



Late Pleistocene to Holocene climate and limnological changes at Lake Karakul (Pamir Mountains, Tajikistan)

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Abstract. Lake Karakul, located in the eastern Pamir Mountains, Tajikistan, is today dominated by the Westerlies. It is a matter of debate whether the Indian Monsoon influenced the region in the past. We analysed an 11.25 m sediment core covering the last 29,000 years to assess and separate lake-internal and lake-external processes, and to infer changes in the predominant atmospheric circulation. Among the parameters indicating lake-external processes, high values in grain-size end-member (EM) 3 (wide grain-size distribution, marking fluvial input) and Sr/Rb and Zr/Rb ratios (coinciding with coarse grain sizes, implying increased physical weathering) are interpreted as a strong monsoonal impact. High values in EM1, EM2 (peaking at small grain sizes reflecting Westerlies-derived dust) and TiO₂ (terrigenous input) are assumed to reflect a

- 25 strong influence of Westerlies. High input of far-transported dust from the pre- Last Glacial Maximum (LGM) to the late glacial reflects the Westerlies influence, while peaks in fluvial input suggest monsoonal influence. The early to early-mid Holocene is characterised by coarse mean grain sizes, increased physical weathering and constantly high fluvial input indicating a strengthened Indian Monsoon that reached further north into the Karakul region. A steady increase in terrigenous dust, decrease in fluvial input and physical weathering from 6.7 cal kyr BP onwards signals that Westerlies
- 30 became the predominant atmospheric circulation and brought an arid climate to the region. Proxies for productivity (TOC, C/N, TOC_{Br}), redox potential (Fe/Mn) and changes in the endogenic carbonate precipitation (TIC) indicate lake-internal changes. Low productivity characterised the lake from the late Pleistocene until 6.7 cal kyr BP and rapidly increased afterwards. The lake level remained low until the LGM, but water depth increased during the late glacial, reaching a high-





stand during the early Holocene. Subsequently, the water level decreased until its present state. Today the lake system is mainly climatically controlled but the depositional regime is also driven by lake-internal limnogeological processes.

1 Introduction

Interactions between the atmosphere and terrestrial environments have increasingly become the focus of research since

- 5 recent climate change has become an acknowledged issue (Pachauri et al., 2014; Pielke et al., 1998; Williamson et al., 2008). In semi-arid and arid mountain regions, the interactions between climate, glacial dynamics, water capacity of mountain lakes and, in consequence, their influence on river water discharge need to be understood. The high mountain ranges of Central Asia are of particular interest within this context due to the complexity of the regional circulation mechanisms (Aizen et al., 2001; Chen et al., 2010; Ramaswamy, 1962), the steep environmental gradients originating from the pronounced relief, and
- 10 especially the many large rivers originating in this region and supplying water to densely-populated mountain forelands in India, China and Inner Asia. Therefore, our understanding of linkages between atmosphere and terrestrial environments should not only be based on observation alone but, as long-term processes are involved, rooted in palaeoenvironmental reconstructions.

Central Asia is located in the transition zone between the Westerlies and the monsoon system (Holmes et al., 2009; Wang et

15 al., 2010). The interplay of these climate systems in the past has been the focus of several studies of decadal (e.g. Loader et al., 2010), centennial (e.g. Aizen et al., 2001) and millennial scale climate records (e.g. Herzschuh, 2006; Holmes et al., 2009; Sato, 2009).

A speleothem study covering the last 500 kyr, revealed that Central Asia was not only influenced by the Westerlies, but also by the Asian Monsoon during warm periods (Cheng et al., 2012). These results are in agreement with reconstructions of the

20 glaciation history in the Central Asian mountain ranges during the late Pleistocene and Holocene (Abramowski et al., 2006; Dortch et al., 2013; Owen and Dortch, 2014; Seong et al., 2009). However, studies focusing on the mid- and late Holocene show a more distinct Westerlies influence in the Pamir (Lei et al., (2014) and the Tian Shan Mountains (Lauterbach et al., 2014).

Generally, lake sediments provide valuable palaeoclimate information. Most of the respective Central Asian studies are either located on the Tibetan Plateau, in lower to moderate mountain areas of western Central Asia, or in bordering basins (Van Campo and Gasse, 1993; Ji et al., 2005; Kramer et al., 2010; Opitz et al., 2012; Gebhardt et al., 2016), but literature research showed that studies from high mountain regions, like the Pamir, are rare. Available studies focus on glacial activity (e.g. Abramowski et al., 2006; Liu et al., 2014; Zech et al., 2005), fluvial system development and climatic-tectonic interactions (Fuchs et al., 2014, 2015). It is still unclear whether large and deep lakes in mountainous environments react

30 directly to climate or with some delay, or whether they are mainly internally driven and thus inert to climate change (Williamson et al., 2008). Signals reflecting changes in the stratification of lakes or ice-cover duration are stored in the sediments (Birks and Birks, 1980). Various sedimentary parameters provide proxy information on changes in





bioproductivity, water chemistry and lake level (e.g. Hudson and Quade, 2013; Lister et al., 1991) and thus portray the lake's relationship with climate.

Here we present a sedimentary record from Lake Karakul (3929 m asl) located in the eastern Pamir, Tajikistan, dating back 29 cal kyr BP. Our first objective is to separate sedimentary geochemical data into proxies for lake-internal conditions and

5 those for lake-external climate change, and assess their reliability. Second, we aim to reconstruct climate changes and, by comparison with other records, we attempt to assign the inferred trends to changes in the dominant atmospheric circulation systems. Third, we hope to show whether lake-internal changes are driven by or are separate from regional climate change.

2 Study site

Lake Karakul (Tajik for 'black lake') is located in the north-east of the autonomous region Gorno-Badakhshan (e.g. Lister et al., 1991) of Tajikistan, in the eastern Pamir Mountains (Fig.1), which are adjoined by the Hindukush and Karakorum in the south and the Tian-Shan in the north. The Karakul Basin is a 50km wide depression located in a complex tectonic setting, formed by a number of faults (Strecker et al., 1995) and resulting in an asymmetric graben (Nöth et al., 1932; Ergashev, 1979; Melack, 1983). The surrounding mountain ranges, which mainly consist of Palaeozoic metasediments and Triassic granites (Nöth et al., 1932; Melack, 1983), reach heights of 5000 m above sea level (asl) with single peaks reaching over

- 15 6000 m asl in the catchment of the lake. Quaternary lacustrine and glacial deposits fill the basin as a result of presumably multiple, but a minimum of two, glaciations (Komatsu, 2009, 2010). Two horst structures form an island and a peninsula in the centre of the basin which divide the lake into a deeper western and a shallower eastern sub-basin. The greater water depth (>240 m) of the western sub-basin originates from pronounced tectonic subsidence rather than sediment starvation (Strecker et al., 1995).
- 20 The modern lake is brackish with a pH of 9.2 (Mischke et al., 2010a) and the endorheic basin is mainly supplied with freshwater originating from the surrounding glaciers, snow fields and frozen ground (Mischke et al., 2010a), while direct discharge from precipitation in the catchment area is of minor importance (Ni et al., 2004). Precipitation is generally low with an annual mean of 82 mm, but characterized by high variability. The Westerlies, which are the main moisture source (Böhner, 2006), are blocked by the mountain ranges to the west of the lake. Air temperature in the region is low due to the
- high elevation. The meteorological station at Lake Karakul recorded a mean annual temperature of -3.9°C, with a mean January temperature of -18.1°C and a mean July temperature of 8.5°C (measuring period 1933 to 2007, excl. 1995-2003). Low winter temperatures cause ice cover from November until May with up to one metre of ice thickness. A maximum Secchi depth of 19 m was recorded during the open-water season (Ergashev, 1979), while depths of 10.7-11.7 m were recorded in June 2008 (Mischke et al., 2010a) and only 3.4 m in August 2013. *Potamogeton pamiricus* and Characeae
- 30 colonize the littoral zone (Hammer, 1986). The terrestrial vegetation in the catchment is dominated by alpine steppe vegetation taxa, such as *Stipa*, *Oxytropis* and *Artemisia*, which have a higher cover in close vicinity to the shoreline, near fluvial inlets and on alluvial plains (Mischke et al., 2010b; and personal observations). The lake is not used for fishing.





