ABSTRACT
The continental settings of Central Asia witnessed increased desertification during the Cenozoic as a result of mountain uplift and the Paratethys retreat. The interaction of these tectonic-scale processes with orbitally forced climate change and their influence on Asia’s atmospheric moisture distribution are poorly constrained. A Miocene succession of continental mudflat deposits, exposed in the Aktau Mountains (Ili Basin, south-east Kazakhstan), has great potential as a terrestrial palaeoclimate archive. About 90 m of the 1700 m thick succession comprise alluvial mudflat deposits and appear as cyclic alternation of coarse sheet floods, mudflat fines and semi-arid hydromorphic soils. In this study, bulk-sediment mineralogy and geochemistry, magnetic susceptibility, sediment colour and palynology are used to reconstruct environmental conditions by determining changes and forcing mechanisms in the intensity of sediment discharge, weathering and pedogenesis. The results presented here indicate four major periods of arid soil formation and one palustrine interval characterized by higher evaporation rates under highly alkaline/saline conditions. A positive correlation between weathering indices and the Mg/Al ratio suggest that these horizons correspond to maximum rates of evapotranspiration and aridity. The formation of mudflat fines is, instead, interpreted as representing higher detrital sediment production by more intense alluvial fan activity during times of higher precipitation. Time series analysis of weathering indices, colour and magnetic susceptibility data yields cycle-to-frequency ratios with the potential to represent Milankovitch cyclicity with short and long eccentricity as dominant periodicities. Periods of pronounced aridity, paced by long eccentricity forcing, reflect changes in moisture availability. On longer tectonic timescales, the persistent appearance of gypsum indicates a shift towards more arid conditions. This trend in climate is considered to result from the closure of the eastern gateway of the Mediterranean to the Indian Ocean that restricted circulation and enhanced salinity within the Eastern Paratethys.

INTRODUCTION
The evolution of Cenozoic climate is characterized by global cooling, increased meridional temperature gradients and the expansion of polar ice sheets in Antarctica and the Northern Hemisphere since ca 35 Ma and ca 15 Ma, respectively (Zachos et al., 2008; De Vleeschouwer et al., 2017). The mechanisms behind this global cooling, its
regional differentiation and the feedbacks involved are still a matter of debate. Continental settings of Central Asia witnessed increased desertification and the establishment of a monsoonal climate during the Cenozoic as a result of India’s collision with Asia and the Paratethys retreat (Molnar & Tapponnier, 1975; Ramstein et al., 1997). However, the timing of this continent-scale climate shift relative to global climate evolution, the interplay between regional and global factors and the effects of orbital-scale processes are not yet well constrained.

Based on loess deposits in China, the existence of energetic winter monsoon winds and large source areas for aeolian dust in the interior of Asia has been traced back to 22 Ma (Guo et al., 2002). Alternatively, desert areas in inner Asia north of the uplifting Pamir and Tian Shan mountain chains may have been mainly influenced by westerly wind flow since Eocene to Oligocene times (Sun et al., 2010; Caves et al., 2015). A variety of proxy records suggests a temporally differentiated pattern for the onset of desertification in Central Asia, ranging from the Eocene/Oligocene transition in north-east Tibet and south-western Mongolia (Dupont-Nivet et al., 2007; Sun & Windley, 2015) to the mid-to-late Miocene north of Tibet (Dettman et al., 2003; Kent-Corson et al., 2009; Sun et al., 2015), and the mid-Pliocene on the Chinese Loess Plateau (Wang, 2006). Mammal diversity changes in Oligocene–Miocene successions in Mongolia provide evidence for intermittent episodes of increased precipitation (Harzhauser et al., 2016) and the aeolian origin of the Valley of Lakes successions was questioned by results of clay mineralogy (Richoz et al., 2017). The relative intensities of the westerlies and monsoonal wind systems played an important role in transporting moisture into Asia’s continental interior (Caves et al., 2015). Climate modelling results suggest reduced moisture transport to inner Asia by weakened westerlies and monsoonal winds after the global shift to cooler climate conditions in the Oligocene (Licht et al., 2014).

The mid-Miocene (17 to 14 Ma) was one of the last warm periods of the Neogene (Zachos et al., 2008; Holbourn et al., 2014, 2015). While the proxy evidence for a warm and relatively humid mid-Miocene world is clear, the mechanisms responsible for this climate state are not. Atmospheric pCO2 variations are supposed to drive changes in the global carbon reservoirs, implying changing rates of silicate weathering and global carbon sequestration (Holbourn et al., 2015). A factor recently invoked to explain mid-Miocene warmth is a lower continental topography than today promoting a more zonal atmospheric circulation with a westerly flow over lowered mid-latitude plateaus (Henrot et al., 2010). However, available proxy data yield somewhat contradictory climate scenarios for the mid-Miocene of Central Asia. While records from Mongolia and China indicate increased desertification since Oligocene to early Miocene times (Guo et al., 2002; Sun & Windley, 2015), the regionally widespread formation of lacustrine deposits in eastern/south-eastern Kazakhstan and the Tarim Basin during the Miocene, described as “the great lacustrine stage”, suggest increased atmospheric moisture transport to Central Asia (Akhmetyev et al., 2005; Liu et al., 2014). Palynological data of mid-Miocene age indicate warm-temperate conditions for the Junggar Basin and the north-east Tibetan Plateau (Hui et al., 2011; Miao et al., 2011; Tang et al., 2011b) pointing towards a transient episode of increased humidity.

A terrestrial alluvial floodplain succession of mid-Miocene age, exposed in the Aktau Mountains of the Ili Basin, south-eastern Kazakhstan, has the potential to provide insights into the Miocene climate evolution in Central Asia (Fig. 1). In this study, bulk-sediment mineralogy and geochemistry (element geochemistry, CaCO3/ CaSO4 content), magnetic susceptibility (MS), sediment colour and palynological data are used to decipher the regional response of sedimentary particle supply, chemical weathering intensity and pedogenesis to changes in regional moisture supply by precipitation and subsurface aquifer recharge. Furthermore, the results provide insights into climate and environmental conditions in the context of atmospheric moisture transport to Central Asia. Time series analysis of chemical weathering indices, (MS) and sediment colour data are used to decipher potential orbital forcing mechanisms.

