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Climate variability during the past 2000 years and past economic and irrigation activities in the Aral Sea basin

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Abstract

The lake level history, here based on the relative abundance of Ca (gypsum), is used for tracing past hydrological conditions in Central Asia. Lake level was close to a minimum before approximately AD 300, at about AD 600, AD 1220 and AD 1400. Since 1960 the lake level is lowering again. Lake water level was lowest during the 14th or early 15th centuries as indicated by a coeval settlement, which today is still under water near the well-dated mausoleum of Kerderi. Pollen data from riparian vegetation indicate relatively moist conditions between AD 400 and AD 900, intermitted by short intervals with drier conditions (AD 550- 600; AD 650-700). Riverbanks were again dry from AD 900 - 1150, AD 1450-1550, and from AD 1970 onward moisture decreased steadily. Irrigation activities were at a maximum between 300 BC and AD 300 (Classical Antiquity) and between AD 800 and AD 1300 (Medieval Age) and after AD 1960.

Key words: Lake levels, hydrology, riparian vegetation, settlement history, Medieval Warm Period, Little Ice Age

INTRODUCTION

The modern regression in the Aral Sea region, which started in 1960, has received great attention (e.g., Aral´skij krizis, 1991; Létolle and Mainguet, 1996; Micklin and Williams, 1996; Nihoul et al, 2004, Ferguson, 2003). Due to extensive irrigation in this area, the exploitation of water resources has not only reduced the lake level but the system reached a critical stage in the water and soil pollution. As a result, a broad scope of studies is required to improve our knowledge on ecosystem functioning, which will help to attenuate environmental and socio-economic risks in future decades. In the context of a policy of appeasement, sustainability rather than searching for new ways to exploit the system should be in the focus of upcoming studies.

However, which have been the links between climate variability and ecology in the Aral Sea basin in the past? Due to the climatically exposed continental conditions (semi-arid or even arid over large areas), western Central Asia with extensive deserts is potentially vulnerable to minimal environmental change. Deserts spread north of the Kopet Dagh - the Karakum Desert – through the foothills of Pamirs and Tien Shan, - the Kyzylkum Desert. For present and past settlements active fresh water resources are restricted to the flood plains and riverbanks along the Syr Darya and Amu Darya, both of them discharging into the endorheic Aral Sea. However, water resources feeding the rivers seem almost unlimited as, in the headwaters of the rivers, extended glacier systems of the Tien Shan and Pamir Mountains are steadily delivering fresh water. Similar climate conditions not only apply for today, but also have been dominating the landscape throughout most of the Holocene though the Amu Darya has transiently bypassed the Aral Sea and directly discharged into the Caspian Sea (e.g., Tolstov, 1962).
The Aral Sea basin hosting one of the Silk Road branches is, therefore, an excellent study area for tracing human agricultural activities but also for highlighting human measures and reactions to past climate changes. To shed light on the past climatic and especially hydrological conditions we launched the INTAS-Project “CLIMAN” (Holocene climatic variability and evolution of human settlement in the Aral Sea Basin; http://climan.gfz-potsdam.de/). The interdisciplinary study was designed to analyse natural climatic variations and anthropogenically controlled environmental changes in the past (Boroffka et al., 2003–2004, 2005, 2006; Sorrel et al., 2006, 2007a,b; Austin et al., 2007 in press). In a geomorphologic survey, we focused on previous lake-level changes as recorded in shoreline marks during the last 5000 years (Figure 1) (Krivonogov et al., 2003; Reinhardt and Wuennemann, 2005) and related these

observations to archaeological findings (Boroffka et al., 2006).

However to date, relatively little attention has been given to connections between local and regional climate changes over the Eurasian region. At a regional scale, past climate variability in the arid Aral Sea basin represents an important key for understanding future climate change, which may affect even more drastically such arid and semi-arid regions. Besides, understanding past climate change it is of great importance to evaluate the anthropogenic impact on present-day and future climates in this highly sensitive semi-arid region.

In this paper we focus on past climatic variations as expressed in humidity and temperature changes and evaluate irrigation activities as inferred from archaeological data. Natural climatic changes evidenced by temperature and precipitation variations during the last 2000 years are inferred from vegetation remains (pollen grains) studied in a core retrieved from Chernyshov Bay, in the northwestern Large Aral Sea (Figure 2). We then use the relative Ca and Sr abundances (mostly contained in gypsum and authigenic carbonates), for tracing salinity changes (Ca) and for discriminating between Syr Darya and Amu Darya river water input (Sr). During the last 2000 years salinity is controlled by river discharge, but indirectly salinity is also reflecting lake level changes (Figure 2). By looking at the displacement of human settlements we try to rate and estimate the controlling factors, e.g., human versus natural climate forcing. Both, though to different extent, might influence the water balance too.

Main features of the hydrology in the Aral Sea Basin

Lake level changes in the endorheic Aral Sea are preferentially controlled by river discharge of Amu Darya and Syr Darya, which are affected by two main factors (i) climatic change in the headwater system of the rivers and/or by (ii) men-controlled irrigation activities. Both play at times a dominating role. Today Global Climate Change affects melting rates in the headwater region but also the precipitation rates; both are increasing due to globally raising average annual temperatures but evapo-transpiration at high altitudes might increase too (Aizen, pers. communication 2006). Besides the riverine drainage, the annual hydrology budget of the endorheic Aral Sea is further controlled by evaporation, which from open water is more than seven times higher than precipitation.

Today the average annual rainfall ranges from 100 to 140 mm/year (Bortnik and Chistyaeva, 1990). The net river discharge, a major fresh water source of the endorheic Aral Sea has changed a lot during the last 100 years. Both rivers Amu Darya and Syr Darya discharged in the range of 56 to 58 km^3/year ± 14 km^3 between 1911 and 1960 (Bortnik and Chistyaeva, 1990). After 1960 the hydrological cycle of western Central Asia has been disturbed fundamentally by (i) the use of river water for irrigation and, (ii) the building of numerous reservoirs and wide channels along the two tributaries and into the Karakum Desert. Since 2002 the discharge had been reduced to less than 10 km^3/year (Zavialov, 2005) and actually the Amu Darya contributes less than 1 km^3/year (Zavialov, pers comm. 2006). The rivers feeding into the lake emerge in the Tien Shan and Pamir Mountains to the east with meltwater.