Grazing occurs in the catchment of the lake and bushes are removed for the production of fire materials. Otherwise, direct human impact on the lake and its catchment is very low.

3 Materials and methods

3.1 Fieldwork

- 5 The core KK12-1 (composite length 11.25 m) was collected during a field campaign in spring 2012 using UWITEC coring equipment ("Niederreiter 60") at a water depth of 12 m operated on the ice cover of Lake Karakul (core site coordinates: 39.0176°N, 73.5327°E; Fig.1.). Coring at a more central position in the eastern sub-basin was impossible due to thin ice cover and the onset of ice breakup in April 2012. Due to the same reason, coring was conducted from a single ice hole without overlapping of sediment core segments. Hence, small gaps occur between each 2 m core segment because of the
- 10 piston in the coring liner. Sediment between 525 and 568 cm composite depth was lost during coring. A second parallel core (KK12-2) was recovered from a position 10 m away, due to time and financial limitations, these sediments were not investigated.

The cores were transported to the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Potsdam and stored in the original 6 cm diameter PVC coring tubes at 4°C after being split into 1 m segments.

15 Nine additional sediment samples collected from different modern depositional settings (e.g. slackwater, pond, dry river channel, sand dune; see supplement) in the eastern to northern vicinity of the lake were analysed as reference materials.

3.2 Laboratory analysis

3.2.1 Core sampling and dating

Sediment core segments were split into two halves along the long axis. The "archive" halves were used for smear slide analysis and non-destructive work such as initial core description and X-ray fluorescence (XRF) scanning. The "work" halves were subsampled for radiocarbon dating and sedimentological analyses (e.g. CNS, TOC, grain-size distribution).

- Fourteen samples, comprising nine plant remains, four bulk sediment samples and one sample of an in-situ living charophyte, were dated at the Poznań Radiocarbon Laboratory, Poland (Table 1). Radiocarbon ages were corrected for the 'lake reservoir effect' of Lake Karakul based on the published lake reservoir effect of and the apparent age of the newly
- 25 collected macro-algae from core KK12-10 (Mischke et al., 2010b). The charophyte species revealed a F¹⁴C (modern fraction; Reimer et al., 2004) of 0.8914, which is equivalent to a lake reservoir effect of 1315 years. An average of both determined lake reservoir effects of 1368 years was applied as a correction to the original radiocarbon age data assuming that the lake reservoir effect did not change through time. The mean lake reservoir effect of 1368 years was used in the age-depth model (Fig.2) created using the Bacon package (Blaauw and Christen, 2011) in R (R Core Team, 2012) and is calibrated to calendar





years using the IntCal13 calibration curve (Reimer et al., 2013). The Bacon parameter settings largely follow Blaauw and Christen (2011), but with mean accumulation set to 20 (yr cm⁻¹), and memory strength set to 20 to account for bioturbation effects originating from dense macrophyte cover. The obtained age-depth models were fairly robust to variations in the parameter settings.

5 The uppermost dated sediment sample from KK12-1 was excluded from the age-depth model as the sediment was probably deposited during and after the nuclear bomb testing period with highly variable F¹⁴C values (Reimer et al., 2004). Nevertheless, the lake-reservoir effect corrected and calibrated age for this sample fits reasonably well with the established age-depth model.

3.2.2 Sedimentology

- 10 Smear slides were prepared and inspected approximately every 40 cm. Total carbon (TC), total nitrogen (TN), total sulphur (TS), total organic carbon (TOC) and the grain-size distribution were analysed for 97 samples taken at 10 cm intervals. The freeze-dried and finely ground samples for elementary analyses were weighed into tin capsules for CNS analyses and measured using an Elementar vario EL III (CNS) analyser. An Elementar vario MAX C was used to quantify TOC. TN values in the lower part of the core were in occasionally at or close to the detection limit at 0.1 %, however the data were
- 15 used to calculate TOC/TN ratios following Meyers and Teranes (2002). Total inorganic carbon (TIC) was calculated by deducting TOC from TC values.

Stable isotope analyses on authigenic carbonat were conducted on 98 samples spaced approximately every 10 cm. The samples were bleached for 24 h with 2.5 % NaOCl to remove the organic content and sieved with a 36 µm mesh to clean the samples of detrital components and shells. The remaining authigenic carbonate fraction was freeze-dried, ground for

20 homogenization and loaded into Labco vialstin capsules. Measurements of $\delta^{13}C_{AuthCarb}$ (AuthCarb = authigenic carbonate) and $\delta^{18}O_{AuthCarb}$ were undertaken with a ThermoFinnigan Gasbench II linked to a DELTA^{plus}XL mass spectrometer and measured after digestion with 103 % H₃PO₄ at 72°C for 60 min at the German GeoForschungsZentrum (GFZ) in Potsdam. The stable isotope data are reported in per mil relative to VPDB and calibrated using NBS19 with an analytic precision error of <0.08 % for both $\delta^{13}C_{AuthCarb}$ and $\delta^{18}O_{AuthCarb}$ on reference material.

25 3.2.3 Grain-size analysis

Sample preparation for grain-size analysis included 24 h treatment with CH_3COOH (10 %) to remove carbonate, sieving with a 2 mm sieve to remove abundant plant remains in most parts of the core, and shaking the samples on a platform shaker in initially 0.3 % H_2O_2 solution with an addition of 10 ml of H_2O_2 (35 %) every second day for up to six weeks in order to remove the remaining organic matter. Grain-size analysis was performed with a Coulter LS 200 Laser Diffraction Particle

30 Analyser, which was equipped with a 1 mm sieve to protect the lens. At least two subsamples were measured for every sample.





3.2.4 XRF analysis

High-resolution non-destructive XRF measurements were performed with an Avaatech XRF Core Scanner at AWI Bremerhaven. After levelling and cleaning the core surface, the sediment core halves were covered with a 4 µm transparent film (Ultralene, USA). X-ray voltage of 10 kV for major elements and 30 kV for minor elements with a Rh X-ray tube at 1
mA was applied at 2 mm resolution. Element signals were measured in counts per second, converted to XRF peak area intensities and averaged over each cm after outliers were eliminated. Due to high mean errors expressed as chi squared (χ²), probably originating from the high content of plant remains and related air pockets, only results of elements with a reasonable low χ² were included in the interpretation: Ti (mean χ² 3.7), Mn (mean χ² 3.8), Fe (mean χ² 10.4), Br (mean χ² 0.8), Zr (mean χ² 0.8), Rb (mean χ² 0.7) and Sr (mean χ² 1.1).). High χ² for Fe was considered as acceptable if applied in the 10 Fe/Mn XRF ratio showing a reasonable trend of the data along the core. To calibrate the XRF scanner data, 26 samples at 30-40 cm intervals from the core KK12-1 were freeze-dried, ground, melted into tablets and analysed with XRF using a PANalytial Axios WDXRF (1 kW) spectrometer at AWI Bremerhaven. Runs were performed once with WROXI standards and once without in the OMNIAN modus to cover the major and some minor elements, and data recorded as oxides. The single sample measurements were used to determine linear regressions in cross plots in order to calculate percentage values

15 from scanner data (see supplement). XRF count ratios were generated directly from the XRF scanner data. Due to good correlation between TOC and XRF Br, we quantified TOC_{Br} from the peak area intensities of Br as a high-resolution proxy for the organic carbon content.

