatcheeana* was reported from the Aral Sea and the Syr Darya delta at salinities of 36 g $l^{-1}$ and 5–7 g $l^{-1}$, respectively (Rusakova, 1995), and has been recorded in hypersaline environments (Prasad and Nienow, 2006). As the abundance of this species declines, others indicative of more dilute conditions increase. *T. incerta* is found in the plankton of the Volga and other large rivers, and although common in the Caspian, Hasle (1978) suggests that it is essentially a freshwater species capable of withstanding brackish conditions. The uppermost samples of DAZ-1 are notable for the presence of *S. parvus* a species found in fresh and oligosaline conditions (Snoeijs, 1993–1996; Yang et al., 2003). This flora, combined with the presence of other freshwater algae (Sorrel et al., 2006), suggests that this zone reflects a period of lake level rise and the dilution of the western basin as flow from the Amu Darya returned to the Aral Sea. According to our age model, this was a rapid event occurring in less than a decade, 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 (Letolle and Mainguet, 1997; Letolle et al., 2004).

Archaeological investigations show that after the 4th–5th centuries AD the Prisarykamysh dried up completely due to the redirection of the Amu Darya back towards the Aral Sea (Tsvetsinskaya et al., 2002). Shnitnikov (1969, cited in Boomer et al., 2000) suggests that during arid episodes the Amu Darya discharges only into the Aral Sea. A reduction in the flow rate during these periods may result in sediment accumulation farther upriver and its subsequent deflection from an east–west to a southeast–northwest axis.

### *Low lake levels between ca. AD 1195 and 1355*

Our age model indicates that by ca. AD 445 the Aral Sea was characterised by high lake levels and dilute conditions. Around the 9th century AD the Amu Darya began to divert naturally towards Lake Sarykamysh as its delta filled with sediment, this is marked by an increase in diatom-inferred conductivity (Fig. 3). By the 10th century AD, the Prisarykamysh region was once again being exploited by humans (Tsvetsinskaya et al., 2002). This period coincides with the introduction of new irrigation laws along the entire lower reaches of the Amu Darya (Blanchard, 2002), which probably enabled some continued discharge to the Aral Sea and is contemporaneous with a shift to mesosaline conditions and low lake levels. The progressive increase in conductivity over this period is also seen in the dinoflagellate record from Chernyshov Bay (Sorrel et al., 2006). In the Pamir, Zech et al. (2000) attribute soil development at around AD 1000 to increased warmth, conditions that may also have been responsible for the contemporaneous peat bog formation on a former glacier bed in the Tien Shan (Savoskul and Solomina, 1996). This also coincides with increased temperatures and reduced precipitation in the Karakorum and Tien Shan (Esper et al., 2002; Treydte et al., 2006).

Diatom-inferred conductivity indicates a second severe regression between ca. AD 1195 and 1355. This interpretation is strengthened by the presence of a narrow gypsum horizon at around AD 1250. This episode of low lake levels corresponds with a date of 970±140 $^{14}$C yr BP (1000±300 cal yr BP) obtained from the remains of saxaul (*Haloxylun aphyllum*) groves found below the AD 1960 lake level (Rubanov et al., 1987) and geochemical analysis that indicates that at this time, discharge to the lake was dominated by the Syr Darya (Le Callonnec et al., 2005). It is apparent from the diatom stratigraphy (Fig. 3) that this low lake level stand is dominated by planktonic and tychoplanktonic diatoms (e.g., *Actinocyclus octonarius*, *C. wighamii*, *C. choctawhatcheeana* and *N. liebetruthii* var. *liebetruthii*), whereas benthic diatoms (e.g., *Amphora pediculus* and *C. neodiminuta*) dominate during dilute conditions and high levels. This process has been described by Stone and Fritz (2004) and is in contrast to other large shallow lake studies, which use increasing ratios of benthic to planktonic taxa as indicators of declining lake levels (e.g., Stager et al., 1997; Tapia et al., 2003). In the case of the Aral Sea, the discrepancy can be accounted for by the distinctive bathymetry of the lake, together with the coring location in the western basin. As levels decline, there is a progressive loss of the extensive littoral region of the shallow eastern basin. This has the effect of reducing the amount of benthic species being transported to the lake's deeper regions. This subsequently results in the observed increase in the proportion of planktonic and tychoplanktonic species incorporated into the sediments at the coring location, as the lake becomes confined to the steeper sided western basin (the littoral zone of which is much less significant when compared with that of the eastern basin).