GEOLOGICAL SETTING

The Ili Basin is a closed (endorheic) basin within the intracontinental Tian Shan mountain system. It is surrounded by continuously uplifting mountain ranges of the Zailiysky and Dzungarian Alatau and became progressively contracted by N-S shortening and fragmented due to the activation of intrabasinal basement uplifts (Kober et al., 2013; Macaulay et al., 2014). The basin fill covers a time span from the late Eocene to present. The Tian Shan mountain ranges grew as a result of India’s collision with Asia with current crustal shortening (ca 20 mm y−1) accounting for nearly half of India’s convergence with Eurasia (Abdrakhmatov et al., 1996). Exhumation and unroofing ages indicate the initial uplift of the Tian Shan to have occurred in the Oligocene to early Miocene (Hendrix et al., 1994; Sobel et al., 2003, 2006; Macaulay et al., 2014). During these times, the central Ili Basin mainly accommodated distal, low-energy sediments on a regionally extensive peneplain while the basin margins were accompanied by alluvial fans (Kober et al., 2013).
In the Aktau Mountains, a Neogene exposure of Ili Basin sediments south of the Dzungarian Alatau (44°09.58′N, 79°14′56.94″E; Fig. 1), a 1700 m thick succession of fine-grained deposits forms an asymmetric anticline with a steeply to vertical dipping southern limb and a gently dipping northern flank (Bazhanov & Kostenko, 1961). Alluvial sediments of Pleistocene age disconformably overlie the succession and are involved in very young folding activity. Aktau means “White Mountains” in the Kazakh language and the succession is characterized by spectacular colour banding of its deposits (Fig. 2). The overall succession and its facies have been documented in a series of earlier studies and expose a quasi-continuous Eocene/Oligocene to Pliocene terrestrial record (Bazhanov & Kostenko, 1961; Bodina, 1961; Lucas et al., 1997; Kordikova & Mavrin, 1996). Previous authors have introduced diverging lithostratigraphic schemes that are summarized by Kober et al. (2013). Here, the formation names of Bodina (1961) are followed together with thicknesses given by Bazhanov & Kostenko (1961) and Kordikova & Mavrin (1996), as both yield the best agreement with field observations (Fig. 3).

The succession is based in red-coloured clays and sandstones of a river system (Arasan Formation, 63 m) that grade into reddish to brown-red mud-dominated deposits, which contain distal alluvial, meandering river deposits and gypsum beds of a saline mudflat with evidence of an ephemeral playa lake (Alakul Fm, 115 m). Higher up the succession, a transition to cross-bedded fluvial sandstones of a meandering river occurs above a significant disconformity (Aidarly Fm, 130 to 140 m) overlain by cyclically bedded, reddish-brown mudflat deposits (Bastau Fm, 90 m). The upper part of the succession consists of greenish grey gypsisols and ephemeral playa lake deposits, as well as perennial lacustrine limestones with freshwater charophytes, ostracods and gastropods, and intercalated coal seems (Koktal and Kokterek Fms, 460 m). The top of the succession is represented by silty mudflat deposits with intercalations of lacustrine, fossil-rich fresh water limestones and channel sandstones indicative of a permanent river system with an adjacent fresh water lake (Ili Fm, ca 880 m; Fig. 2). Parent rocks for the alluvial plain deposits of the Arasan, Alakul, Bastau and Koktal formations are Permo-Carboniferous volcanics exposed in the Katutau and Dzungarian Alatau mountain ranges at the northern edge of the Ili Basin today. They comprise andesites, rhyolites and trachytes that belong to the Palaeozoic accretionary arc complex of the Central Asian Orogenic belt (Jahn et al., 2000, 2004; Li et al., 2015). The provenance of major parts of the basin fill from these sources is proven by proximal alluvial fan deposits close to the basin margins. In contrast, sandstones of the Arasan, Aidarly and Ili formations were mainly derived from a distant quartz-rich and mica-rich source often mixed with volcanics derived from local sources (Lucas et al., 1997; Kober et al., 2013).

Biostratigraphic ages are available from the fluvial Arasan and Aidarly formations and lacustrine floodplain deposits of the Ili Formation. Dating of the late Eocene (Ergilian) Arasan Formation is based on mammal bones of Brontotheriidae and the hyracodontid Ardynia sp. (Gromova, 1952; Lucas et al., 1997). The lower Aidarly Formation is of late Oligocene age based on occurrences of the giant rhinoceros Indricotherium (Lucas et al., 1997), while the upper Aidarly Formation is placed into the late Burdigalian to Langhian mammal zones MN4 to MN5 based on records of plants and mammals (rodents, carnivores, insectivores, the odd-toed Gomphotherium and early deers such as Stephanoceras and Lagomeryx) (Fig. 3; Lucas et al., 1997; Kordikova, 2000; Kordikova & de Bruijn, 2001). The lower Ili Formation yields charophytes.
typical for the late Miocene to early Pliocene (Dzhamangaraeva, 1997). Early palaeontological excavations in the Ili Formation provided records of the gomphotere *Anancus avernensis*, an extinct elephant living 7 to 1.8 Ma ago (Bazhanov & Kostenko, 1961). Based on these biostratigraphic data, the age of the here studied Bastau Formation is constrained to the mid-Miocene between 17 and 14 Ma (Fig. 3).

**METHODS**

During field work in 2011 and 2015, the 91 m thick Bastau Formation was logged in centimetre-to-decimetre-scale resolution. Direct measurements of bed-thickness were adjusted to the total thickness of the sedimentary succession determined with a laser distance and angle meter to correct for erroneous thickness measurements related to variable slope.

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*Fig. 2.* Outcrop images showing the Aktau succession. (A) View of the western flank of the Aktau Hills with the range of lithostratigraphic formations. Length of exposure is ca 5 km. The hill in (B) is marked by a star. (B) Southward view from the studied Bastau Formation (Fm) with the Ili Basin and Tian Shan Mountains in the background.
angles. The succession was sampled in 20 to 25 cm spacing for bulk-sediment geochemistry. Potentially prospective strata were also sampled for palynology. Sediment colour scans were performed in 5 to 8 cm spacing with a Konica Minolta CM-700d spectrophotometer, and volume-specific magnetic susceptibility (MS) was measured every 10 cm with a hand-held SM 30 magnetic susceptibility meter (ZH Instruments, Brno, Czech Republic).

**Element geochemistry**

To account for the different components of Bastau Formation sediments (silicates, carbonates, sulphates and salts) and to isolate the silicate fraction, the geochemical composition of powdered sediment samples was analysed in two steps, by separating the acetic acid-leachable fraction from the non-leachable fraction. Following the method of Goldberg & Humayun (2010) 400 to 600 mg of sample powder was treated with 4.5 ml of 50% acetic acid at 50 to 75°C for ca 18 h; 250 μl of the leached solvent was then analysed by ICP-OES. The remaining sediment was repeatedly washed to ensure complete removal of dissolved ions from the sediment pore water. The 100 mg of decalcified sample powder was then digested in HF-enhanced aqua regia with the microwave Multiwave 3000™ by Anton Paar.

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**Fig. 3.** Stratigraphic overview of parts of the Aktau Mountains succession with (A) the lithology and position of biostratigraphic marker beds (stars) in the Miocene (f2, f3, Lucas et al., 1997) and Late Miocene to Pliocene (f1, Bazhanov & Kostenko, 1961; Dzhamangaraeva, 1997), and (B) an overview of regional divisions, biozonations, tectonic and climate events in Europe and Central Asia and the estimated age for the Bastau Formation (green bar). Ages are after GTS12. Lithostratigraphic formations are from Bazhanov & Kostenko (1961)1 and Bodina (1961)2. Mammalian biostratigraphy3 is from Bazhanov & Kostenko (1961) and Lucas et al. (1997), and the relative Paratethys sea-level curve4 is after Popov et al. (2010). Uplift ages of the Tian Shan are from Sobel et al. (2003, 2006) and Macaulay et al. (2014). MMCO, Middle Miocene Climatic Optimum.
An internal reference material and a blank were included in each session.