3.2.5 Multivariate statistics

Different transport and deposition processes can be deciphered from grain-size distribution data using end-member

- 20 modelling analyses (EMMA; Weltje, 1997). The obtained grain-size data were analysed with the EMMAgeo package (Dietze and Dietze, 2013) in R (R Core Team, 2012). In order to achieve the best fit between modelled and measured data, we performed several model runs with different percentiles (P3/P97, P4/P96, P5/P95, P6/P94, P7.5/P92.5 and P10/P90) (see supplement). The minimum number of potential end-members was determined by the cumulative explained variance that explained 95 % of the total variance of the original grain-size data, while the maximum number of potential end-members
- 25 was determined by the mean coefficient of determination which reflects the explained variance (mean r²). To avoid overfitting, a model with P3/P97 and four robust and one residual EM, representing the unexplained variance, was used. A number of statistical analyses were applied in order to portray the main structure in the data set such as the relationship among the single variables, and between variables and samples. The obtained proxies were separated into lake-internal and lake-external parameters in order to decipher and explain the recorded signals. Principal component analyses (PCA) were
- 30 applied after the data were square-root transformed, centred and standardized in CANOCO Version 5 (Braak and Šmilauer, 2012). A stratigraphically constrained incremental sum of squares analysis (CONISS) in Tilia version 1.7.16 was applied to the square-root transformed data to identify significant changes in the data and assign zones (Grimm, 1987).





4 Results

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4.1 Age-depth relationship of core KK12-1 from Lake Karakul

A 'lake-reservoir effect' of 1368 yrs was determined using two in-situ collected living charophytes. The results of the lake reservoir-effect corrected and calibrated samples (Table 1) and the age-depth model (Fig.2) show an approximate age of 29 cal kyr BP at the base of core KK12-1. The sediment accumulation rate ranges from 0.15 mm yr⁻¹ in the lower part of the

core to 0.84 mm yr^{-1} at the top.

4.2 TIC, TOC, C/N, $\delta^{18}O_{AuthCarb}$ and $\delta^{13}C_{AuthCarb}$

The core KK12-1 consists of a sequence of fine-grained, greyish sediment with a variable amount of plant remains. Plant remains are absent at the base of the core (1087-1012 cm; 28.6-26.5 cal kyr BP), rare in the lower part (1012-725 cm; 26.5-

10 19.1 cal kyr BP), absent in the middle part (698-464 cm; 17.4-6.9 cal kyr BP) and abundant in the upper part (464-0 cm; 6.9 cal kyr BP to present).

TIC ranges between 1.7 and 8.6 % (median: 3.0 %) (Fig.3B) and is generally characterized by a high sample-to-sample variation. Lowest values occur between 982 and 692 cm (26.3 and 17 cal kyr BP) and the highest values between 682 and 402 cm (16.5 and 5.3 cal kyr BP).

- 15 TOC ranges from 0.1% to 2% from the base at 1082 cm (28.5 cal kyr BP) to 452 cm (6.6 cal kyr BP), followed by a sharp increase with values reaching up to 5.3 % in the upper part of the core and an overall median of 1.6 %. TOC/TN ratios display low values. Results from below 692 cm (17 cal kyr BP) are rather unreliable because TN was close to detection limit. The highest values were determined between the two maxima both 17.1 at 332 cm and 172 cm (4.1 and 2.0 cal kyr BP) (Fig.3B).
- 20 Values of $\delta^{13}C_{AuthCarb}$ vary between 1.4 and 4.9 ‰ (median: 3.74 ‰). $\delta^{18}O_{AuthCarb}$ displays values from -7.4 to -0.3 ‰ (median: -3.1 ‰). Both stable isotope datasets show similar trends over the core with high values from core base until 1025 cm (28.6 to 26.5 cal kyr BP), a rapid decrease with generally lower values until 652 cm (14.7 cal kyr BP), a period of higher values until 292 cm (3.5 cal kyr BP) and a decreasing trend up to the core top (present day; Fig.3A).

4.2 Grain-size distribution and results of endmember modelling

- Mean grain-size varies mainly between 7 and 31 µm (median: 12 µm). A slight mean grain-size decreasing trend and generally less variation were identified in the upper 500 cm (<8.1 cal kyr BP). The final endmember model (P3/P97) results in four robust EMs and one residual EM (Fig.4B). All four EMs show bimodal or polymodal grain-size frequency distribution curves with the main peak at 2-4 µm for EM1, 10-20 µm for EM2, 20-50 µm for EM3 and 100-300 µm for EM4. EM1 accounts for 15.2 % of the detrital sediments over the core, EM2 for 30.1 %, EM3 for 18.5 % and EM4 for 35.6</p>
- 30 %. EM1 and EM2 have relatively high abundances throughout the core, whereas EM3 and EM4 show larger fluctuations





(Fig.3A). The very fine-grained EM1 reaches its highest values up to 67 % between 672 and 622 cm (15.8 and 13.6 cal kyr BP). EM2 is most abundant from 982 to 942 cm (25.8 to 25.0 cal kyr BP) with a maximum of 78 %, and between 772 and 732 cm (21.0 to 19.5 cal kyr BP) with a maximum of 76 %. It is constantly recorded in medium to high proportions (>25 %) from 492 cm upward (8 cal kyr BP until present). EM3 shows peaks of 61 % at 832 cm (22.7 cal kyr BP), 60 % at 452 cm (6.6 cal kyr BP) and 65 % at 72 cm (0.8 cal kyr BP). Peaks for EM4 with maxima up to 73 %, 79 % and 72 % are recorded

from the core base until 992 cm (28.6 to 26.2 cal kyr BP), from 822 to 782 cm (22.4 to 21.2 cal kyr BP) and at 502 cm (8.6 cal kyr BP).

Tests with models of five or six endmembers yielded a further EM differentiation within the fine grain-size range, but also a higher risk of overfitting and were therefore discarded.

10 **4.3 XRF data**

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XRF scanning analyses revealed values from 1.7 to 70.3 for Sr/Rb ratios (median 11.0), 1.4 to 4.6 for Zr/Rb ratios (median 2.1), and 17.3 to 703.1 for Fe/Mn ratios (median 114.3). TOC_{Br} ranges from 0.8 to 5.7 % (median 1.51 %); showing a rapid increase at 449 cm (6.6 cal kyr BP) and high variability in the upper part of the core. The calibrated TiO₂ concentrations vary between 0.64 and 0.79 % (median 0.69 %). TiO₂ shows relatively large fluctuations with an overall decrease from the base to

15 the middle of the core and constantly increasing values towards the top. The TiO_2 curve is anticorrelated to the mean grainsize variations in the middle and upper part of the core (Fig.3A). Peaks in Sr/Rb and Zr/Rb ratios are mainly correlated with high EM4 portions.

4.4 Ordination results of sediment parameters

The first two PCA axes of the lake-external parameters explain 62.9 % of the variance (Fig.5A). TiO₂, EM1 and EM2 plot on the positive end of the first axis. Opposite to EM1 and correlated with each other are the Zr/Rb ratio and the $\delta^{18}O_{AuthCarb}$ values which are also correlated with the $\delta^{13}C_{AuthCarb}$ values, the Sr/Rb ratio and EM3 in the lower left of the PCA plot. EM4 and EMres plot in the upper left and are strongly anticorrelated with EM2.