During this period, high levels of the Dead Sea (Bookman et al., 2004) were accompanied by humid conditions and a possible MWP across the EM (Schilman et al., 2002). In contrast, pollen from the corresponding sediments of core CH1/2 (Sorrel et al., 2007) suggests the expansion of steppe vegetation and a reduction in precipitation. Arid conditions are similarly recorded in the Karakorum and Tien Shan (Esper et al., 2002; Treydte et al., 2006) where levels of Lake Issyk-Kul are also low (Giralt et al., 2004). As with the previous regression, cyclonic activity may have been concentrated in the EM while failing to penetrate eastwards into Central Asia.

Human intervention in the flow of the Amu Darya is also highly likely. This was a time of immense social upheaval in Central Asia, and while this regression is synchronous with increased aridity across the region, it also coincides with the westward expansion of the Mongols under Genghis Khan. In one particularly devastating encounter in AD 1221, they are known to have destroyed irrigation facilities and flooded the Khwarzem capital of Urgench, resulting in the diversion of water towards Lake Sarykamysh (e.g., Kes, 1995; Letolle and Mainguet, 1997).

## Low lake levels from ca. AD 1780 to the present

Diatom-inferred conductivity indicates that fresh and oligosaline conditions and high lake levels persist until ca. AD 1780. An increasing trend in conductivity is then observed so that by AD 1940 values in the mesosaline range are consistent with instrumental records (salinity = ~10 g l$^{-1}$). From AD 1967 to the present, this has stabilised at around 15 mS cm$^{-1}$. During this period, levels of the Dead Sea remained relatively high, only undergoing a severe regression in the mid-1960 s due to the artificial diversion of water from the Jordan River (Enzel et al., 2003). Similarly high levels of Lake Issyk-Kul are recorded ca. AD 1800 with a progressive decline since ca. AD 1900 due to both increased irrigation in the region and a shift to more arid conditions (Giralt et al., 2004). It has been suggested by Shermatov et al. (2005) that increased solar activity and reduced Amu Darya discharge since AD 1962 has contributed to the present lake level decline and was similarly responsible for fluctuations of ca. 3 m between AD 1790–1840 and AD 1840–1910. If correct, this natural element has obviously been overridden by the anthropogenic withdrawal of water for irrigation purposes since AD 1960.

Two points stand out during this regression. Firstly, the diatom-inferred conductivity reconstruction contradicts the last 40 yr of instrumental observations. This is, however, explained by the presence of *C. choctawhatcheeana* and *N. fonticola*, which dominate the diatom assemblages and have mesosaline optima in the EDDI training set. Second, documentary and historical evidence suggest high lake levels with minor fluctuations and dilute conditions until ca. AD 1960. This contrasts with the record derived from Chernyshov Bay. However, the increase in the abundance of *C. choctawhatcheeana* at ca. AD 1780 is contemporaneous with the ~3-m reduction in lake level at AD 1790, resulting in an extensive loss of the littoral habitat. For the reasons discussed earlier, this will result in increased abundance of planktonic species, which has been maintained during the present regression.

## Conclusion

The diatom-inferred conductivity reconstruction of the Aral Sea highlights three episodes of low levels since ca. AD 400, coinciding with archaeological, documentary and historical evidence for such fluctuations. While discharge of the Amu Darya may have declined naturally since the early 1960s, the severity of the present regression has been a direct result of human activity. Ascribing earlier regressions to either human activity or natural climatic variability is, however, more difficult. Both of these earlier low lake-level stands are accompanied by increased aridity. In the case of the earliest regression this occurs at around AD 400 and may be due to the failure of storm tracks to penetrate the Eastern Mediterranean. The later regression is concordant with dry conditions in the

Pamir and Tien Shan, which would tend to reduce river discharge. However, both these regressions also occurred during periods of social upheaval in Central Asia. Consequently, stating with any certainty whether natural processes (namely, increased moisture and changes in the direction of the Amu Darya flow) were ultimately more responsible than human activity (such as the withdrawal of water and the destruction of irrigation facilities) is difficult. While natural processes probably had a role in these regressions, historical evidence indicates that human activity, in common with the present-day regression, almost certainly contributed to these severe low lake-level stands.

## Acknowledgments

The CLIMAN project was funded by INTAS (grant number 00-1030) and coordinated by Hedi Oberhaensli. P.A. undertook this research whilst in receipt of an NERC studentship (NER/S/A/2002/10422) which is gratefully acknowledged. We also welcome the comments made by three reviewers Suzanne Leroy, Rene Letolle and Jane Reed, thereby improving the manuscript.