Geomorphologic settings

Geomorphologic surveys and analyses of satellite images reveal distinct shoreline fluctuations in the past (Figure 1) by tracing positions of ancient littoral terraces, beach ridgesand wave-cut escarpments, and by mapping features such as channel alignments to paleoshorelines and abandoned delta areas. For characterisation of the past local drainage network and lake level reconstruction we combined field observations, and used LANDSAT satellite images together with a digital elevation model (DEM) (e.g., Krivonogov, et al., 2003; Reinhardt and Wuennemann, 2005). The highest shoreline along the northern Small Aral Sea (Tastubek Bay, Figure 1) was observed at 53–54 m a.s.l (Boroffka et al. 2006). The perimeter at different lake stages shown in Figures 1a,b shows large surfaces due to the flat topography around the lake and in the delta. For settlement activities even the slightest lake level changes might open new perspectives as will be shown in the discussion below.

Methods

Sediment coring was performed at Chernyshov Bay, a 22-m deep basin located at the northwestern shore of the Aral Sea and today still attached to the Large Aral Sea (Figure 1). With a Usinger piston corer (http://www.uwitec.at), we retrieved sediment cores of 6 and 12 m in length. The description of the core lithology is based on macroscopic and smear slide observations (Sorrel, 2006). The relative calcium and strontium abundance in sediment cores was measured by scanning cores with the XRF Core Scanner (®AVAATECH) (Jansen et al, 1998) at a 1-cm resolution, representing less than a decadal time resolution. The chronology for the sediment core is based on AMS ^{14}C dates on the green alga *Vaucheria* sp., which are reported as calibrated ages (Nourgaliev et al., 2003; Sorrel et al., 2006).

For tracing moisture and temperature variations in the past (Figure 3) we studied the vegetation changes. Pollen slide preparation followed the Cour's method (Cour, 1974). A transmitting light microscope using ×400 and ×1000 magnifications was used for pollen identification. This was performed using the pollen photograph bank and several atlases of the 'Laboratoire PaléoEnvironnements et PaléobioSphère (PEPS)' (UMR CNRS 5125, Lyon, France) as well as its pollen database "Photopal" (http://medias.obs-mip.fr/photopal). Concentration in palynomorphs varies from <500 to >45,000 grains/g. Minimums of 100 pollen grains, excluding *Amaranthaceae-Chenopodiaceae* and *Artemisia*, which are usually over-represented in arid environments, were counted in each sample. Generally more than 25 different taxa were found in each sample, but a total of 79 different taxa have been identified (Sorrel et al., 2007a).

Pollen grains transported either by air or by rivers reflect the local to regional vegetation. Here we present the results inferred from the quantification of pollen data. For the quantification of palaeoclimate signals recorded in plant assemblages, the "probability mutual climatic spheres" (PCS) method described in detail by Klotz and Pross (1999) and Klotz et al. (2003, 2004) was used. The main restriction in applying modern analogue methods in this study is the general poorness of the available database of surface pollen spectra from the Aral Sea region (only 91 in Kazakhstan, Tarasov et al., 1998), which may serve as modern analogues for reliable climate reconstructions. Hence the use of the PCS method is more suitable than modern analogues for the reconstruction of climate change in the Aral Sea basin during the last 2000 years. For more compelling information on the application of the PCS method to our case study, we refer to Sorrel et al. (2007a).

Besides, we investigated the northern and southern shores of the Aral Sea for archaeological remains during two expeditions in 2002 and 2003. During these studies, archaeological traces were positioned by geographic positioning system (GPS) and dated by (i) conventional archaeological methods and, (ii) by comparing archaeological assemblages to radiocarbon-dated material from analogous sites (Boroffka et al., 2006). The complete repertoire of archaeological finds (the toolkit) was studied to reconstruct the economic basis through time. Previously collected archaeological data is re-evaluated in light of new informations, and placed within the context of results from both palaeontological and geological investigations.

Lithology: Gypsum and Sr content as hydrological indicators

From sediments retrieved at Chernyshov Bay, in the northwestern Aral Sea, we used dinoflagellate cysts and diatoms, both sensitively reacting on salinity changes, for tracing variations in lake levels (Sorrel et al, 2006; Austin et al., 2007). Furthermore, the sediments, mostly consisting of dark clayey and silty muds with changing organic contents (Sorrel, 2006), contain four levels of gypsum-rich mud, forming distinct light-coloured beds or dark clayey muds with abundant idiomorphic gypsum crystals (Fig. 2, in Sorrel et al., 2006). The observed lithologic changes measured at a time resolution of less than a decade are coeval with the increase of the relative contents in calcium (Boroffka et al., 2006). Gypsum ($CaSO_4 \cdot 2H_2O$) precipitates when salinity reaches concentrations beyond a certain level; it is, therefore, a typical indicator of progressive salinization, and we use the element scans of calcium to keep track of the lake's desiccation state. In the Aral Sea, the stage of over saturation for gypsum was reached in the early 1960s when salinity exceeded 26–28 ppt (Bortnik and Chistyaeva, 1990). Thus, we can use the relative abundance of Ca to estimate beginning of changes in the river inflow, which control, together with the annual evaporation (approximately 100 cm/y), the water balance and at a longer time range the lake level of the Aral Sea. In Figure 2, the relative calcium abundance indicates distinct changes through the last ca. 2000 years. High relative calcium content reflects rising salinities and lowering of lake levels. Minimum lake levels, with precipitation of chloride salts are following the Ca-sulphate maximum but are not reported in Figure 2a. According to the age model, these events culminate around AD 600, AD 1220, AD 1500 and slightly elevated values occur at about AD 750, AD 1000, and AD 1800. Between AD 0 and AD 300 (?) we observe an increased variability with average values similar to the event at AD 600. Most of these events match with salinity changes as reflected by dinoflagellate cyst assemblages. With dinoflagellate cysts we also have 2 phases of higher salinity at ca. AD 1500 and ca. AD 1600/1650, which is matching well with results obtained on ostracods by Boomer et al., (2000) despite a coarser time resolution. Lake-level low stands from the eastern basin dated to approximately AD 350–450 and AD 1550–1650 are also concurrent with our observations (Rubanov et al. 1987; Maev & Karpychev, 1999). Comparing the salinity record (Figure 2a) with the precipitation as reconstructed from pollen (Figs. 2e, 3), lower precipitation rates generally fall into intervals when salinity levels are elevated

Another element, strontium, may further be applied for reconstructing the river discharge in the Aral Sea basin. Indeed recent studies on river water (Le Callonnec et al., 2005) have shown that only the Syr Darya, due to the specific rock composition in the watershed, discharges dissolved Sr into the Aral Sea. Therefore we use the relative Sr content in the sediment core to discriminate between the water discharge of the Amu Darya and Syr Darya. In Figure 2 the relative abundance of Ca and Sr show enrichments of 6 to 8 times above average levels at about AD 1220. During the 2nd half of the past century Sr is also drastically increasing. In between Sr shows only some minor fluctuations, like at around AD 600 and AD 1400. We may therefore conclude, that during short intervals between ca. AD 1200 and AD 1250 and since AD1970 onwards, the Syr Darya discharge into the Aral Sea has increased disproportionately.