The first two PCA axes of the lake-internal parameters explain 81.1 % of the variance of the data. TOC, TOC_{Br} and the TOC/TN ratio plot in the lower right quadrant, while TIC and the Fe/Mn ratio plot in the upper right part of the PCA plot

25 (Fig.5B).

The stratigraphically constrained cluster analysis suggests a division of the core into three zones for the external parameters. External parameter zone 1 (core base to 613 cm; 28.6 to 13.3 cal kyr BP) shows negative PCA axis 1 scores up to 1012 cm depth (26.5 cal kyr BP) and mostly positive values above, while PCA axis 2 scores are almost exclusively positive (Fig.3A). Zone 2 (602 to 452 cm; 13 to 6.7 cal kyr BP) plots with a decreasing trend from positive to negative axis 1 scores and

30 variable, mainly positive axis 2 scores. The external parameter zone 3 (442 to 0 cm; 6.6 cal kyr BP to present day) is characterised by increasing trends for axis 1 and slightly increasing axis 2 sample scores (Fig.3A).





The stratigraphically constrained cluster analysis for the internal parameters results in three zones as well. Samples from internal parameter zone 1 (core base to 713 cm; 28.6 to 19.2 cal kyr BP) present negative PCA axis 1 and positive and negative PCA axis 2 scores. PCA axis 1 sample scores for the internal parameter zone 2 (712 to 462 cm, 17.5 to 6.9 cal kyr BP) show an increasing trend with mainly negative values, while axis 2 scores are positive throughout zone 2 after rapidly increasing at the beginning of the zone (Fig.3B). The internal parameter zone 3 (452 to 0 cm; 6.7 cal kyr BP to present) shows slightly decreasing, still positive, axis 1 scores and both positive and negative, also slightly decreasing axis 2 scores (Fig.3B).

5 Discussion

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5.1 Palaeoenvironmental indicators from sedimentary parameters

- 10 TOC concentrations reflect preserved organic matter content (Fig.3B), i.e. the balance between allochthonous organic matter input, autochthonous organic matter production, and degradation (Meyers and Lallier-Vergés, 1999), which is affected by runoff, temperature, proximity of the shoreline, ventilation, turbation and other factors (Meyers and Teranes, 2002). We consider Br as a proxy for organic matter content consistent with previous studies of marine (Mayer et al., 1981; Ziegler et al., 2008) and lake sediments (Kalugin et al., 2007; Biskaborn et al., 2013).
- 15 The TOC/TN ratios (Fig.3B) probably reflect the source of sedimentary organic matter at the coring position. Values below 10 indicate a dominance of phytoplankton, whereas values of ≥18 indicate a stronger contribution from vascular plant sources (Meyers and Lallier-Vergés, 1999). However, vascular aquatic plants, which can have a wide range of C/N values (Herzschuh et al., 2010), may have dominated, particularly during the last 7 cal kyr BP consistent with the observation of abundant macrophyte remains in the sediments. Hence, the TOC/TN ratios of core KK12-1 most likely indicate a mixed
- 20 signal from different sources of organic matter. The combined interpretation of organic content and TOC/TN ratios may indicate bioproductivity variations in Lake Karakul. Total inorganic carbon (TIC) reflect the carbonate content (Fig.3B), most likely originating from allochthonous input of

detrital sediments from the catchment and/or as dust, and/or through precipitation from the water column (Cohen, 2003). Visual inspection of smear slides indicated that the carbonate fraction comprises endogenic aragonite crystals, shells and

25 shell fragments of ostracods and gastropods from Lake Karakul. However, it cannot be ruled out that detrital carbonate from the southern part of the catchment is transported to the lake during sporadic floods and that fine-grained carbonate particles of aeolian origin accumulated in the lake basin as well (Strecker et al., 1995).

The good correlation between δ^{13} C and δ^{18} O (r=0.82), measured from the authigenic carbonate fraction, reflects the closedbasin setting of Lake Karakul (Talbot, 1990). δ^{13} C values (Fig.3A) are influenced by the productivity in the surface waters of

30 the lake, where phytoplankton preferentially incorporate ¹²C, which enriches ¹³C in the water. δ^{13} C values are also controlled by climate conditions. For example, groundwater generation and runoff to the lake is higher during wetter periods, causing





an enhanced transport of soil-derived CO₂ with low δ^{13} C values to the lake (Talbot, 1990). While δ^{18} O values of waters from open lakes generally reflect changes in moisture source, δ^{18} O values in closed-lake settings generally reflect changes in the evaporation/precipitation ratio. Higher δ^{18} O values represent stronger evaporation and/or less freshwater inflow to the lake. Lower δ^{18} O values reflect lower evaporation effects and/or higher runoff entering the lake (Talbot, 1990). Precipitation in the

- 5 high elevation and very continental location of Lake Karakul is, however, generally low and accordingly, glaciers and snowfields represent the main water source. Therefore, we assume that δ^{18} O values mostly display evaporation/freshwater input ratios depicting temperature changes rather than changes in the amount of precipitation. The long-term δ^{18} O signal is additionally affected by changes in the δ^{18} O signature of the water source (i.e., the ice-volume effect) and the large temperature change over a glacial-interglacial cycle.
- 10 End-member modelling of grain-size data from the sediment core was applied to decipher different transport and deposition processes of the organic- and carbonate-free sediment fraction (Weltje, 1997). Taking the grain-size distribution in the sediments from core KK12-1 and of modern reference samples into account (Fig.4), the end-member modelling results from Lake Karakul sediments imply that the core sediments represent four different sediment populations (Fig.3A). EM1, with its narrow peak in the fine-grained fraction represents very fine aeolian dust which was probably transported over large
- 15 distances in high suspension clouds (Wu et al., 2006) and deposited from the atmosphere via precipitation (Vandenberghe et al., 2006; Dietze et al., 2012). Thus EM1 might be indicative of the influence of the Westerlies air stream. EM2 shows a main peak in the fine-moderate silt fraction and probably also reflects remote sources of wind-transported material (Tsoar and Pye, 1987). Loess deposits are not commonly found in the Pamir-Alay region above 3000 m asl, so EM2 likely represents aeolian sediments transported mostly over long distances (Vandenberghe, 2013). However, the fine-grained
- 20 sediments of EM1 and EM2 may also include the suspension load of glacial outwash material (glacier milk; Wang et al., 2015). EM3 covers a wide grain-size range similar to the reference samples of fluvial deposits. Hence, its downcore distribution probably represents the fluvial input into the lake and hence summer precipitation events. Accordingly, high portions of EM3 sediments in core KK12-1 are tentatively interpreted as proxies for pronounced summer precipitation, mostly attributed to the Asian Monsoon. However, meltwaters from glacier tongues approaching the lake and local aeolian
- 25 sediments from alluvial fans and plains may have also contributed to the accumulation of the relatively poorly sorted silts and fine sands of EM3 (Vandenberghe, 2013). EM4 shows similarities with a reference sample of well-sorted aeolian sand. Its coarse grain size indicates a local source area of hundreds of metres to a few kilometres distance and transportation by strong local winds, especially during winter and under snow-free conditions, which enable saltation and creep of grains and transport onto the frozen lake surface (Tsoar and Pye, 1987; Mischke et al., 2010b). The occurrence of EM4 probably
- 30 reflects strong episodic cyclonal sand and dust storms attributed to an enhanced influence of the Siberian High (Vandenberghe, 2013).