## References

Aleshinskaya, Z.V., Tarasov, P.E., Harrison, S.P., 1996. Aral Sea, Kazakhstan-Uzbekistan. Lake Status Records FSU and Mongolia. Available online at: http://www.ncdc.noaa.gov/paleo/lakelevel.html.

Austin, P.J.E., 2006. Palaeoconductivity, lake-level fluctuations and trace element history of the Aral Sea since 400 AD: assessing the impact of natural climatic variability and anthropogenic activity. Unpublished PhD thesis, University College London.

Battarbee, R.W., Juggins, S., Gasse, F., Anderson, N.J., Bennion, H., Cameron, N.G., 2000. European Diatom Database (EDDI). An information system for palaeoenvironmental reconstruction. European Climate Science Conference, Vienna City Hall, Vienna, Austria, 19–23 October, pp. 1–10.

Birks, H.J.B., 1998. Numerical tools in palaeolimnology—progress potentialities and problems. Journal of Paleolimnology 20, 307–332.

Blanchard, I.M., 2002. Mining, Metallurgy and Minting in the Middle Ages. Asiatic Supremacy, 425–1125 AD, vol. 1. Franz Steiner Verlag, Stuttgart.

Bookman, R., Enzel, Y., Agnon, A., Stein, M., 2004. Late Holocene lake levels of the Dead Sea. Bulletin of the Geological Society of America 116, 555–571.

Boomer, I., Aladin, N., Plotnikov, I., Whatley, R., 2000. The palaeolimnology of the Aral Sea. Quarternary Science Reviews 19, 1259–1278.

Boroffka, N.G.O., and 10 others, 2005. Human settlements on the northern shores of Lake Aral and water level changes. Mitigation and Adaptation Strategies for Global Change 10, 71–85.

Bronk Ramsy, C., 2005. OxCal 3.10.

Dearing, J.A., Battarbee, R.W., Dikau, R., Larocque, I., Oldfield, F., 2006. Human–environment interactions: learning from the past. Regional Environmental Change 6, 1–16.

Enzel, Y., Bookman, R., Sharon, D., Gvittzman, H., Dayan, U., Ziv, B., Stein, M., 2003. Late Holocene climates of the Near East deduced from Dead Sea level variations and modern regional winter rainfall. Quaternary Research 60, 263–273.

Esper, J., Schweingruber, F.H., Winiger, M., 2002. 1300 years of climatic history for Western Central Asia inferred from tree-rings. The Holocene 12/3, 267–277.

Esper, J., Shiyatov, S.G., Mazepa, V.S., Wilson, R.J.S., Graybill, D.A., Funkhouser, G., 2003. Temperature-sensitive Tien Shan tree ring chronologies show multi-centennial growth trends. Climate Dynamics 21, 699–706.

Friedrich, J., Oberhaensli, H., 2004. Hydrochemical properties of the Aral Sea water in summer 2002. Journal of Marine Systems 47 (1–4), 77–88.

Fritz, S.C., Juggins, S., Battarbee, 1993. Diatom assemblages and ionic characterisation of lakes of the Northern Great Plains, North America: a tool for reconstructing past salinity and climate fluctuations. Canadian Journal of Fisheries and Aquatic Sciences 50, 1844–1856.

Frumkin, A., Magaritz, M., Carmi, I., Zak, I., 1991. The Holocene climatic record of the salt caves of Mount Sedom, Israel. The Holocene 1 (3), 191–200.

Gasse, F., Juggins, S., Ben Khelifa, L., 1995. Diatom-based transfer functions for inferring hydrochemical characteristics of African palaeolakes. Palaeogeography, Palaeoclimatology, Palaeoecology 117, 31–54.

Giralt, S., and 20 others, 2004. 1000 year environmental history of Lake Issyk-Kul. In: Nihoul, J.C.J., Zavialov, P.O., Micklin, P.P. (Eds.), Dying and Dead Seas: Climatic Versus Anthropic Causes. NATO ASI Series, vol. 36. Kluwer Academic Publishers, Dordrecht, pp. 253–285.

Glazovsky, N.F., 1995. Aral Sea. In: Mandaych, A.F. (Ed.), Enclosed Seas and Large Lakes of Eastern Europe and Middle Asia. SPB Academic Publishing bv, Amsterdam, pp. 119–155.

Grimm, E.C., 1987. CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Computers and Geosciencs 13, 13–55.

Hasle, G.R., 1978. Some freshwater and brackish water species of the diatom genus *Thalassiosira* Cleve. Phycologia 17 (3), 263–292.

Heim, C., 2005. Die Geochemische Zusammensetzung der Sedimente im Aralsee und Sedimentationsprozesse während der letzen 100 Jahre. Diploma thesis, Alfred-Wegener-Institut, Bremerhaven.