Vegetation changes as climate indicator

The pollen-based temperature and precipitation reconstructions document shifts in vegetation development that reflect climate changes in western Central Asia linked to the atmospheric circulation in the eastern Mediterranean region (Figure 3). In the Aral Sea basin, the climate during the first few centuries AD according to our chronology was featured by cold winter temperatures, relatively cool summers and arid conditions (mean annual rainfall <300 mm). Similar conditions were reported from Syria with reduced winter / spring rains (Bryson, 1996), while a pronounced decrease in humidity and lake levels occurred in Lake Van, Turkey, between ca. 1500 BC and AD 0 (Landmann et al., 1996, Lemcke and Sturm, 1996). In Soreq Cave (Israel), the time span AD 0–400 is characterized by decreasing precipitation (Schilman et al., 2002) implying a diminishing activity of cyclones in the eastern Mediterranean region. This arid phase was followed by a general increase in temperature and moisture conditions between ca. AD 400 and AD 900, although some fluctuations in the precipitation (MAP) and temperature (MTW) records are evident especially around AD 550–600 and AD 650–700. This milder period (cool winters, warm summers), however, was probably favourable for the development of some arboreal vegetation in the less dry edaphic areas and the replacement of subdesertic herbs by steppe vegetation (Sorrel et al., 2007a). This is coevally a period of elevated temperatures and favourable conditions for the growth of trees in Israel (Lipschitz et al., 1981), linked to increased rainfall over the eastern Mediterranean (Bar-Matthews et al., 1998; Schilman et al., 2002). By ca. AD 900–1150 climate switched back to drier and somewhat cooler conditions in the Aral Sea basin, with cold winter temperatures (–7° to –10°C), cool summers (15°–21°C) and reduced precipitation rates (< 250 mm/yr). 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 δ^{18}O values in Soreq Cave carbonate deposits (Schilman et al., 2002).

After ca. AD 1150, reconstructed climatic parameters suggest the onset of less arid conditions in western Central Asia with increased precipitation (370–500 mm.yr^{-1}) and warmth (mean annual temperature: 7°–11°C), which were maintained until the beginning of the 15th century AD ("Medieval Warm Period"). These conditions probably favoured the establishment of a riparian forest vegetation and the regression of both steppe herbs and shrubs in the Aral Sea region, coevally with the development of some trees along river valleys. At the onset of more humid conditions in the Aral Sea basin, the climate signal from the Eastern Mediterranean indicates a conspicuous decline in terrestrial δ^{18}O values from the Soreq Cave. This is interpreted as strong positive rainfall anomalies in Israel (Schilman et al., 2002), reflecting enhanced cyclonic activity in the eastern Mediterranean during winter and early spring. It also coincides with high-stand levels of the Dead Sea (Issar et al., 1991) and the Sea of Galilee (Frumkin et al., 1991) implying thus elevated moisture conditions. From ca. AD 1450 to AD 1550, the Aral Sea region probably experienced a brief aridification with colder and drier conditions. This short interval has been identified in other regions within Eurasia (Mackay et al., 2005), and corresponds to the Little Ice Age. In the eastern Mediterranean Region this period is characterized by higher $\delta^{18}O$ values from the foraminifera *G. ruber* (Schilman et al., 2002) within marine deposits off Israel (Bar-Matthews et al., 1998; Schilman et al., 2002), indicating lower sea surface temperatures and thus lower moisture transported to western Central Asia. From AD 1550 onwards (to ca. AD 1970), the pollen reconstruction indicates a progressive warming of the climate and evidences enhanced aridity and higher temperatures during recent decades. For the last ca. 50 years, our reconstructed values are in accordance with present-day measured data from Central Asia (Sorrel et al., 2007a).

The climate reconstruction provides evidence that centennial-scale events are recorded for the last 2000 years, implying that the precipitation pattern in the Aral Sea basin is strongly linked to atmospheric changes in the eastern Mediterranean region, which modulates the moisture distribution towards the Middle East and western Central Asia. The climatic reconstruction is in agreement with former paleo-environmental, historical and archaeological studies from Russian scientists who attributed the decline of the classical and medieval civilization of Turkestan to an enhanced aridity (Shnitnikov, 1969; Doluhanov, 1985; Varuschenko et al., 1987). For the last 2000 years, however, no human activity exerting control on vegetation change has been detected from the pollen record of Chernyshov Bay. Hence a pervasive and strong impact of human-induced processes on climatic and environmental changes in western Central Asia during the last millennia, as suggested by Kharin et al. (1998), is unlikely.

Archaeological features and water availability

As to the settlement history there is a tight link between climate and hydrology. Levina (1998) and Boroffka et al. (2003–2004; 2005; 2006) have recently demonstrated that ancient settlement development is quite well understood for the region south of the Aral Sea. Along the northern shore, however, the knowledge of human life is still patchy, although the CLIMAN expeditions have filled many chronological gaps in the human settlement history, Human settlement around the Aral Sea begins in the middle Palaeolithic (50.000–35.000 BC). After a long period without information, a gap not yet well understood, Neolithic (5.000–3.000 BC) sites of the Kel´teminar culture are well known north and south of the lake. During Eneolithic and Early Bronze Age (3000–2000 BC) the Kel´teminar culture remains restricted to the south. Along the northern shore settlers change their cultural and economic orientation. They used large projectile points for hunting big game which shows analogies to finds from the forest and forest-steppe zones of the Tobol-Ishim-Irtysh River system and the eastern Ural Mountains, indicating that forest and forest-steppe zones had extended further to the south. This vegetation change heralds more humid conditions, as humans did not apply irrigation systems in this region at that time (Boroffka et al., 2003–2004; 2005; 2006). From the classical Bronze Age (beginning around 2000 BC), the earliest canals for irrigation agriculture are known from the southern foreland of the Aral Sea (Figure 4). It is therefore from this period onwards, that the human factor needs to be taken into account when studying hydrological changes in the Aral Sea basin.