Quantitative single sample XRF measurements over the core enabled the calibration of XRF-scanner data (Weltje and Tjallingii, 2008; Biskaborn et al., 2013). As indicated by the relatively high χ^2 values, large uncertainties in the quantitative data occurred which probably originate from inhomogeneities of sediments containing large macrophyte remains and related





air pockets, low element concentrations, and differing sample preparations (freeze-dried, homogenised milled single samples vs. wet 'in situ' surface core scans (Tjallingii et al., 2007)). Nevertheless, the XRF measurements provide valuable information if the results are regarded as semi-quantitative data (Weltje and Tjallingii, 2008).

Titanium (Ti) and its affiliated oxide (Fig.3A) are often associated with detrital input and clay mineral assemblages,
interpreted here as fine clastic input into the lake (Fey et al., 2009; Kylander et al., 2011). This assumption is supported by the opposing trends of TiO₂ and the mean grain size of the sediments from Lake Karakul. Sorrel et al. (2007) point out that at Lake Aral in western central Asia, Ti is correlated with the strength of the atmospheric circulation as dust is most likely the dominant source of the detrital-input of Ti in arid and semi-arid regions.

Rubidium (Rb) is commonly found in many K-bearing minerals such as K-feldspar and mica and associated with clay minerals (Kalugin et al., 2007; Liu et al., 2014). As the crossplot of XRF scanner data and XRF single sample measurements show, Rb exhibits a very low R². This can be explained by the extremely low concentration of Rb and the methodological needs to compare the values from prepared single samples with averaged scanner data from the wet and organic-rich sediment core. The main source of Zirconium (Zr) is the heavy mineral Zircon, which is more often released by physical

rather than chemical weathering and associated with coarse silt and sand fractions (Chen et al., 2006; Kylander et al., 2011).

- Strontium (Sr) is usually related to silicates and carbonates because Ca is often substituted by Sr in both, feldspar and aragonite (Kalugin et al., 2007; Kylander et al., 2011). The good correlation between the Sr/Rb and Zr/Rb ratios (Fig.3A) indicates that both ratios apparently serve as grain-size indicators with high ratios tracing larger mean-grain sizes and vice versa. This relationship was also observed in other studies of lake systems (Biskaborn et al., 2013) and other sedimentary environments such as loess deposits on the Tibetan Plateau (Chen et al., 2006). The Zr/Rb and Sr/Rb ratios of the KK12-1 sediments display an opposite trend to TiO₂, which is correlated with the finer grain-size fractions.
- 20 sediments display an opposite trend to TiO₂, which is correlated with the finer grain-size fractions. Fe/Mn ratios (Fig.3B) are generally regarded as a proxy for redox conditions at the bottom of the lake because high values reflect the higher solubility of Mn relative to Fe under reducing conditions (Boyle, 2001). Accordingly, low values indicate a low redox potential (Cohen, 2003). Changes in the redox conditions at the lake floor may have various causes such as changes in lake level, chemical or thermal lake stratification, bioproductivity (e.g. macrophyte growth), or mixing
- 25 conditions, for example, due to changes in the proximity of a river mouth or the ice-cover duration (Cohen, 2003). Ordination in the PCA biplots (Fig.5A) displays relationships among the external lake proxies. The first axis separates the wind and dust signal (EM1 and EM2) on the right (positive end) and the precipitation and runoff indicator EM3 on the left (negative) part of the plot. The second axis most likely divides the detrital sediment input into a summer (runoff, EM3) and winter (aeolian sand, EM4) signal, which plot on opposing ends of the axis. The main data structure of the internal lake
- 30 proxies is shown in Figure 5B. Bioproductivity indicators are plotted along the first PCA axis, whereas the second axis reflects lake-bottom ventilation and possibly lake-level, indicated by the strong correlation with the Fe/Mn ratio and TIC. Carbonate precipitation in a Mg^{2+} and SO_4^{2-} dominated closed-basin lake normally occurs during periods of sufficient runoff and relatively warm conditions, both facilitating the establishment of a more stratified water column with oxygen deficiency at the lake floor (Mischke et al., 2010b). Thus, axis 2 of PCA_{internal} possibly indicates lake level changes.



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5.2 Assigning local climate to Asian Monsoon and Westerlies circulation change

5.2.1 Pre-LGM to late glacial (28.6 – 13.3 cal kyr BP)

The pre-LGM phase of the KK12-1 record (zone 1; Fig.3A) is characterized by a high input of EM4 sediments probably indicating strong local cold-season storms. Comparably moderate values of EM1 and low values of EM2 reflect wet deposition of far-transported fine dust but a generally low accumulation of coarser-grained dust. Moderate Zr/Rb and Sr/Rb ratios possibly result from the presence of feldspars and other minerals susceptible to chemical weathering. High $\delta^{18}O_{AuthCarb}$ values could result from significant aridity and strong evaporation from the lake surface which was apparently not sealed off by a long-lasting ice cover.

A dominance of EM2 sediments in the LGM indicates high influx of dust and generally arid and cold conditions. EM4 reaches high proportions between 22 and 20 cal kyr BP pointing to dry and stormy winters and low Zr/Rb and Sr/Rb ratios 10 reflect the dominant role of physical weathering in comparison to chemical processes. Generally decreasing $\delta^{18}O_{AuthCarth}$ values during the LGM presumably result from the global cooling, which led to isotopically depleted precipitation in the Karakul region, and decreasing evaporation effects from the lake surface due to prolonged periods of ice-cover.

High values of EM1 during the late glacial point towards a strong Westerlies influence and fine-dust accumulation with 15 precipitation. Increasing EM3 values suggest significant fluvial input into the lake, likely due to increasing temperatures and glacial meltwater discharge. Increasing Zr/Rb and Sr/Rb ratios mirror the increasing influence of chemical weathering under warmer conditions. Accordingly, high $\delta^{18}O_{AuthCarb}$ values probably result from relatively warm temperatures and isotopically less depleted precipitation in the Lake Karakul region.

Strong landslide activity in the north-western Himalaya recorded from 29-24 kyr BP has been interpreted to indicate an

- 20 intensified Monsoon originating from a steep thermal ocean-land gradient (Bookhagen et al., 2005). Zech et al. (2005) proclaim glacial advances around 27 kyr BP in the southern Pamirs. Dortch et al. (2013), investigating glacial deposits in the western Himalayan range using ¹⁰Be surface exposure ages, propose several glacial advancing stages termed semi-arid western Himalayan-Tibetan stages (SWHTS) of which one occurred around 30±3 kyr BP (named 2F). These results are in agreement with an increase in moisture availability as pointed out by Bookhagen et al. (2005) but do not necessarily support
- the stated Monsoon impact during the pre-LGM phase. Komatsu and Tsukamoto (2015) recorded a late glacial glacier advance in the Karakul catchment at 15 kyr BP and suggested that glaciers responded to enhanced moisture availability from the Westerlies. Their suggestion tallies with the inferences of increased Westerlies precipitation (EM1) and higher fluvial input (EM3) to the lake from the KK12-1 core. Dortch et al. (2013) identified three local glacial stages in the Himalayan-Tibetan mountains between 17 and 14 kyr BP apparently
- 30 synchronous with the Oldest Dryas and Heinrich event 1 of the Northern Hemisphere and likely controlled by precipitation from the Westerlies. Owen and Dortch (2014) compare the SWHTS with Monsoonal Himalayan-Tibetan stages (MOHITS; Murari et al., 2014) and argue that at times SWHTS and MOHITS were concurrent and probably had similar moisture





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sources while at other times only one of the stages is evident, implying differing climate controls. Various pollen studies from the present monsoonal realm on the eastern Tibetan Plateau report a prevailing cold and dry climate for the LGM period, e.g. from Lake Donggi Cona (Wang et al., 2014), Lake Kuhai (Wischnewski et al., 2011), Lake Naleng (Kramer et al., 2010) and Lake Ximencuo (Herzschuh et al., 2014), which is in agreement with the proxy-record syntheses in Herzschuh (2006) and Wang et al. (2010) that postulate low moisture availability in typical Monsoon areas during Marine Isotope Stage 2. Records of a shut-down of the Asian Summer Monsoon circulation during the LGM also agree with results from various climate modelling studies (Hoffmann and Heimann, 1997; Braconnot et al., 2007). In summary, available proxy information

indicate the dominance of the Westerlies in the mountain ranges of Central Asia in the pre-LGM, LGM and late glacial.