Heim, C., Nowaczyk, N.R., Negendank, J.F.W., Leroy, S.A.G., Ben-Avraham, Z., 1997. Near East Desertification: evidence from the Dead Sea. Naturwissenschaften 84, 398–401.

Kes, A.S., 1995. Chronology of the Aral Sea and the sub-Aral region. Geo Journal 35, 7–10.

Klinger, Y., Avouac, J.P., Bourles, D., Tisnerat, N., 2003. Alluvial deposition and lake level fluctuations forced by late Quaternary climatic change: the Dead Sea case example. Sedimentary Geology 162, 119–139.

Krammer, K., Lange-Bertalot, H., 1986–1991. Süβwasserflora von Mitteleuropa, vols. 2/1–2/4. Gustav Fischer Verlag, Stuttgart.

Kreutz, J.K., Wake, C.P., Aizen, V.B., DeWayne, C.L., Synal, H.A., 2003. Seasonal deuterium excess in a Tien Shan ice core: influence of moisture transport and recycling in Central Asia. Geophysical Research Letters 30/18. doi:10.10/29/2003GL017896.

Le Callonnec, L., Person, A., Renard, M., Letolle, R., Nebout, N., Ben Khelifa, L., Rubanov, I., 2005. Preliminary data on chemical changes in the Aral Sea during low-level periods from the last 9000 years. Comptes Rendus Geosciences 337, 1035–1044.

Letolle, R., 2002. Histoire de l' Ouzboi, cours fossil de l' Amou Darya: synthese et elements nouveaux. Studia Irinaca 29 (2), 195–240.

Letolle, R., Mainguet, M., 1997. Histoire de la mer d'Aral (Asie centrale) depuis le dernier maximum glaciaire. Bulletin Societe Geologique de France 168 (3), 387–398.

Letolle, R., Aladin, N., Filipov, I., Boroffka, N.G.O., 2004. The future chemical evolution of the Aral Sea from 2000 to the years 2050. Mitigation and Adaptation Strategies for Global Change 47 (1–4).

Lioubimtseva, E., Cole, R., Adams, J.M., Kapustin, G., 2005. Impacts of climate and land-cover changes in arid lands of Central Asia. Journal of Arid Environments 62, 285–308.

Mirabdullayev, I.M., Joldasova, I.M., Mustafaeva, Z.A., Kazakhbaev, S., Lyubimova, S.A., Tashmukhamedov, B.A., 2004. Succession of the ecosystems of the Aral Sea during its transition from oligohaline to polyhaline waterbody. Journal of Marine Systems 47 (1–4), 101–108.

Nourgaliev, D.K., Heller, F., Borisov, A.S., Hajdas, I., Bonani, G., Iassonov, P.G., Oberhänsli, H., 2003. Very high resolution paleosecular variation record for the last 1200 years from the Aral Sea. Geophysical Research Letters 30 (17), 41–44.

Prasad, A.K., Nienow, J.A., 2006. The centric diatom genus *Cyclotella* (Stephanodiscaceae: Bacillariaophyta) from Florida Bay, USA, with special reference to *Cyclotella choctawhatcheeana* and *Cyclotella desikacharyi* a new marine species related to the *Cyclotella striata* complex. Phycologia 45 (2), 127–140.

Reed, J.M., 1995. The potential of diatoms and other palaeolimnological indicators for Holocene palaeoclimate reconstruction from Spanish salt lakes, with special reference to the Laguna de Medina (Cádiz, southwest Spain). Unpublished PhD thesis, University College London.

Reed, J.M., 1998. A diatom inferred transfer function for Spanish salt lakes. Journal of Paleolimnology 19, 339–416.

Rubanov, I.V., Ischniyanov, D.P., Baskakova, M.A., 1987. Geology of the Aral Sea. Tashkent (248 pp.; in Russian).

Rusakova, O.M., 1995. Brief characteristics of the qualitative content of phytoplankton of the Aral Sea during Spring and Autumn 1992. Proceedings of the Zoological Institute, Russian Academy of Science 262 (1), 195–207 (in Russian).

Ryves, D.B., Juggins, S., Fritz, S.C., Battarbee, R.W., 2001. Experimental diatom dissolution and the quantification of microfossil preservation in sediments. Palaeogeography, Palaeoclimatology, Palaeoecology 172, 99–113.

Savoskul, O.S., Solomina, O.N., 1996. Late Holocene glacier variations in the frontal and inner ranges of the Tien Shan, central Asia. The Holocene 6 (1), 25–35.