Settlement economy and irrigation

There is general agreement that, before the expansion of irrigation since 1960, fluvial discharge by Syr Darya and Amu Darya was sufficient to maintain the endorheic Aral Sea during several thousand years (Andrianov 1969; Létolle and Mainguet 1996). However, from historical descriptions we understand that already in the past some cultures populating Turkestan used the river water in a more abusive than in a sustainable way (Tolstov, 1962). Hence depending on the population density and the economic power, the irrigation on the riverbanks and flood plains of Amu Darya and Syr Darya may, besides the climate, have put additional pressure on the regional hydrology already in the past.

For the Neolithic Kel´teminar culture (5000–3000 BC) the toolkit (with harpoon insets and small projectile points) and the site distribution along ancient river courses and around former lakes, indicate an economy in which hunting and fishing played a major role (Boroffka et al., 2003–2004; 2006). For the following period, especially in the north, we observed large projectile points, which indicate a reorientation towards hunting of larger animals (e.g., horses). This proves that economic strategy has been reverted and adapted to a forest steppe environment. The expansion of the forest steppe zone towards the south reflects a more humid climate between 3000 and 2000 BC. By this time men did not influence the environment to any significant point, but rather reacted to natural environmental changes adapting settling and economic strategies (Boroffka et al., 2003–2004; 2005; 2006).

During the Bronze Age (2000–1000 BC) man became more independent of the environment, and the first irrigation channels have been documented near the southern Aral Sea (Itina 1977) (Figure 4). However these systems were of local scale and did not, therefore, have any major effect on the hydrology of the Aral Sea. Besides, water level at this time was low, as could be observed in a coeval settlement located at the southeastern part of the Aral Sea, which was later buried under lake sediments. Moreover, a high density of Neolithic settlements may be observed along the Uzboj channel (Tolstov, 1962). We conclude that, due to a change in the river course before the Neolithic, the Amu Darya had been diverted from the Aral Sea and drained to a great extent the Caspian Sea. A lack of coeval sites along the Akcha Darya channel to the north of the Khorezm basin indicate that this channel was not active at that time, hence confirming this interpretation. Conditions changed during the Bronze Age, when intense settling occurred along the Akcha Darya (now clearly carrying water to the Aral Sea), while river flow almost ceased along the Uzboj (Tolstov 1962; Itina 1977; Boroffka et al., 2005; 2006). These shifts in water-courses may have been due to tectonic uplift in the lower Amy Darya river valley, as observed in other regions of Central Asia (Gentelle, 1989). However there are no early historical sources referring to earthquakes, which could help to unravel the chronology of geodynamic events. Further research is needed before this aspect can be evaluated at large.

Irrigation intensified during the 1st Millennium BC and reached a first maximum extension during Classical Antiquity (4th Century BC – AD 4th Century) (Figures 2d, 5). Traces of ancient canals, some more than 20 m wide and stretching over many kilometres, have been observed. According to Tolstov (1962), Andrianov (1969, 1991), Gerasimov (1978), Baipakov & Groshev (1991) and Levina & Ptichnikov (1991) the network of canals would allow to irrigate 5 to 10 million hectares, an area equivalent to the northern and southern banks of the Amu Darya, the Khorezm Basin, the Sarykamysh Basin and the entire area between Syr Darya and Zhana Darya (Figure 6). A regression of the Aral Sea has been reconstructed for this period (Aladin & Plotnikov, 1995; Boomer et al., 2000; Sorrel et al., 2006). The increased irrigation activity possibly helped to accelerate the desiccation of the Aral Sea during Classical Antiquity, as increased aridity at this time has been observed in several regions of the Old World (Bryson, 1996; Landmann et al., 1996; Lemcke & Sturm 1996; Schilman et al., 2002; Schmidt & Gruhle, 2003). The irrigated surface in this region surprisingly was of similar extent, 6.5 million hectares, when the Soviet Union collapsed (Boomer et al., 2000). Today we know that irrigation is indeed one of the factors controlling the extent of lake regression.

During the medieval period (9th-14th centuries) irrigation (Figures 2d, 7) again reached roughly the extent it had during Antiquity (Tolstov 1962; Andrianov 1969; 1991; Gerasimov 1978; Baipakov & Groshev 1991; Levina & Ptichnikov 1991) and could have also influenced the water balance of the lake. These irrigation systems, controlling the river discharge to the Aral Sea in the north and the Sarykamysh basin in the west, were destroyed repeatedly. After the destructions assigned to the Mongol invasion in the year 1221, the Amu Darya appears to have changed its course towards the Uzboj and the Caspian Sea (Barthold 1910). Support comes from the Sr record when we observe increased Sr input indicating that possibly at this time mainly Syr Darya water was discharging into the lake. During the 1370´s and 1380´s, coeval to Timurs campaigns against Khorezmia, dams and weirs were again destroyed and the Amu Darya filled lake Sarykamysh (Yagodin, 2005). However this event did not have a deep impact on the lake’s chemistry like at the beginning of the 13th century. Salinity levels, as inferred from dinoflagellate cysts, diatoms and Ca values, were maintained at low levels and enrichment of Sr was moderate to minor, indicating that the Amu Darya was probably only partly deviated towards Lake Sarakamysh and still discharged a major amount of water into the Aral Sea (Figure 2 b). Based on archaeological data it was only during the AD 14th or early 15th centuries when the lake level was well below the present day lake level (Figure 2c). This regression is, however, witnessed by the mausoleum at Kerderi situated at 31 m a.s.l. (Figure 2c, d), and it also corresponds to the period when settling activities at Pulzhaj ceased.