5.2.2 End of the late glacial and early to mid-Holocene (13.3 - 6.7 cal kyr BP)

- 10 Indicators of fine aeolian input to the lake (EM1 and 2) have low values between the end of the late glacial and the early Holocene (zone 2; Fig.3A) indicating a diminished Westerlies influence. High values of EM3 imply increased precipitation and surface runoff. A maximum of EM4 and the residual EM at ca. 8.5 cal kyr BP may indicate the occurrence of especially dry and stormy winters analogous to the LGM or the formation of a single event layer of aeolian sand. Maximum Sr/Rb and Zr/Rb ratios probably reflect increased grain-size due to intensified chemical weathering and physical weathering. Lowest
- 15 TiO₂ values result from decreased far-distant detrital input of fine aeolian sediments. The $\delta^{18}O_{AuthCarb}$ values are high at the end of the late glacial and during the early and mid- Holocene, most likely reflecting the rising global temperatures and arrival of less depleted precipitation in Lake Karakul's catchment. The high $\delta^{18}O_{AuthCarb}$ values could be further amplified by increased evaporation due to increased temperatures and shorter ice-cover periods. A significant change in the prevailing climate system and a shift from a Westerlies-driven to a more Monsoon-influenced climate is inferred at the start of the
- 20 Allerød period.

Global temperature rose strongly during the Bølling/Allerød and early Holocene until approximatly 9.5 kyr BP and stayed high until about 5.5 kyr BP (Marcott et al., 2013). At Lake Donggi Cona wetter conditions were reconstructed during the early and mid-Holocene (Wang et al., 2014), as well as at Lake Sumxi Co, where early-Holocene high-stands are derived from ¹⁰Be-dated shorelines (Kong et al., 2007). This also agrees with several pollen-derived palaeoclimate studies from

- 25 Central Asia (Lake Sumxi Co, Van Campo and Gasse, 1993; Lake Bangong Co, Gasse et al., 1996; Van Campo et al., 1996; Lake Kuhai, Wischnewski et al., 2011). Zhu et al. (2015) investigated modern pollen spectra at Lake Nam Co, assigning certain taxa to dominant wind directions/circulatory systems and developing a pollen discrimination index which was used to reconstruct the predominant circulations over time. Their study suggests that an enhanced Asian Monsoon, driven by increased solar radiation, was responsible for increased moisture availability on the Tibetan Plateau in the early Holocene.
- 30 Seong et al. (2009) infer several glacial advances in the Muztag Ata and Kongur Shan during the early Holocene and argue towards a moisture transport from the middle latitude Westerlies. Other studies from Westerlies-impacted regions such as the Eastern Mediterranean and the Levant likewise indicate a wet early Holocene, after a dry phase during the Younger Dryas





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(Robinson et al., 2006). However, Herzschuh (2006) relates the wet conditions on the Tibetan Plateau during the early Holocene to a strengthened Asian Monsoon influence on the Tibetan Plateau that decreased towards the mid-Holocene. Chen et al. (2008), on the other hand, propose an out-of-phase relationship between arid Central Asia and the Monsoon-influenced regions of Asia and point out that a dry early and moist mid-Holocene prevailed in the former and maximum moisture availability during the early and mid-Holocene in the latter. However, their review does not include any study from the Pamir, western Himalaya or northern Tibetan Plateau. Zhao et al. (2009) also compare moisture availability and proclaim

Pamir, western Himalaya or northern Tibetan Plateau. Zhao et al. (2009) also compare moisture availability and proclaim asynchrony as expected, yet draw a more differentiated picture and reconstruct the wettest conditions on the northern Tibetan Plateau at the onset of the Holocene, which is in accordance with our findings from the Pamir Mountains.

5.2.3 6.7 cal kyr BP until present

- 10 From 6.7 cal kyr BP onward (zone 3; Fig.3A) EM1 and EM2 show an increasing trend, reflecting an enhanced influence of the Westerlies. EM4 shows a more sporadic pattern towards the present day which likely reflects reduced winter storms and the weakening influence of the Siberian High. EM3 displays slightly declining values accelerated in the last 2 cal kyr BP, which implies decreasing monsoonal precipitation. Decreasing Sr/Rb and Zr/Rb ratios correspond to a decreasing mean grain size and a steady increase in TiO₂ emphasizing the increasing far-distance dust input and diminishing influence of chemical
- 15 weathering. Declining $\delta^{18}O_{AuthCarb}$ values are probably recording the global cooling trend since the mid-Holocene with a strong depletion of incoming moisture. However, decreasing $\delta^{18}O_{AuthCarb}$ values may also indicate a reduction in commonly less depleted monsoonal precipitation in comparison to more depleted precipitation from the west and/or a declining evaporation and longer ice cover of the lake.

Liu et al. (2014), in their study of glacial activities in the westernmost Tibetan Plateau based on multi-proxy analyses of

- 20 glaciolacustrine sediments from Lake Karakuli (~150 km south-east of Lake Karakul), find a general correlation of local glacier advances with Holocene ice-rafting events in the northern Atlantic. However, glacier retreats reflect the general global warming and were not compensated by short phases of higher moisture availability. Ricketts et al. (2001) infer for Lake Issyk-Kul, located ~480 km north-east of Lake Karakul, a wet period preceding 6.9 cal kyr BP, suggesting an increased moisture transport from the west or a possible Asian Monsoon influence. Lake Issyk-Kul experienced an increasing
- 25 influence of the Siberian High, causing drier air masses and decreasing moisture availability in the region between 6.9 and 4.9 cal kyr BP. Subsequently the lake changed from an open freshwater system to a closed basin after a regression of the lake level, which corresponds with the findings at Lake Karakul for the mid- to late Holocene. Many case studies including speleothem records, lake sediments, dating of paleo-shorelines and reviews of such studies,

suggest a decreasing Asian Monsoon during the mid- to late Holocene related to the decreasing Northern Hemisphere

30 summer insolation (Kutzbach, 1981; Hulu Cave, Wang et al., 2001; Dongge Cave; Dykoski et al., 2005; caves in Oman and Yemen, Fleitmann et al., 2007; Lake Qinghai, Ji et al., 2005; An et al., 2012; Lake Sumxi Co, Van Campo and Gasse, 1993; Lake Bangong Co, Gasse et al., 1996; Van Campo et al., 1996; Lake Tangra Yum Co, Rades et al., 2015; reviews,





Herzschuh, 2006; Chen et al., 2008). More Westerlies-influenced study sites such as Lake Van experienced a climatic optimum between 6 and 4 kyr BP reflected in a higher lake level and in the spread of oak trees, implying increased moisture availability during the growthing season. After 4 kyr BP, a more continental climate influenced the region, resulting in drier conditions (Wick et al., 2003).