Geochemical analyses were carried out by ICP-OES on an iCAP6300 Duo™ by Thermo Scientific. Matrix concentrations were reduced by diluting the primary preparation solutions by a factor of three. Yttrium was added to all samples as an internal reference. Calibration solutions were prepared separately for the leached and bulk-digested samples using certified single and multi-element standards (SPEXCertifPrep). Acetic acid-leached and bulk samples were then analysed in separate sessions. Reproducibility of repeated sample and standard measurements was within 5% (2σ) for most elements.

The weight loss caused by leaching of the rock powders ranged from 3.8% to 75%. As not only calcite was removed from the sediment, the carbonate content (calcite) was calculated by using the Ca concentration in the leachable fraction (Calcite [wt%] = mCa*100-1). Gypsum abundances were assessed using the sulphur content of totally dissolved samples, which show a strong correlation of sulphate (SO₄) and Ca for sulphate concentrations above 1 wt%. The content of gypsum was determined by assuming that all sulphur in the non-leachable fraction is related to gypsum (Gypsum [wt%] = mS (silicate) * 172-14). Some samples experienced a mass loss during the washing process after leaching. Stoichiometric calculations of the Ca content in the leachable fraction and the bulk sediment show the mass loss to be related to dissolution of gypsum. This mass loss has been added to the calculated gypsum content from the non-leachable fraction. Element concentrations of the non-leachable fraction are used to calculate indices of chemical weathering (see below).

**Grain size and sediment mineralogy**

Grain-size and X-ray diffractometry (XRD) analyses were performed on a subset of samples of the Bastau (n = 14) and Alakul formations (n = 10) and from stratigraphic equivalent horizons (n = 18) from the more proximal Kendyrlisay Valley section (Hellwig et al., 2017). For grain-size analyses, 20 mg of each sample was decalcified with 20% formic acid, and after neutralization and homogenization wet sieved to remove grain sizes >100 μm. The fine fraction (<100 μm) was held in suspension in a Na-polyphosphate solution before 5 ml of the suspension was measured using a HORIBA LA-950 laser particle analyzer.

For XRD analyses, powdered rock samples were mounted on sample holders with the back-loading technique to reveal poor orientation and texturation. The measurements were performed on a PANALYTICAL X’Pert Bragg-Brentano diffractometer, using a copper beam powered by 30 mA and 40 KV generator current, Ni filter, programmable divergence slit, sample spinning and X’Celerator 1D detector. The characteristic diffraction maxima of each identified mineral phase was determined using MacDiff software. Intensities were converted to fixed 1° divergence characteristics and weighted by reference intensity ratios (RIR) to calculate the relative contribution from each mineral phase. Samples with a clay mineral composition containing palygorskite and/or mixed layer structures with expandable layers were treated for 24 h with ethylene glycol to aid in the identification of such phases. Palygorskite needles were also identified by Scanning Electron Microscopy.

The following phases were detected (in brackets: main diffraction maxima positions and RIR value as used for semiquantitative data calculation): mixed layer illite–smectite (around 12 to 13 Å, 0-4), palygorskite (10.35 Å, 0-52), illite/muscovite (10 Å, 0-43), chlorite/clinochlore (14, 7-1, and 3-54 Å, 1-0), quartz (4.26 and 3.34 Å, 3-03), K-feldspar (3.23 to 3.25 Å, 0-6), albite (3.18 to 3.2 Å, 0-64), calcite (3.04 Å, 3-32), ankerite (2-91, 3-15), dolomite (2-9 Å, 2-51), gypsum (7-6 Å, 1-7), halite (2-82 Å, 4-71).

**Scanning electron microscopy (SEM)**

Single samples from the Bastau Formation were prepared for SEM with a Zeiss Sigma VP. The suspended sediment was mounted on a slice, dried at 40° and afterwards sputtered with platinum. SEM microscopy was performed with a voltage of 10 to 15 kV.

**Palynology**

Six samples from the Bastau Formation were processed for palynological analysis using standard techniques previously applied to lake sediments from Central Asia including freeze-drying, weighing, HCl (30%) and HF (40%) treatment, and sieving through a 10 μm nylon mesh (Herb et al., 2015). At least 300 pollen grains were counted per sample under 400 × magnification. Identification of taxa and nomenclature followed Hoorn et al. (2012), Han et al. (2016) and Miao et al. (2016).

**Time series analysis**

Time series of colour data, MS and element geochemistry were used for spectral analysis. In particular, the time series of the Red/Blue colour ratio (700/480 nm), the chemical proxy of alteration (CPA) and the Ti/Al ratio are used because of its high sensitivity to variations in the detrital sediment flux, redox conditions and degree of weathering (Salminen et al., 2005; Buggle et al., 2011). Spectral analysis was performed on each time series
following the method of Weedon (2003) in order to identify dominant cycle lengths. Prior to the algorithm, each record was normalized by mean value subtraction and sampled evenly by linear interpolation. The record of MS was plotted on a logarithmic scale to achieve variance stabilization. Redfit power spectra were calculated with the “PAST” software (Hammer et al., 2001) following the algorithm by Schulz & Mudelsee (2002). Dominant cycle frequencies were used for Gaussian band-pass filtering in order to identify potential cycle-frequency ratios typical for orbital forcing in the Miocene Bastau Formation. In addition, average spectral misfit (ASM) calculations and evolutive harmonic analysis (EHA) was performed with the Mg/Al time series using the astrochron software package by Meyers (2014). For ASM analysis, candidate frequencies which reflect possible Milankovitch forcing were identified from the Mg/Al redfit power spectrum at 90% confidence level. Miocene orbital target frequencies and their uncertainties are derived from Laskar et al. (2004) following the approach in Meyers et al. (2012).

WEATHERING INDICES

Chemical weathering indices rely on the concept that mobile elements are selectively removed from weathering profiles relative to rather immobile elements. A number of element indices have been applied to different terrestrial sediments as palaeoenvironmental indicators. Here, a modified Ca-free version of the chemical index of alteration (CIA; Nesbitt & Young, 1982), the CPA (Bugge et al., 2011), and the molar Mg/Al ratio were chosen as an analogue for magnesium-bearing minerals (Maynard, 1992).

The CIA, derived from the silicate fraction, is a quantitative measure of feldspar weathering by relating Al, enriched in the residues, to Na, Ca and K removed from a soil profile by plagioclase and K-feldspar weathering (CIA = [Al₂O₃/(Al₂O₃ + Na₂O + CaO* + K₂O)]*100; Nesbitt & Young, 1982). Changes in sediment provenance, hydrologic sorting and post-depositional processes lead to K⁺ addition, as for instance, diagenetic illitization. Illitization is also reported as pedogenic process in soils forming under arid climates (Singer, 1988) when smectite is altered during repeated wetting and drying cycles in the presence of K⁺ (Eberl et al., 1986). The most interfering element for Bastau Formation sediments, however, is Ca, which is commonly present both in detrital plagioclase and pedogenic carbonates and sulphates. Some of the Ca content of the acid insoluble fraction is related to gypsum, therefore we used a Ca-free version CIA-Ca of the CIA.