Both Kerderi and Pulzhaj are important medieval sites, only have only been observed during the CLIMAN expeditions. The mausoleum of Kerderi is located in the northeastern part of the Large Aral Basin while Pulzhaj is situated at the southern end of the former Aibugir Bay on the southwestern edge of the Aral Sea (Figures 1, 6). At Pulzhaj the dated archaeological materials together with dated sediments from an adjacent outcrop allow to identify transgressions around the AD 4th Century and after AD 1400. Between these transgressions, people lived on the lowlands indicating that the water level (53 m a.s.l.) must have been lowered by at least a few meters. Lowering of lake levels, however, should be minimal because dinocyst assemblages, according to Sorrel et al. (2006), still indicate lower salinity levels between ca. AD 400 and AD 900. A short lasting prominent lowering, however, might have occurred at about 600 AD and this is also corroborated by increased Ca contents (Figure 2a).

The Medieval regression seems at least partly related to human activity (Boroffka et al., 2006; Austin et al., 2007). Dinoflagellate cyst assemblages like the negative sheet-wash index are rather in favour of a climatically driven Medieval regression starting at around AD 900 and lasting until about AD 1220 (Sorrel et al., 2006). A climatically driven decreased river discharge is confirmed by the tree ring record of Esper et al. (2002) from the Tien Shan and northwestern Karakorum Mountains the high catchment areas of the Syr Darya and Amu Darya rivers. During this interval when lower river discharge are reported, tree-ring growth was minimal, still an indication that late spring and summer temperatures were at a minimum. At about 1220 AD this regressive event terminates, which matches quite well with pollen data indicating that climate became transiently more humid. However, it is at about the time when a drastic event changed the lake’s chemistry. It may be a combination of several events, which fall into this time window. At AD 1208 a major earthquake with magnitude above 6 occurred in this area. This might have caused major damages including destroying the river channel thus changing the flow direction of Amu Darya towards the Caspian Sea. Furthermore, historical sources document another event, which might have affected the discharge of the Amu Darya. In AD 1221 the Mongols destroyed great parts of the irrigation system in the delta plain. As a result both events might have deviated the Amu Darya for some decades during which only the Syr Darya was feeding the lake as shown by the dramatic increase of Sr in the Aral Sea sediments (Figure 2b).

After AD 1550 the pollen reconstruction documents a steady warming, with only minor oscillations. Since the 19th century reliable reports exist on irrigation in the Aral Sea region (Sarybaev, 2002). At about AD 1815–1816 construction of dams is well documented. The first dam was built on the Syr Darya, causing the Tanghi-Daria (= Zhana Darya?) to fall dry (Murchison & Khanikoff, 1844; Wood 1875; Meiendorf, 1975). A following dam cut off the Kuvan Darya (south of the Syr Darya) from the Aral Sea (Butakoff 1853; Michell 1868; Wood 1875). Along the Taldyk several dams were constructed (Wood, 1875) and remains of dams were observed on the Kuldun (Wood, 1875). In AD 1857 the Laudan canal, branching west from the Amu Darya, was closed; before AD 1863 a dam was built near Khodzeili to close the Kok Uzak (Wood, 1875). Some of the actions were politically intended. The Khan of Khiva shut down the Laudan and the Kok Uzak to impose a penalty for nomads or Turkmen raiders. This resulted in the drying up of Aigubir Bay (Butakoff & Michell, 1867; Wood, 1875 and map). However, this basin was already flooded again by AD 1891 (Blanc 1891) and at least the northern part remained under water until AD 1931 (Arkhangelskii, 1931), which Kropotkin (1904) ascribed to a climatic change. Indeed there is no indication, that the Laudan canal was re-opened at that time. These well-documented records showing abundant manipulations on the irrigation system during the 19th century, match with minor to moderate water level (Sorrel et al., 2006; Austin et al, 2007) and vegetation (Sorrel et al., 2007a) changes recorded in the sediment cores retrieved from the Aral Sea.

Conclusions:

Reconstruction of past climate from proxy data is important for improving constraints on the role and the scope of natural climate variability onto environments that have been persistently influenced by anthropogenic activities. Most observations show that the changes in climate were a prominent factor controlling the environment and human irrigation activities (most probably during the Antiquity and the Middle Ages) exerted some controlling function. But only for the last decades we have compelling evidences that mankind is unequivocally controlling the environmental changes in the Aral Sea basin. Given the different time resolution it is not always unequivocal to match single anthropogenic influences with climatically driven events. Highest time resolution is provided from chemical data (X-Ray Fluorescence scanning data), which allow a resolution better than a few years, while from archaeological toolkits, unless written documents are available, the spatial and temporal resolution is rather sketchy. Therefore the presented interpretations on mutual influences between climate and man are a first attempt to highlight past interaction between men and climate in this region.

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Figure captions:

Fig. 1 Ancient lake level reconstruction for the Aral Sea (a) and a close-up of the Pulzhaj area SW of the Aral Sea (b) (after Krivonogov et al., 2003)
Coloured lines outline different lake levels: blue 54 m asl.; rose 53 m asl.; red 46 m asl.; dashed green and red lines are hypothetical sea levels above 54 m asl. earlier reported by Boomer et al. (2000).

Fig. 2 Sediment core from Chernyshov Bay: a) Lithology with relative Ca and b) Sr concentrations through the core reflecting salinity change within the lake water body, c) lake level changes related to d) human and/or e) climate causes.

Fig.3 Climatic variations in the Middle East and western Central Asia based on reconstruction from pollen data (Sorrel et al., 2007a). MTC: mean temperature of the coldest month (°C); MAT: mean annual temperature (°C); MTW: mean temperature of the warmest month (°C), and MAP: mean annual precipitation (mm/yr) in the Aral Sea basin during the last 2000 years. These climatic parameters are compared to the $\delta^{18}O$ record from carbonate deposits in the Soreq Cave, Israel (Schilman et al., 2002).