5 5.3 Assigning lake internal development to climate change

5.3.1 Pre-LGM and LGM (28.6 - 19.2 cal kyr BP)

Low PCA_{internal} axis 1 sample scores and low TOC suggest low bioproductivity and poor preservation of organic matter. Bioproductivity reaches minimum during the LGM. TOC/TN values are only measurable in four samples during the pre-LGM due to very low TN values, confirming the low productivity during the pre-LGM and LGM (zone 1; Fig.3B). Moderate TIC and PCA_{internal} axis 2 values during the pre-LGM show that inflow to the lake and resulting carbonate precipitation was

- 10 TIC and PCA_{internal} axis 2 values during the pre-LGM show that inflow to the lake and resulting carbonate precipitation was still significant before the onset of the LGM. TIC and PCA_{internal} axis 2 values decreased rapidly towards the LGM where minimum values were reached. Thus low inflow, reduced carbonate precipitation and a low lake level existed during the LGM. Low Fe/Mn ratios, as a redox proxy, imply a well-mixed waterbody with sufficient dissolved oxygen at the lake bottom. This inference corresponds with the reconstructed cold and windy climate. Accordingly, climate is surmised to be the main driver of the lake's internal conditions during the pre-LGM and LGM.
- 15 the main driver of the lake's internal conditions during the pre-LGM and LGM. Low primary production and low lake levels are also reconstructed by Wünnemann et al. (2012) for Lake Hala in the Qilian Mountains on the northern Tibetan Plateau, which is located in a comparable alpine setting. Very low TOC values have also been recorded from many other lakes on the Tibetan Plateau, suggesting low bioproductivity and cold temperatures during the LGM (An et al., 2012; Zhang and Mischke, 2009; Zhu et al., 2015). Although only few dates are available at Lake Issyk-
- 20 Kul in Kyrgyzstan, situated north-east of lake Karakul, lacustrine terrace sediments 33 m above current lake level indicate a period of lake-level high-stands starting around 26 kyr BP and lasting until the late glacial (non-accessible literature in Russian quoted in Romanovsky (2002) and Ricketts et al. (2001)). However, better chronological evidence from the exposed shorelines of Lake Issyk-Kul is required for a detailed assessment of its history in the late Pleistocene. Similar dates for high-stands were recorded for Lake Van in eastern Turkey, west of our study region, at approximately 26 kyr BP and the end of
- 25 the LGM (Kuzucuoğlu et al., 2010; Reimer et al., 2008). At Lake Karakul moderate to low lake levels were reconstructed during this period. Thus although the system is climate driven, it does not show the same lake evolution as the other two Westerlies-influenced lakes and reacts, at least in part independently, which might be due to a relocation of the Westerlies during the LGM or to the buffering capability of Lake Karakul.



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5.3.2 Late glacial and early to mid-Holocene (17.5 until approx. 6.9 kyr BP)

The late glacial is characterized by continuously low and slightly increasing TOC values indicating that the production of organic matter and its preservation increased slightly but remained comparably low. TOC/TN data reveal values below 10 and signal a prevailing bioproductivity by algae. The slight increase in bioproductivity is indicated from the continuously increasing PCA_{internal} axis 1 values. TIC values rise rapidly and reach maximum values during the late glacial, indicating high runoff and enhanced carbonate precipitation. The Fe/Mn ratios show a significant increase during the late glacial and

- culminate during the onset of the Holocene. The increase in bioproductivity and runoff was apparently accompanied by a decreasing availability of dissolved oxygen at the lake floor. The PCA_{internal} axis 2 scores are high during the late glacial and early to mid- Holocene, probably reflecting a high lake level (zone 2; Fig.3B). This inference is supported by the study of
- 10 Komatsu and Tsukamoto (2015) who propose a maximum lake level of 35 m for Lake Karakul during the late glacial. They argue that cold and wet conditions with moisture of Westerlies' origin caused glacier advances down to the lake at 15 kyr BP. Further evidence for relatively wet conditions during the late glacial and advancing glaciers is provided by Dortch et al. (2013) who infer several glacier advances (SWTHS 2D-2A) during the late glacial. Seong et al. (2009) investigated moraines in the Muztag Ata and Kongur Shan massifs 170 km to the south-east of Lake Karakul, and suggest glacial advances around
- 15 17 and 13.7 kyr BP. Regional differences in the timing of glacier advances are probably related to the specific topographic settings of glaciers and related response times, and to age uncertainties. Similar to the KK12-1 record other lakes such as the Monsoon influenced Lake Donggi Cona experienced an increase in lake level between 17.8 and 13.8 cal kyr BP (Opitz et al., 2012) due to increased meltwater input triggered by late-glacial
- warming. In contrast, lakes farther west of Lake Karakul such as Lake Van in Anatolia or the Dead Sea in the Levant
 experienced a rapid drop in lake level after 21 kyr BP (Landmann et al., 1996a, 1996b; Çağatay et al., 2014; Stein, 2014).
 This lake level regression lasted until the early Holocene at Lake Van (Landmann et al., 1996; Çağatay et al., 2014) or until 14 cal kyr BP in the Dead Sea (Stein, 2014). The contrary scenarios for Lake Karakul and Lake Van and the Dead Sea in the west during the late glacial possibly result from a latitudinal re-arrangement of the Westerlies after the disappearance of the Scandinavian ice sheet, and from the late glacial water sources in the Karakul catchment stored as snow and ice.
- 25 Early Holocene TOC values remained relatively low in contrast to rapidly increasing Fe/Mn ratio (zone 2; Fig.3B). The high TIC values indicate that runoff to the lake was high. In consequence, a relatively unchanged bioproductivity and rapidly increasing lake level is inferred for the early Holocene, which led to the establishment of poorly oxygenated bottom waters in Lake Karakul. The inferred moderate bioproductivity in the lake possibly results from relatively low lake-water temperatures in comparison to air temperatures due to the enhanced input of glacial meltwater. Climate is suggested as the
- 30 main driver of the internal lake development, with the Monsoon considered as the main influence in agreement with studies identifying a stronger Monsoon during the early and mid-Holocene as result of high summer insolation in temperate latitudes (Kutzbach, 1981). This inference is in accordance with Ricketts et al. (2001), who examined trace elements and □¹⁸O values of ostracod shells, and reconstructed a high freshwater input into Lake Issyk-Kul either due to increased moisture of





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Westerlies' origin or due to a monsoonal influence from the beginning of their record at 8.7 to 8.3 cal kyr BP. A relatively stable high lake level with sufficient inflow prevailed at Lake Issyk-Kul until 6.9 cal kyr BP, coinciding with our findings for the early and mid-Holocene. On the other hand, Lake Ulungur experienced low lake levels between 10 and 6 cal kyr BP with a minimum around 7.6 cal kyr BP (Mischke and Zhang, 2010), while Boston Lake did not exist before approx. 8 kyr BP (Wünnemann et al., 2006; Huang et al., 2009). It remains speculative whether Lake Karakul was influenced by the northward penetration of the Indian Monsoon during the early and mid-Holocene whilst the lakes in north-west China remained unaffected by monsoonal precipitation.

5.3.3 6.6 cal kyr BP until present

High TOC values and PCA_{internal} axis 1 scores signal high bioproductivity during the last 6.6 cal kyr BP (zone 3; Fig.3A).