The CPA, defined as the molar ratio of Al and Na (CPA = [Al₂O₃/(Na₂O + Al₂O₃)]*100), is a weathering index for carbonate-rich shales, siltstones and sandstones because of the small ionic radius of Na and its interference with non-silicate minerals in non-saline soils (Bugge et al., 2011). The paired elements, Na and Al, minimize biases due to variable mineralogical composition of the parent material.

Climates with low to moderate precipitation reduce the intensity of weathering. Soluble cations such as Mg²⁺ can accumulate in soil pore waters by the limited flux of water through the soil profile which leads to the formation of alkaline and alkaline earth-rich secondary minerals (e.g. smectite and carbonates; Calvo et al., 1999; Sheldon & Tabor, 2009; Torres & Gaines, 2013). In highly alkaline/saline solutions, rich in dissolved silica, Mg²⁺ is incorporated into triotahedral clay minerals as Mg-smectite and sepiolite (Deocampo, 2004, 2015; Cuadros et al., 2016). Here, the molar Mg/Al ratio from the total dissolved fraction is used as a measure of clay authigenesis in times of elevated rates of evaporation and higher groundwater table.

In addition, the molar ratio of Ti/Al from the non-leachable fraction (Ti*100/Al) is used as a geochemical index for palaeoenvironmental interpretation. The Ti/Al ratio is a classical indicator for sediment provenance, the more Ti present the more mafic the parent rock is (Salminen et al., 2005; Sheldon & Tabor, 2009). Higher Ti/Al ratios indicate higher abundances of heavy minerals such as rutile, anatase, brookite, titanite and/or ilmenite (titanomagnetite) or detrital Ti-rich pyroxenes and amphiboles in the catchment area. If the chemical composition of the parent rock in the source area remains unchanged through time, the Ti/Al ratio can be interpreted as an indicator of weathering intensity and sedimentary discharge from the catchment area (Sheldon & Tabor, 2009). Physical weathering readily removes Ti from igneous and metamorphic rocks where it subsequently becomes enriched in the fine fractions of floodplain sediments (Salminen et al., 2005; Taboada et al., 2006; Minyuk et al., 2014). The Ti/Al ratio is used here as a proxy for the intensity of alluvial sediment discharge in times of unchanged provenance.

DATA AND RESULTS

Sedimentary facies

The Bastau Formation consists of reddish-brown mudstones with intercalated greyish-green and reddish sandstones that appear cyclically throughout the succession (Figs 2B and 4A). A typical sedimentary cycle begins with thin (5 to 20 cm) beds of medium-grained to coarse-grained sandstones, composed of several units separated by thin pelitic layers, finally grading into several metres thick mudstones. The base of the single sandstone beds
may be slightly erosive or channelized. Although sandstone units can be traced over hundreds of metres, individual layers pinch out over short distances (10 to 50 m). Grain size varies in different layers from well-rounded granules to medium-grained sand of moderate roundness. Especially, thin lobate units have significant matrix content, pointing to hyper-concentrated flows. The topmost centimetres of single sandstone layers often show secondary clay infiltration. The poorly sorted sandstones, rich in unweathered volcanic rock fragments and plagioclase grains, are interpreted as representing distal lobes of sheet flood deposits of terminal splays and their related feeder channels (Fig. 4C).

The mudstones are homogeneous, structureless rocks on average with less than 1% to 2% sand content. Often, they display a mottled texture or polyedric fracturing. They yield secondary carbonates and salts and the grain-size distribution (<100 μm) is bimodal with modal peaks at 0-2 to 0.3 μm and 9 to 10 μm, respectively (Fig. 5). The small grain-size fraction is mainly represented by authigenic components while the larger modal peak is indicative of detrital silt particles. The grain-size pattern is supported by

Fig. 4. Outcrop images showing the Bastau Formation facies types: (A) alternation of greyish sandstones and reddish-brown mudstones between 9 and 32 m representing sheet flood deposits (black arrows) and phreatic carbonates (white arrows) in a mudflat, (B) detail of (A) showing nodular phreatic carbonates on top of a bleached sandstone at 9 m, (C) enrichment of unweathered rock fragments in badly sorted sandstones, (D) reddish mottled grey gleysol at 16-2 m, (E) well-bedded calcareous marl with gypsum deposited in a playa lake system overlain by reddish mudstones at 61-4 m, and (f) abundant occurrence of displacive gypsum in mudstone deposits above the first lake (Horizon IV). Note people in bottom right corner of A.
the results of powder XRD analyses (Fig. 5). Relatively high abundances of unweathered minerals (quartz + albite + K-feldspar) sum up to 60% of the mudstone’s composition. The mean clay mineral content is 29% and comprises mixed layer illite/smectite (0.7%), palygorskite (7.8%), illite (15.1%) and chlorite (5.0%). The relatively high abundance and needle-like preservation of palygorskite underlines its authigenic formation under arid to semi-arid depositional conditions (Fig. 5). At some horizons, distinct nodular calcareous horizons occur (Fig. 4A and B). Mostly, they form 5 to 10 cm thick beds above massive sheet flood deposits. The nodular appearance of carbonates demonstrates its phreatic origin from saturated solutions in times of elevated groundwater table. Episodes of elevated groundwater table and pedogenic reworking are also evident from reddish or greyish mottling structures (Fig. 4D). Accordingly, the mudstones are interpreted as dry mudflat deposits, homogenized by plant growth and bioturbation and, in part, overprinted by in situ weathering and authigenesis.

Fig. 5. Overview of the mineralogical composition and grain size of Bastau Formation sediments, (A) mean relative abundance of mineral phases estimated by powder X-ray diffractometry (XRD), (B) Scanning electron microscopy (SEM) image of sample AB 133, (C) relation of relative percentages of illite to quartz and feldspar in the Bastau and Alakul formations (closed circles) in comparison to a more proximal site (open circles, see text), (D) mean grain-size distribution of the <100 µm fraction with the 1 σ standard deviation (grey area). Unweathered source rock minerals sum up to 60% (albite + kalifeldspar + quartz). Abundant occurrence of small palygorskite needles in the mudstones refer to their authigenic formation. The bimodal grain-size distribution shows the grain-size separation of authigenic and detrital components.
Above 59 m, a prominent change in sedimentary facies occurs with a 3 m thick green horizon ("green band", GB) of calcareous mudstones (Fig. 4E). It consists of bedded nodular carbonates in its lower part and increased contents of gypsum towards the top (Fig. 6). This horizon is interpreted as the first occurrence of prolonged palustrine conditions in the Aktau succession. The shift from carbonates to gypsum represents an increase in salinity from almost freshwater to hypersaline conditions indicative of high rates of evaporation. Higher up, the succession consists again of alternations of sandstones and mudstones, however, with abundant gypsum (Fig. 4F). Gypsum is present as single idiomorphic lenticular crystals within the sediment and forms up to 1 m thick crusts of chicken wire gypsum on top of the Bastau Formation (Fig. 2B). Thin sections show the gypsum also as secondary precipitates in the pore space suggesting a phreatic zone origin. Lenticular gypsum crystals and chicken wire-textured massive gypsum indicate mechanical replacement of soft, water-saturated mud. The abrupt appearance of gypsum above 60 m corresponds to elevated rates of evaporation in a progressively hydrologic restricted basin and indicates a facies shift from dry to saline mudflat and playa lake environments (Fig. 6).