Schilman, B., Ayalon, A., Bar-Matthews, M., Kagan, E.J., Almogi-Labin, A., 2002. Sea-land palaeoclimate correlation in the Eastern Mediterranean region during the Late Holocene. Israel Journal of Earth Sciences 51, 181–190.

Servant-Vildary, S., Roux, M., 1990. Multivariate analysis of diatoms and water chemistry in Bolivian saline lakes. Hydrobiologia 197, 267–290.

Shermatov, E., Nutrayev, B., Muhamedgalieva, U., Shermatov, U., 2005. Analysis of water resources variability of the Caspian and Aral Sea on the basis of solar activity. Journal of Marine Systems 47, 137–142.

Snoeijs, P. (Ed.), 1993–1996. Intercalibration and Distribution of Diatom Species in the Baltic Sea, vols. I–V. Opulus, Upsala.

Sorrel, P., 2006. The Aral Sea: a Palaeoclimate archive. Doctoral thesis Institut für Geowissenschaften, Universtät Potsdam.

Sorrel, P., Popescu, S.-M., Head, M.J., Suc, J.P., Klotz, S., Oberhänsli, H., 2006. Hydrographic development of the Aral Sea during the last 2000 years based on a quantitative analysis of dinoflagellate cysts. Palaeogeography, Palaeoclimatology, Palaeoecology 234, 304–327.

Sorrel, P., Popescu, S.-M., Klotz, S., Suc, J.-P., Oberhaensli, H., 2007. Climatic variability in the Aral Sea basin (Central Asia) during the late Holocene based on vegetation changes. Quaternary Research 67, 357–370.

Stager, J.C., Cumming, B., Meeker, L., 1997. A high-resolution 11,400-yr diatom record from Lake Victoria, East Africa. Quaternary Research 47, 81–89.

Stone, J.R., Fritz, S.C., 2004. Three-dimensional modelling of lacustrine diatom habitat areas: improving paleolimnological interpretation of planktic:benthic ratios. Limnology and Oceanography 49/5, 1540–1548.

Tapia, P.M., Fritz, S.C., Baker, P.A., Seltzer, G.O., Dunbar, R.B., 2003. A late Quaternary diatom record of tropical climatic history from Lake Titicaca (Peru and Bolivia). Palaeogeography, Palaeoclimatology, Palaeoecology 194, 139–164.

ter Braak, C.J.F., Šmilauer, P., 2002. CANOCO reference manual and user's guide to Canoco for Windows: software for Canonical Community Ordination version 4.5. Microcomputer Power, Ithica, NY.

Treydte, K.S., Schleser, G.H., Helle, G., Frank, D.C., Winiger, M., Haug, G.H., Esper, J., 2006. The twentieth century was the wettest period in northern Pakistan over the past millennium. Nature 440, 1179–1182.

Tsvetsinskaya, E.A., Vainberg, B.I., Glushko, E.V., 2002. An integrated assessment of landscape evolution, long-term climate variability, and land use in the Amu Darya Prisarykamysh delta. Journal of Arid Environments 51, 363–381.

Wilson, S.E., Cumming, B.F., Smol, J.P., 1996. Assessing the reliability of salinity inference models from diatom assemblages: an examination of a 219 lake data set from Western North America. Canadian Journal of Fisheries and Aquatic Sciences 53, 1580–1594.

Witkowski, A., 1994. Recent and fossil diatom flora of the Gulf of Gadansk. Southern Baltic Sea. J. Cramer, Berlin.

Witkowski, A., Lange-Bertalot, H., Metzelin, D., 2000. Diatom Flora of Marine Coasts, vol. I. Koeltz, Koenigstein.

Yakir, Y., Issar, A., Gat, J., Adar, E., Trimborn, P., Lipp, J., 1994. $^{13}C$ and $^{18}O$ of wood from the Roman siege rampart in Masada, Israel (AD 70–73): evidence for a less arid climate in the region. Geochimica et Cosmochimica Acta 58 (16), 3535–3539.

Yang, X., Kamenik, C., Schmidt, R., Wang, S., 2003. Diatom-based conductivity and water level inference models from Eastern Tibetan (Qinghai-Xizang) Plateau lakes. Journal of Paleolimnology 31, 1–19.

Zavialov, P., 2005. Physical Oceanography of the Dying Aral Sea. Springer, Chichester.

Zech, W., Glaser, B., Ni, A., Petrov, M., Lemzin, I., 2000. Soils as indicators of the Pleistocene and Holocene landscape evolution in the Alay Range (Kyrgystan). Quaternary International 65/66, 161–169.