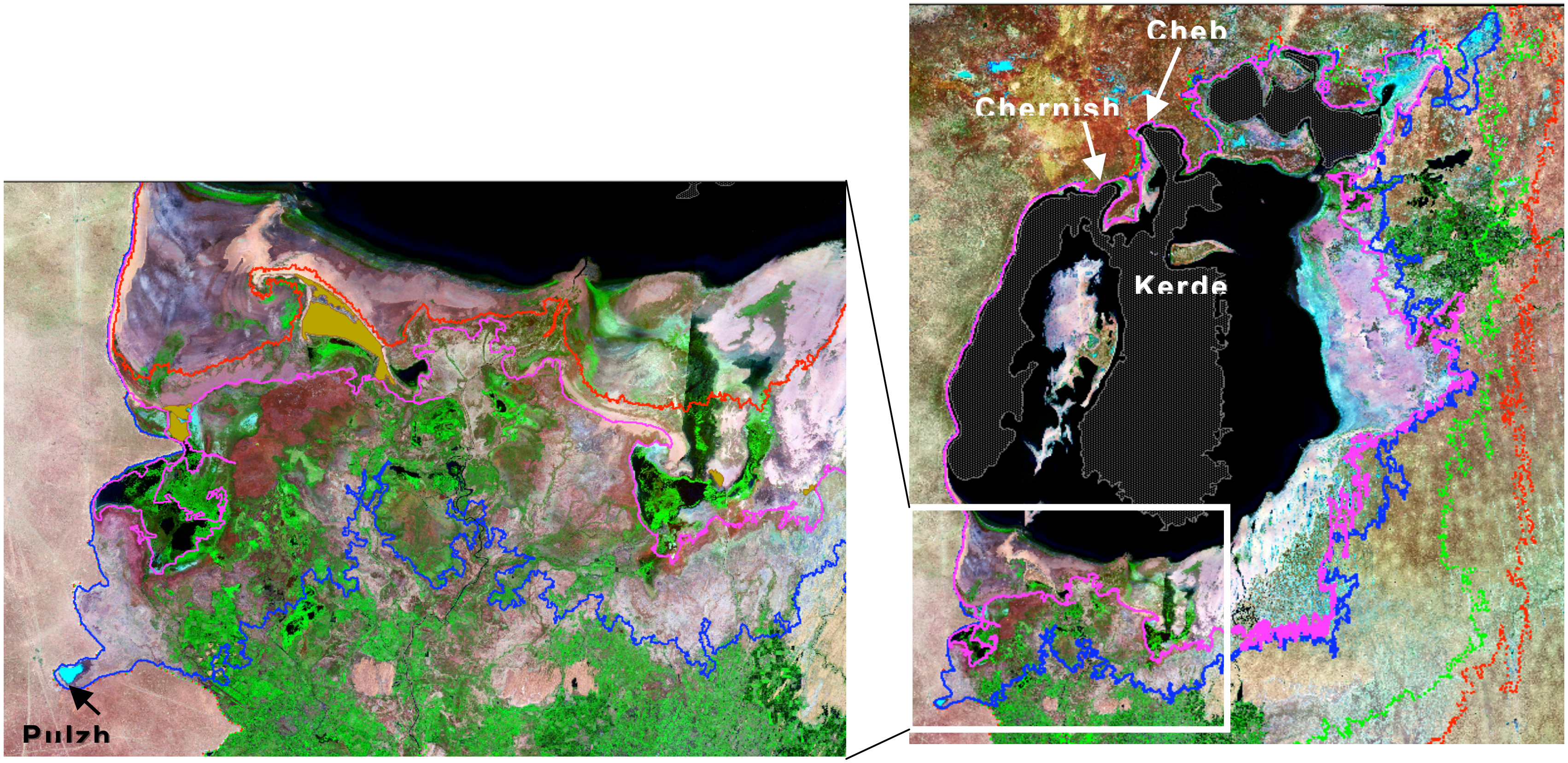
Fig. 4 Settlement and irrigation systems of the Bronze Age (4000–3000 BP) at Kokcha, site 15: 1 pit-dwellings, 2 surface dwellings, 3 irrigation canals (adapted from Itina, 1977).

Fig. 5 Settlements and irrigation systems near Bazar-kala. A: general plan, 1 Bronze Age canals, 2 canals of the 7th–5th Century BC, 3 canals of Antiquity (4th Century BC – AD 4th Century), 4 Earthworks connected to irrigation, 5 rivers, 6 Bronze Age settlements, 7 settlements of the 7th–5th Century BC, 8 settlements of earlier Antiquity (4th Century BC – AD 1st Century), 9 settlements of later Antiquity (AD 2nd – 4th Century); B: Aerial photograph of Bazar-kala with one of the major canals; C: cross section of a major canal at Bazar-kala (point 423). A-C adapted from Andrianov 1969.

Fig 6 Areas with archaeological traces of ancient irrigation systems (shaded) around the Aral Sea, with location of some important sites.

Fig. 7 1 Aerial view of irrigated field systems near Koi Krylgan Kala (4th Century BC – AD 4th Century) (adapted from Andrianov, 1969), 2 irrigated field system of the AD 11th – 13th Century north of Kokcha (CLIMAN Expedition, 2003).