Fig. 6. Lithologic log of the Bastau Formation with carbonate and gypsum content, weathering indices in the acid-leachable fraction (CPA, CIA-Ca, Mg/Al; see text), Ti/Al ratio, sediment colour (normalized Red/Blue ratio) and MS. Numbered grey bars mark horizons of intensified weathering and clay mineral authigenesis. Arrows mark the position of productive palynological samples.
Element geochemistry, sediment colour and magnetic susceptibility

The carbonate content of mudstones in the Bastau Formation is on the order of 10% to 15% (Fig. 6). Elevated values between 20% and 30%, with single maximum values up to 60%, occur in beds with phreatic cementation above sheet flood deposits and in the palustrine horizon between 58-2 m and 61-4 m. The gypsum content is negligibly small below 60 m. A first significant occurrence of 10% to 75% at 60-0 to 61-4 m is associated with the upper part of the lacustrine horizon.

The weathering indices CIA-Ca, CPA and Mg/Al have mean values of 71 ± 3, 86 ± 5 and 0.29 ± 0.05, respectively, typical for sustained chemical weathering conditions. In addition, the three indices show relatively similar variations (Fig. 6). Elevated values occur in four horizons characterized by pedogenic reworking evident from mottling and associated colour changes. Namely these horizons occur at 1 to 3 m (I), 19 to 23 m (II), 27 to 30 m (III) and 65 to 68 m (IV). A fifth horizon is marked by the palustrine horizon GB (58 to 61-4 m). Very low weathering indices are associated with coarse sheet flood deposits rich in unweathered rock fragments. The CPA shows an almost identical pattern of variability as the CIA-Ca but differs from it by having higher amplitude variations. The Mg/Al ratio shows similar relative trends as the CPA and CIA-Ca but displays pronounced maxima which are caused by additional Mg enrichment in horizons of elevated pedogenesis (Figs 6 and 7). Prominent Mg enrichment occurs in Horizon IV.

Median concentrations of TiO₂ are 0.7 ± 0.1% and the Ti*100/Al ratio displays small variations around a mean value of 2.8 to 2.9, typical for a source rock with rather uniform chemistry (Fig. 6). Elevated values at the base of the succession are the only exception and refer to a different provenance for the fluvial Aidarly Formation sediments. Throughout the remainder of the succession, low Ti/Al ratios occur in the horizons of pedogenic reworking, and chemical weathering paces the more elevated values into 20 to 30 m long depositional cycles. A similar pattern exposes the Red/Blue colour ratio with low and high frequency variations indicative of changes in lithology and redox conditions of the sediment. The low frequency variations display 20 to 30 m long cycles separated by lower values in horizons of elevated weathering. Superimposed variations of higher frequency are associated with colour banding.

The MS displays cyclic variations with significant drops in the more weathered horizons. The minima are stratigraphically more expanded and include horizons of mudstone mottling reflecting changes in iron mobility and thus the sediment redox state after deposition. Elevated values occur mainly in the lower and upper part of the successions (e.g. at 7 to 8 m and 22 to 23 m or beneath the palustrine horizon (GB) associated with enhanced detrital input.

Palynology

Only two of the six analysed samples (KAZ-10 and KAZ-11 at 62.20 m and 62.55 m, respectively) yielded moderately preserved palynological assemblages consisting predominantly of pollen and spores; in addition, the assemblages contain abundant non-pollen palynomorphs, including algal cysts of unknown affinity, rare organic-walled dinoflagellate cysts of presumably freshwater origin and fungal spores (Fig. 8).

The pollen and spore assemblages extracted from samples KAZ-10 and KAZ-11 contain substantial numbers of conifer-derived bisaccate pollen grains (i.e. Pinuspollenites, Piceapollenites and Abiespollenites in order of decreasing abundance). They make up 70-2% and 14-2% of the assemblages, respectively; Taxodiaceapollenites reaches 0-6% and 7-3%. With regard to pollen from deciduous trees, the assemblages are dominated by (in order of decreasing abundance) Ulmipollenites (9-9% and 55-0%, respectively) and Pterocaryapollenites (1-4% and 3-3%); other deciduous tree-pollen taxa occurring in low (i.e. ≤2%) percentages are Alnuspollenites, Carpinuspollenites, cf. Caryapollenites, Fraxinopollenites, cf. Juglansspollenites, Quercoidites, Striaticolpites, Tiliaepollenites and Triporopollenites. Non-arboreal pollen grains are mainly from Cyperaceae (6-8% and 4-8%, respectively) and Graminidites (5-1% and 13-0%); other non-arboreal pollen taxa occurring in low (i.e. ≤2%)

![Fig. 7. Cross plot of CPA and Mg/Al ratios for Bastau Fm sediments that demonstrates the process of Mg enrichment during early diagenetic authigenic clay formation (white arrows). Black symbols represent the lowermost 2 m of the succession; white symbols mark horizons of phreatic carbonate precipitation and evaporative enrichment, and grey diamonds all other samples (see text).](image-url)
percentages are Chenopodipollis, Compositoipollenites and Ephedripites spp. Fern spores account for 3-7% of the pollen and spore assemblage of sample KAZ-10, and pollen from aquatic plants (i.e. Sparganiaceae pollenites) account for 1-5% of the pollen and spore assemblage of sample KAZ-11.

**Time series analysis**

Average Middle to Late Miocene sedimentation rates of the Aktau succession (bases Bastau to Ili formations) are on the order of 5-0 to 8-5 cm ka$^{-1}$ based on its overall thickness of 530 ± 40 m and biostratigraphic age (8 ± 1 Ma; Bazhanov & Kostenko, 1961; Bodina, 1961). The prevalence of fine-grained sediments indicates rather stable subsidence without tectonically enhanced deepening of the Ili Basin.

Time series analysis was performed on the records of CPA, Ti/Al, Mg/Al, Red/Blue and MS. Spatial resolution of the CPA and Ti/Al time series (25 ± 6 cm, 1σ) is not sufficient for a robust detection of precession periods. Spatial resolutions of MS and the Red/Blue ratio are higher (6 ± 2 cm and 9 ± 5 cm, 1σ), however, both time series are measured directly on rock fragments in the field and can be inaccurate because the lack of plain surfaces may cause signal noise and distortion. Redfit spectra were calculated to identify cycle lengths of dominant periodicities and filter outputs of significant cycles were generated to identify cycle-frequency ratios diagnostic for orbital forcing. ASM was calculated for the Mg/Al time series (Meyers, 2014). The method offers a statistical test to reject the null hypothesis (no orbital signal) at a certain significance level. If the null hypothesis can be rejected, the ASM metric estimates the most probably sedimentation rate for a stratigraphic interval by comparing candidate frequencies to the fixed target frequencies from the orbital solution for a given range of sedimentation rates (Meyers & Sageman, 2007). In addition, EHA was performed to test the stability of sedimentation rate.