- 10 Values for TOC/TN between 10 and 16 reflect a shift in organic matter origin from purely planktonic to more mixed sources: planktonic, macrophytes, macroalgae, and/or terrestrial. This shift is most likely explained by the occurrence of *Potamogeton*, a C3 submerged macrophyte (Edwards and Walker, 1983), as abundant remains of recorded in the upper part of the core, rather than the increased input of terrestrial plants. Continuously decreasing Fe/Mn ratios point towards increasing ventilation, probably due to a decreasing lake level and better oxygenation of bottom waters. The inferred lower
- 15 lake level after 6.6 cal kyr BP likely resulted from a weaker Monsoon, which retreated from the study area, and from reduced meltwater inflow from glaciers in the catchment. The lowered lake level probably favoured the expansion of macrophytes at the lake bottom due to sufficient mixing and light penetration. At approximately 6.6 kyr BP, a threshold seems to have been crossed, enabling an increased growth of the lake bottom at the core position. The decreasing TIC values probably reflect a decreasing inflow. The lake interior development is assumed to be mainly related to the aridification of climate during the
- 20 last 6.6 cal kyr BP.

A similar development to Lake Karakul is inferred at Lake Issyk-Kul where the \Box^{18} O values of ostracod shells suggest a major change in hydrology in the lake between 6.9 and 4.9 kyr BP (Ricketts et al., 2001). Ricketts et al. (2001) surmise a shift from an open lake system to a mostly closed lake system related to increasing aridity and changes in atmospheric circulation patterns with a dominance of drier air masses compared to the mid-Holocene. The study by Ricketts et al. (2001)

- 25 suggests increased biological productivity at Lake Issyk-Kul during the second half of the Holocene, after the shift to a closed system, corresponding to our findings from Lake Karakul for the last 6.7 cal kyr BP. A trend towards cooler conditions from about 3.5 to 1.9 cal kyr BP is reported for Lake Karakul by Mischke et al. (2010) and Taft et al. (2014), who investigated the last 4.2 kyr BP at high resolution. Low TOC values and low Fe/Mn ratios in core KK12-1 support these assumptions, implying decreased bioproductivity and increased mixing and ventilation of the lake floor. From approximately
- 30 1.9 cal kyr BP onwards a warmer phase led to increased meltwater supply (Mischke et al., 2010b; Taft et al., 2014) reflected by increased Fe/Mn values in core KK12-1 until 0.6 kyr BP and drier conditions afterwards in accordance with Mischke et al. (2010b).





6 Conclusions

The results of record KK12-1 from Lake Karakul, covering the last 28.6 cal kyr BP, contribute to our understanding of the interactions between the atmosphere and high-mountain environments and to the current discussion about atmospheric circulation in arid central Asia. First, we assessed the palaeoenvironmenal indicator value of each sedimentary parameter.

5 We assigned $\delta^{18}O_{AuthCarb}$, $\delta^{13}C_{AuthCarb}$, TiO₂, Sr/Rb, Zr/Rb, EM1-4 to indicate lake-external climate and TOC, TOC_{Br}, TIC, TOC/TN and Fe/Mn to reveal lake internal variations, identifying suitable proxies to investigate changes in lake-external and lake-internal conditions.

Based on the assessed proxies we identified three climatic phases:

- 1) The Karakul region was predominantly influenced by the Westerlies during the pre-LGM, LGM and late glacial.
- 2) Towards the end of the glacial and in the early and first half of the mid-Holocene (until approx. 6.7 cal kyr BP) the Monsoon appeared to increase in strength in response to increased summer insolation, allowing the transport of moist air masses farther north into the Pamir Mountains during summer.
 - 3) The monsoonal influence started to decrease during the second half of the mid-Holocene and the Westerlies regained their dominant role again, causing arid conditions in the Pamir Mountains during the late Holocene.
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Reconstructed lake-internal changes were mainly related to changes in the productivity and redox condition at the lake bottom. A low lake level, coinciding with high ventilation and low productivity prevailed during the pre-LGM and LGM at Lake Karakul, followed by a lake level high-stand during the late glacial and early to mid-Holocene (17.5 until ~ 6.7 cal kyr BP). Productivity increased rapidly with enhanced ventilation and reducing lake levels from 6.7 cal kyr BP onwards.

20 Comparisons of lake-internal signals from Lake Karakul with those from other relatively deep lakes in the Westerlies region suggest that the sedimentary regime in Lake Karakul was largely driven by climate, which is not unexpected, as it is mainly fed by glacial meltwater.

Lake Karakul has proven to be a suitable archive of paleoenvironmental data and our study contributes to the understanding of the region, adding to the few paleolimnological studies that have been conducted in Central Asia so far.

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 Table 1. Radiocarbon dates from dated materials, including a living charophyte. Ages have been corrected for the lake reservoir

 effect of 1368 years and were calculated in BACON (Blaauw and Christen, 2011) (Fig.2).

				Calibrated and	
				corrected age (yr	
Sample No	Depth (cm)	Material	¹⁴ C age (yr BP)	BP)	Laboratory ID
KK12-10	0	insitu plant April 2012	$950\pm25 \text{ BP}$	0	Poz-53829
KK12-1 01	0-1	Plant remains	$1615\pm30 \text{ BP}$	n.d.	Poz-53820
KK12-1 115	114-115	Plant remains	$2755\pm35~BP$	1181-1419	Poz-56643
KK12-1 250	249-250	Plant remains	$4175\pm30 \text{ BP}$	2796-3112	Poz-53822
KK12-1 370	371-372	Plant remains	$5340 \pm 35 \text{ BP}$	4332-4827	Poz-56644
KK12-1 468	469-470	Bulk sediment/TOC	$7530\pm40 \text{ BP}$	6841-7228	Poz-53823
KK12-1 538	559-560	Plant remains	$2430\pm30 \text{ BP}$	10313-12057	Poz-53826
KK12-1 560	581-582	Bulk sediment/TOC	$11900\pm60~\text{BP}$	11797-12637	Poz-56556
KK12-1 625	646-647	Bulk sediment/TOC	$13550\pm60~BP$	13849-15092	Poz-56555
KK12-1 689	737-738	Moss	$18790 \pm 100 \text{ BP}$	17851-20954	Poz-53827
KK12-1 775	823-824	Plant remains	$21400 \pm 110 \text{ BP}$	21109-23307	Poz-56648
KK12-1 851	899-900	Plant remains	$21280\pm100~BP$	23523-24520	Poz-53828
KK12-1 935	1002-1003	Plant Remains	$23230\pm130\text{ BP}$	25834-27023	Poz-56649
KK12-1 1019	1086-1087	Bulk sediment/TOC	$27300\pm200 \text{ BP}$	27578-29773	Poz-53821

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Figure 1: Lake Karakul in the Pamir Mountains, Tajikistan, in arid Central Asia.



Figure 2: Age-depth model for core KK12-1 constructed in Bacon (Blaauw and Christen, 2011) with 12 radiocarbon dates and a

5 calculated reservoir effect of 1368 yr.

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10 Figure 4: End-member modelling for core KK12-1. A - Grain-size distribution of the nine reference samples in the vicinity of Lake Karakul, B - Loading of grain size based end-member modelling of Lake Karakul.



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Figure 5: Biplot for principal component analyses (PCA) of geochemical and sedimentological parameters for core KK12-1. A - for external parameters zone 1: 28.6 to 13.3 cal kyr BP, zone 2: 13.3 to 6.6 cal kyr BP, zone 3: 6.6 cal kyr BP to present; B - for interal parameters zone 1: 28.6 to 18.4 cal kyr BP, zone 2: 18.3 to 6.7 cal kyr BP, zone 3: 6.7 cal kyr BP to present.

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