Fig. 1



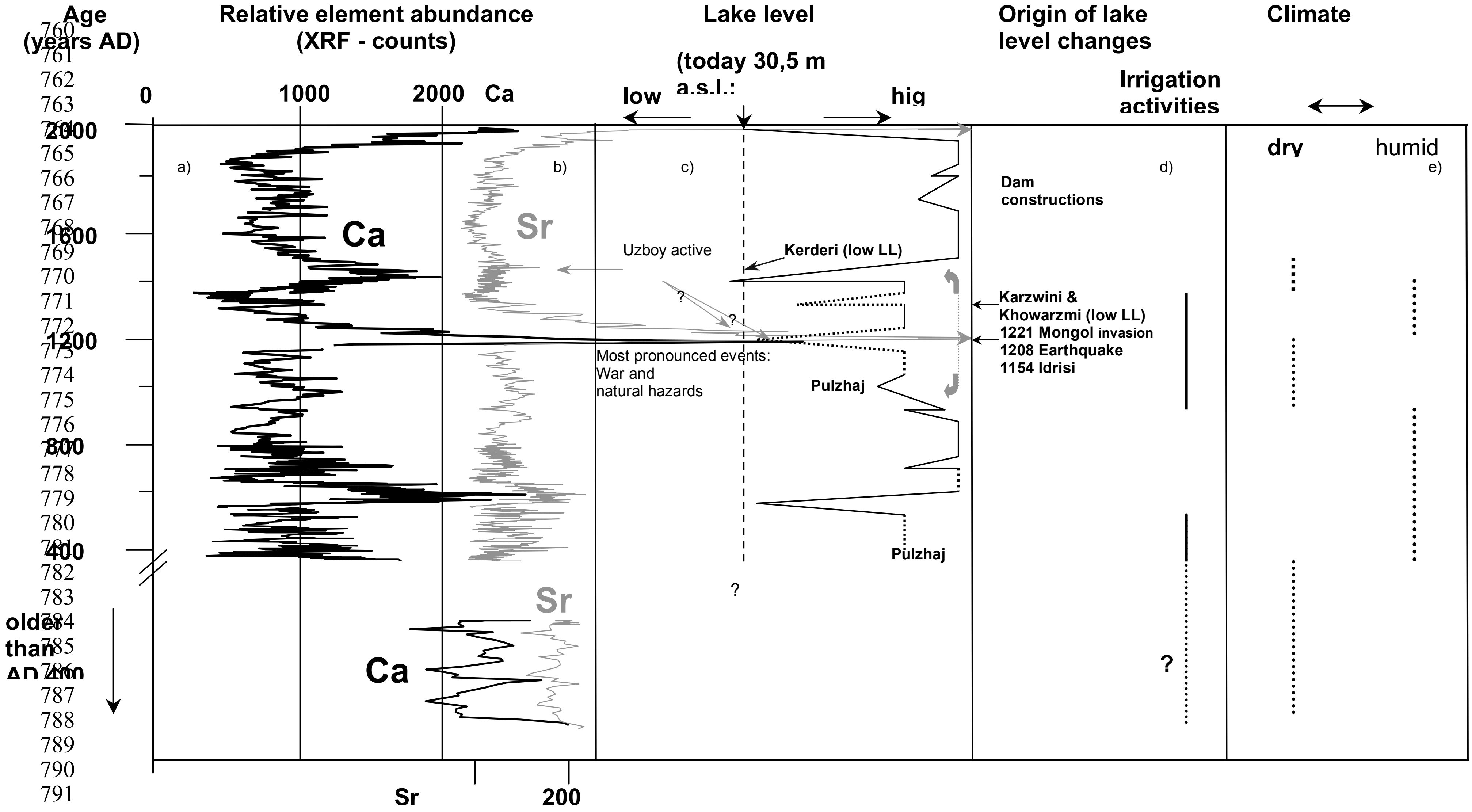
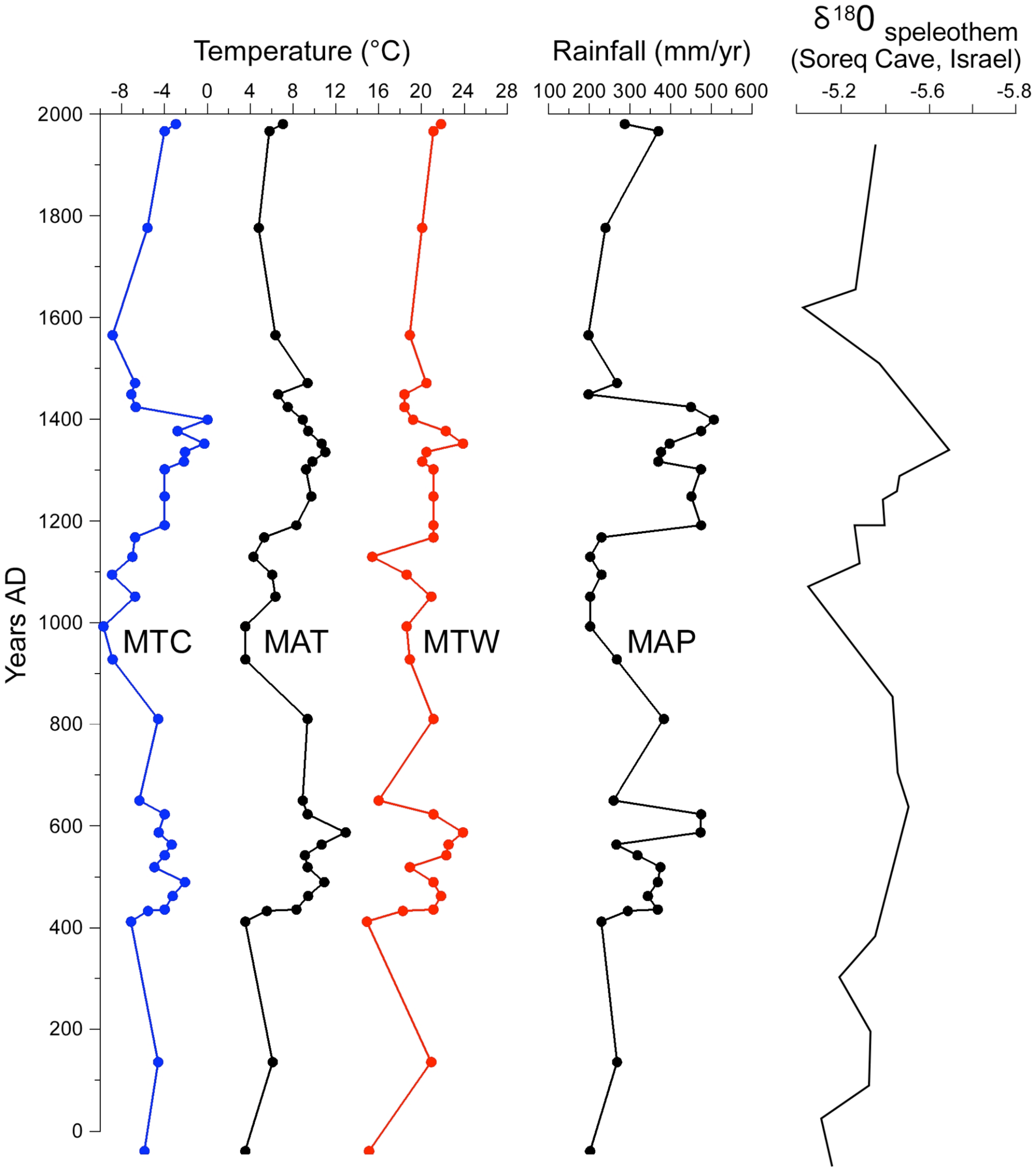

Age
(years AD)
Relative element abundance
(XRF - counts)
Lake level
(today 30,5 m
a.s.l.:
Origin of lake
level changes
Irrigation
activities
Climate
0
1000
2000
Ca
low
hig
dry
humid
2000
1600
1200
800
400
older
than
AD 400
a)
b)
c)
d)
e)
Ca
Sr
Uzboy active
Kerderi (low LL)
?
?
Most pronounced events:
War and
natural hazards
Pulzhaj
Pulzhaj
?
Dam
constructions
Karzwini &
Khowarzmi (low LL)
1221 Mongol invasion
1208 Earthquake
1154 Idrisi
Sr
Ca
?
Sr
200