Redfit spectra of the four studied time series display different dominant cycle lengths (Fig. 9). The Ti/Al ratio has only one dominant cycle 27 to 28 m in length, with more than 99% significance. Similar periodicities are also visible in the logMS (22 to 30 m, >95%) and the Red/Blue (20 to 40 m, >99%) time series. While the Ti/Al ratio shows a clear peak, the broad range of cycle lengths of the logMS and Red/Blue time series refers to the amalgamation of different cycles, which cannot be addressed because of the short length of the time series. The CPA, MS and Red/Blue ratio show dominant peaks between 6-4 to 7-3 m (>90 to 95%) and 5-0 to 5-4 m (>95%). Their common occurrence in different time series with different spatial resolution argues for a common forcing. Further significant peaks (>95%) occur at variable cycle lengths between 1-5 m and 2-5 m, with the four time series lacking consistency.

Results from the ASM calculation of the Mg/Al time series show that for a sedimentation rate of 5-1 cm kyr$^{-1}$ the null hypothesis can be rejected with a H$_0$ significance level of 0-18% (Fig. 10A and B). This sedimentation rate would assign the 5-0 to 5-4 m cycle to the periodicity of short eccentricity. Furthermore, the EHA normalized amplitude spectrum shows spectral power for the frequencies of long and short eccentricity and obliquity (Fig. 10C). A shift towards higher sedimentation rates higher occurs above 27 m and explains the increased cycle length of 6-4 to 7-3 m for the short eccentricity signal (Fig. 10C). Short eccentricity is weakly developed between 35 m and 55 m where the dominance of a ca 3 m cycle suggests a stronger control by obliquity. Gaussian band-pass filter outputs were generated for the 6-4 m cycle in the CPA, the 27 m, 22 m and 7-3 m cycle in the MS, the 27 m cycle in the Ti/Al, and the 30 m, 20 m, 7 m and 5-1 m cycle in the Red/Blue ratio (Fig. 9). The long 22 to 30 m cycle displays minima in the horizons of elevated weathering intensity. Here, the 6-4 to 7-3 m cycle has its highest amplitudes (grey bars in Fig. 9) while it weakens in the intervals between. The 6-4 to 7-3 m filters of MS and CPA display anti-phase correlated cycles. The filter output of the 5-1 m cycle in the Red/Blue ratio shows the 5-0 to 5-4 m cycle closely related to the 6-4 to 7-3 m cycle representing similar sedimentary cycles in horizons of lower sedimentation rate.

The arrangement of spectral peaks (frequency ratios), such as the 1 : 4 relationship between long (405 ka) and short (ca 100 ka) eccentricity is robustly expressed by the 20 to 22 m and 5-0 to 5-4 m cycles in the lower part of
Fig. 9. Gaussian filter outputs (A) and Redfit spectra (B) for dominant frequencies of CPA, logMS, Ti/Al and the Red/Blue colour ratio. Filter frequencies for the time series are $0.037 \pm 0.015$ cycles m$^{-1}$ for logMS, Ti/Al and Red/Blue, $0.155 \pm 0.047$ cycles m$^{-1}$ for CPA, $0.137 \pm 0.041$ cycles m$^{-1}$ for logMS and $0.191 \pm 0.057$ cycles m$^{-1}$ for Red/Blue. The 6.4 to 7.3 m and 5.0 to 5.4 m cycles, probably related to the 100 ka short eccentricity cycle, are prominently developed in the CPA, MS and Red/Blue time series. The 27 to 30 m cyclicity is significantly developed in the logMS, Ti/Al and Red/Blue data and is interpreted as representing the 405 ka long eccentricity cycle. Further subsidiary cycles occur between 1.5 m and 2.5 m in the CPA, logMS and Red/Blue data.

DISCUSSION

Weathering and authigenic clay mineral formation

Chemical weathering under arid and semi-arid conditions responds sensitively to changes in the hydrologic system of the basin, either through tectonically driven changes in the discharge system, or by climatically driven changes in the hydrological balance. A plot of the Bastau Formation sediment chemistry in the A-CN-K diagram (Fig. 11;
Nesbitt & Young, 1984, 1989) shows the sediments to derive from source rocks with a composition typical for the upper continental crust in accordance with their origin from volcanic arc complexes (Jahn et al., 2000). Mean CIA-Ca values of 71 indicate that Bastau Formation sediments underwent sustained chemical weathering. Plagioclase weathering is the main mineral reaction causing the preferential removal of Ca and Na. Furthermore, the sediment chemistry data display in agreement with results of XRD analyses a trend towards elevated K concentrations, typical for the formation of illite. Illite can be directly formed from weathering of K-feldspar and muscovite or by post-depositional processes as diagenetic illitization. Illite can also be formed by low-temperature illitization of smectite (Baldermann et al., 2015; Cuadros et al., 2016) when K is fixed during repeated wetting and drying processes in the soil (Singer & Stoffers, 1980). In the Bastau Formation, the relative abundance of illite is negatively correlated with those of quartz and feldspar indicating a predominant detrital origin of illite, additionally supported by stratigraphic equivalent XRD data from a proximal site 40 km distant (Fig. 5C; Hellwig et al., 2017). Illite formation by post-depositional alteration, as observed for Oligocene sediments in south-western Mongolia (Richoz et al., 2017), is not considered a relevant process here. Illite percentages of mudflat sediments in the Bastau Formation are about 10% higher than those of the underlying Alakul Formation which underwent higher burial temperatures, but show a similar proximal-distal relationship in the abundance of unweathered quartz and feldspar to illite typical for detrital transport (Fig. 5C).

Sedimentary facies and geochemical indices in the Bastau Formation refer to five horizons of elevated weathering intensity (Figs 5 and 6). The horizons are characterized by hydromorphic features of soil formation (mottling), phreatic carbonate precipitation close to the

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**Fig. 10.** (A) ASM of the Mg/Al time series calculated for sedimentation rates between 1 and 30 cm ky⁻¹ with 400 sedimentation rates investigated, resulting in a critical significance level H₀ for null hypothesis rejection of 0.25%. (B) Significant spectral peaks from Mg/Al redfit >90% CL (=candidate frequencies, black) and their match with seven orbital target frequencies (0.00247, 0.00786, 0.01035, 0.01913, 0.02475, 0.04366, 0.05305, red). The null hypothesis of no orbital forcing can be rejected for a mean sedimentation rate of 5.1 cm ky⁻¹. (C) EHA amplitude spectrum of the Mg/Al time series at the 80% significance level.

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groundwater table or by palustrine sedimentation, typical features in distal parts of endorheic basins. The higher abundance of clay minerals together with elevated CIA, CPA and Mg/Al, and low Ti/Al values suggest that these beds formed in times of low detrital sediment supply and landscape stability.

Intensified weathering can be explained either by (1) elevated water/moisture supply to the vadose zone by precipitation and/or surface and subsurface discharge; (2) longer periods of landscape stability with lower rates of sediment discharge from the hinterland; and (3) elevated rates of evaporation and capillary groundwater rise. An important feature of Bastau Formation sediments in addressing these processes is the covariance of CPA/CIA and Mg/Al which refers to more intense weathering under highly evaporative conditions (Fig. 7).

Magnesium fixation in silicates requires Mg enrichment in the aqueous environment by either by Ca removal by the early formation of carbonates and sulphates or by evaporative capillary groundwater rise (Calvo et al., 1999; Deocampo, 2015). Primary controls for the authigenic formation of Mg-rich clays (e.g. smectite, palygorskite) are high magnesia and silica activities and elevated pH (Deocampo, 2004; Deocampo et al., 2009). Studies in modern arid environments have shown that a strong enrichment of elements in pore waters takes place in areas sheltered from detrital input and subjected to strong evaporation as in marginal lacustrine settings, in interdune clay pans and ponds where groundwater is discharging (Calvo et al., 1999). The K, Mg and Si are extracted from supersaturated solutions to form interstratified illite and trioctahedral Mg-rich smectite (Jones & Weir, 1983; Banfield et al., 1991). The presence of palygorskite in calcic soils results from incongruent dissolution precipitation (Jones & Galan, 1988), direct precipitation from oversaturated solutions or from transformation of inherited clay precursors (Cuadros et al., 2016). Badau & Risacher (1983) observed authigenic Mg-smectite formation under conditions of silica saturation where the pH was above 8.2 in lakes in Bolivia. High salinity/alkalinity, dissolved silica enrichment and high pH values (>9.5 to 10) also favour Mg enrichment and trioctahedral clay formation in palaeolake Olduvai, Tanzania (Deocampo, 2004). Fibrous clays such palygorskite and chlorite degrade to smectite when the climate is more humid and annual rainfall exceeds 300 mm (Calvo et al., 1999).

The source of K, Mg and Si needed for clay mineral formation in Bastau Formation sediments is derived from feldspar weathering of the volcanic source rocks in the catchment area. The presence of fibrous palygorskite and abundant chlorite argue for their authigenic formation under more arid conditions. This process is most intense in the intervals of elevated Mg/Al ratios. Accordingly, it is possible to state that the highest degrees of weathering were achieved when the regional climate was at its driest and elevated rates of potential evapotranspiration supported capillary groundwater rise. On the other hand, hydromorphic soil features and phreatic carbonate precipitation argue for a higher groundwater table in the weathered horizons and thus for higher water supply to the vadose zone. The most probably explanation for this water supply is an elevated subsurface discharge from montane areas in the surroundings of the Ili Basin. In an analogue to modern observations, the highest weathering intensities probably occurred when mean annual precipitation values were at or below 300 mm, soil water pH reached values above 8.5 and the phreatic zone was at or close to the surface. Regarding the interpretation of weathering indices as proxies in paleoclimatology, we can state, if covariance with CPA and/or CIA is achieved, the Mg/Al ratio serves as an aridity index.

**Regional hydrology**

The primary water source for arid to semi-arid basins is precipitation, and in a long-term steady-state system, precipitation is balanced by the water loss to evapotranspiration, underlying aquifer recharge, surface runoff and vadose infiltration of soil moisture (Maliva & Missimer, 2012). In the distal depositional setting of the Ili Basin,
water supply is provided either by rainfall or by surface and subsurface discharge from the head of the alluvial systems of the Tian Shan mountain system (Hellwig et al., 2017). Orogenic uplift reinforced in the late Oligocene to early Miocene at rather low and continuous rates (4 to 5 cm ka\(^{-1}\)) and created a hilly landscape (Burtman, 2012). Sedimentological and geochemical data of this study provide evidence for variable water availability with wetter and more arid phases within the alluvial plain of the Ili Basin.

Deposition of medium-grained to coarse-grained sandstones indicates episodes of rapid unchannelled surface drainage with transport of coarser detritus from local source areas. Episodes of distal sheet flood deposition are characterized by low CIA, CPA and Mg/Al ratios, larger grain sizes and poorly sorted fine-sized to medium-sized sandstones. These beds have the lowest Ti/Al ratios, characteristic of unweathered source rock. Sheet flood deposits are overlain by mudstones with hydromorphic features of soil formation (mottling) and phreatic carbonate precipitation close to the groundwater table. Mottling results from reduction of ferrous iron to ferric during periods of waterlogging and is indicative of pronounced seasonal wetting (Huggett & Cuadros, 2005; Gale et al., 2006). In addition, high CIA, CPA and Mg/Al ratios and the occurrence of palygorskite indicate arid soil formation by capillary groundwater rise as well as starvation of detrital sediment supply. Elevated groundwater inflow was probably maintained through the underlying relatively permeable sandstones, an effective mechanism described for semi-arid alluvial systems in Miocene basins of Spain (Sanz et al., 1995). Furthermore, incongruent dissolution of detrital Ti-oxides by reducing ground waters and alteration to anatase, as observed for the Jurassic Morrison Formation in Colorado (Adams et al., 1974; Sanford, 1994), is a probably process which led to the observed lowering of Ti/Al ratios. The several metres thick structureless mudstones, instead, are well drained and represent higher rates of vertical mudflat accretion when ongoing detrital sediment production at moderate weathering rates occurred. The well-drained mudflat deposits show the highest Ti/Al ratios. It has been shown by several studies that Ti can be enriched in the fine fraction of detrital sediments (Taboada et al., 2006; Yan et al., 2006; Minyuk et al., 2014). Detrital Ti enrichment occurred by fluvi-aeolian processes when heavy Ti-bearing minerals were concentrated by episodic flooding events and aeolian blowout of ancient surfaces (Figs 5 and 6). Furthermore, successive Ti enrichment in mudflats occurs by in situ weathering and oxidation and the formation of sedimentary anatase (Bestland, 1997).

The Ti/Al ratio is considered as a proxy for sedimentary discharge here. The average TiO\(_2\) concentration (0.7 ± 0.1%) in the Bastau Formation is typical for sediments sourced by weathering of igneous and metamorphic parent materials (Salminen et al., 2005). The rather small variability in Ti/Al does not indicate significant provenance changes in the catchment. Climate exerts a major control on sediment supply and fan activity. Ahlborn et al. (2015) found a strong relationship between precipitation and sediment supply in a small catchment area on the southern-central Tibetan Plateau. Modelling results have shown that climate variability, in particular precipitation, produce extremely fast responses throughout the catchment–fan system and overprint lower frequency tectonic variations (Allen & Densmore, 2000). Higher rates of alluvial fan activity are directly linked to higher hinterland precipitation and water availability. A similar pattern emerges for sediment accumulation in the Ili Basin. Horizons with elevated Ti/Al correspond to periods of higher detrital sediment supply and thus to overall wetter conditions. Lowered Ti/Al ratios represent intervals of reduced detrital influx and intensified soil formation under more arid conditions (Horizons I to IV and GB).

Accordingly, sheet flood deposition with subsequent pedogenic mottling and deposition of unstructured mudflats represent two climate end-members in the water balance of the local hydrologic system. Flash floods, formed when the water supply exceeds the soil infiltration capacity, allow for the formation of short-term ponds and ground water recharge (Amiaz et al., 2011). At a later stage, evaporative capillary ground water rise led to pore water enrichment and intensified authigenic clay mineral formation under arid conditions. Such a scenario is supported by strong seasonal gradients in both discharge and evaporation. Instead, periods of rather steady detrital supply during mudflat accretion represents a balance of continuous sediment production and in situ weathering without the formation of hydromorphic soil features during periods of less extreme climate. Such a scenario is supported by less pronounced seasonality of discharge and evaporation.