Fig. 2

795 **Figure 3**



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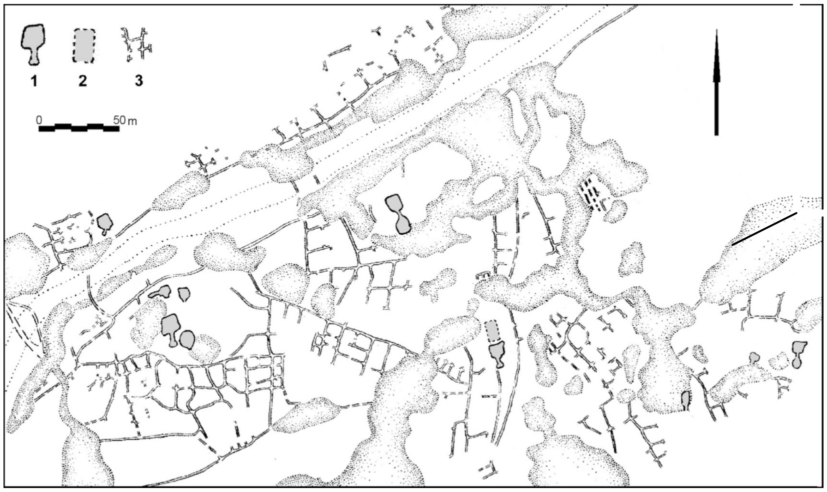

Figure 4

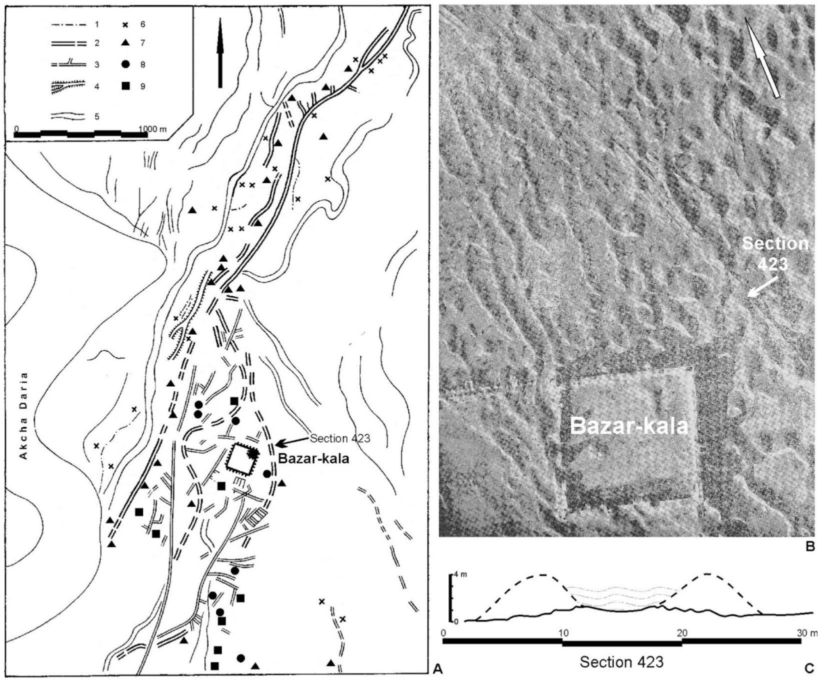

Figure 5

Figure 6

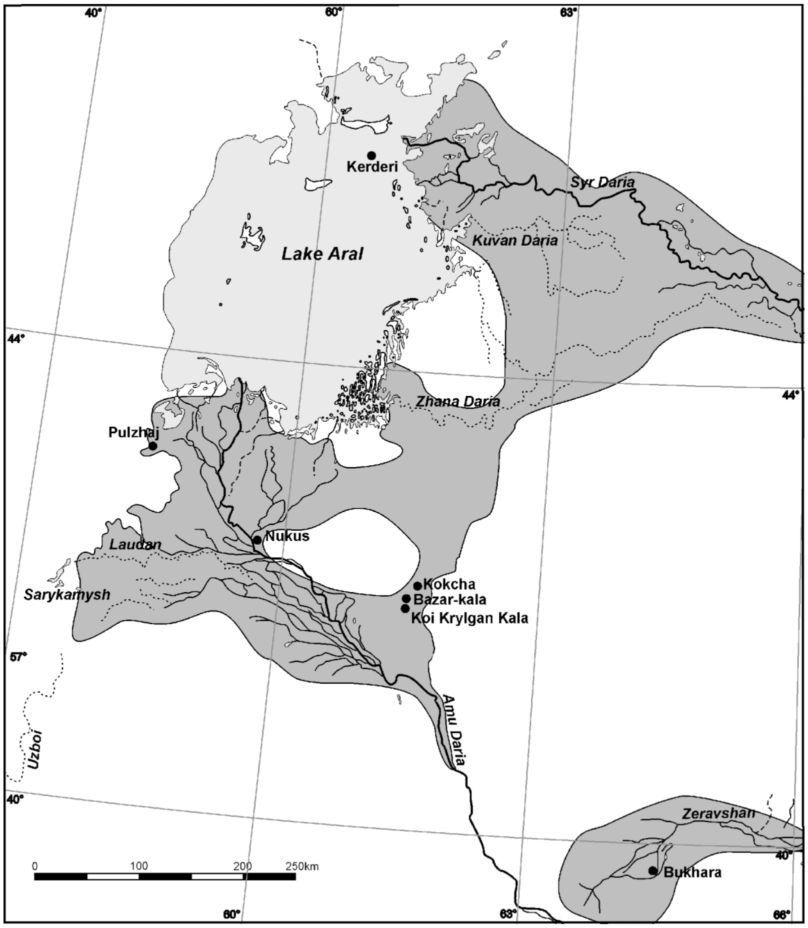
40°
60°
63°
Kerderi
Syr Daria
Lake Aral
Kuvan Daria
44°
Zhana Daria
44°
Pulzhaj
Nukus
Laudan
Sarykamysh
Kokcha
Bazar-kala
Koi Krylgan Kala
57°
Amu Daria
Uzboi
40°
Zeravshan
40°
Bukhara
0
100
200
250km
60°
63°
66°

Figure 7