**Vegetation**

The palynological assemblages from samples KAZ-10 and KAZ-11 yield a consistent picture of the vegetation and environment characterizing the study site at the time of sediment deposition. Based on the ecological preferences of their nearest living parent plants, the identified pollen and spores can be attributed to different vegetation units.

The occurrences of *Sparganium eurycarpum* (nearest living relative: *Sparganium* – common name: bur-reed) and *Cyperaceae* (Cyperaceae – sedges) along with dinoflagellate cysts of presumably freshwater origin
indicate the existence of perennial marshland and at least temporary open-water bodies. This aquatic/marshland setting was surrounded by riparian forests as documented by the occurrences of substantial amounts of Alnus pollen (Alnus – alder) and Ulmipollenites (Ulmus – elm), and the co-occurrences of Carpinuspollenites (Carpinus – hornbeam), Fraxinopollenites (Fraxinus – ash), Pterocaryapollenites (Pterocarya – wingnut) and notably Taxodiaceapollenites (Taxodium – swamp cypress). Ferns and Poaceae (grasses), represented by fern spores and Graminidites, respectively, thrived as part of the forest understory.

Further away from the marshland and under drier conditions, a steppe vegetation prevailed that was characterized by Poaceae along with Asteraceae (represented by Compositopollenites) and xerophytic herbs such as chenopods (goosefoot – represented by Chenopodipollis), and different taxa of Ephedra (joint-pine – represented by Ephedrrites spp.).

Finally, the slopes of higher altitude settings in the surroundings supported – possibly patchy – montane, conifer-dominated forests represented by Pinuspollenites (Pinus – pine), Piceapollenites (Picea – spruce) and Abiespollenites (Abies – fir); they may have benefited from enhanced soil moisture and air humidity in comparison to that available to the lower elevation steppe vegetation.

The palynological results derived from samples KAZ-10 and KAZ-11 are in excellent agreement with other palaeobotanical evidence from the upper Middle to lowermost Upper Miocene of Central Asia, such as from eastern Kazakhstan (Akhmetyev et al., 2005) and the Qaidam Basin of the north-eastern Tibetan Plateau (Miao et al., 2011).

**Orbital control on mudflat deposition**

The period of the Bastau Formation sediment deposition falls into the juvenile stage of Tian Shan’s orogeny of weak crustal deformation and low uplift rates (Burman, 2012). Corresponding sedimentation rates were in the range of 6 to 13 cm ka⁻¹ in the inner and outer basins of the Tian Shan (Huang et al., 2006; Heermance et al., 2007; Charreau et al., 2008). Estimates of average sedimentation rates in the Aktau succession (5-0 to 8-5 cm kyr⁻¹) based on biostratigraphic data presented here fall into this range. The spectral analysis results show two dominant cycle lengths (5-0 to 5-4 m and 20 to 22 m, 6-4 to 7-3 m and 27 to 30 m) at different levels in the Bastau Formation, which we interpret as the signals of short and long eccentricity based on its cycle-to-frequency ratio. The very significant 27 to 28 m cycle in the Ti/Al time series argues for the presence of roughly three 405 kyr cycles (Fig. 9) with an overall duration of deposition of the Bastau Formation of 1-0 to 1-2 Myr. However, lower sedimentation rates in the lower Bastau together with the filter outputs of the 5-0 to 5-4 m and 20 to 22 m cycles show the presence of four 405 kyr cycles, which would extend the duration to 1-4 to 1-6 Myr.

Filter outputs of the two dominant frequencies appear noisy with the highest amplitudes of the 6-4 to 7-3 m cycle at horizons, where the 27 to 30 m cycle displays minima and a very weak signal in the intervals between (Fig. 9). Changes in the sedimentation rate, for example, by elevated/lowered clastic supply or by the longer presence of stable landscapes, can lead to signal distortion (Abels et al., 2009, 2014; Hilgen et al., 2014). Complex interactions between climate and depositional processes as described above involve non-linear feedbacks, which affect the significance of spectral peaks. Together with the low resolution of biostratigraphic age control, cyclostratigraphy is therefore not developed for the Bastau succession, instead the discussion is centred on cycle pattern and amplitudes, which might have been forced by orbitally controlled climate change.

Of interest here is the anti-phase correlation of MS and CPA. Maxima in MS correspond to higher supply rates of unweathered detrital components. Following the notion that higher rates of alluvial activity correspond to higher rates of precipitation and vice versa, maximum amplitudes of the 6-4 to 7-3 m cycle should represent the intervals of highest climate variability by recording the most pronounced extremes between evaporation and precipitation in the hydrological balance. The long 27 to 30 m cycle is best expressed in the Ti/Al ratio. The filter output shows minima in the horizons of most elevated climate extremes between pronounced water supply and aridity (Horizons I-IV, GB) and maxima in the interval where the 6-4 to 7-3 m cycle is hard to detect in CPA and MS (Fig. 9). Long-term variability of the Ti/Al paced by the 405 ka cycle describes variations between two climate stages. Minima in Ti/Al correspond to high amplitude climate shifts expressed by abundant discharge of sheet floods during times of elevated precipitation alternating with periods of low detrital supply and alkaline weathering in times of high evaporation. Maxima in Ti/Al reflect periods of more stable sediment production and moderate weathering intensity in times of less extreme climate change. Insolation-driven climate changes strongly affect seasonality, and the observed pattern argues for changes in the seasonal contrast as driving force.

The biostratigraphic age control for the Bastau succession does not allow for direct comparison of the observed orbitally driven climate pattern with the orbital solution (Laskar et al., 2004). However, based on the observations presented here it is possible to speculate that maxima in
the Ti/Al filter output could correspond to long eccentricity minima and the Ti/Al minima to long eccentricity maxima. Individual horizons of maximum aridity represent individual short eccentricity or obliquity cycles. Long eccentricity minima represent periods of higher precipitation and fan activity, corresponding to overall wetter conditions as a result of lower seasonality of precipitation in both the catchment area and the site of deposition. Long eccentricity maxima, instead, refer to lower rates of fine-grained sediment supply and drier periods. At the same time, there is a higher probability for the deposition of coarse-grained sheet flows. This is best expressed around the GB horizon. Stronger seasonal gradients promote seasonally intensified precipitation in the catchment area which discharged into the basin by surface and subsurface flow. Higher MS values and a lower CPA (56 to 58 m) refer to the accumulation of coarser and less weathered clastic material. More subsurface discharge resulted in a groundwater table rise until the formation of palustrine conditions. Parallel to increased water supply, seasonally elevated rates of evaporation led to drying, capillary groundwater rise and gypsum formation. Evidence from palynology describe the low-lying landscape as dry steppe with patchy conifer-dominated forests at higher elevations. Such an open landscape without closed vegetation cover does not provide favourable conditions for the formation of thick soil horizons in the catchment area which could stabilize the erosion of freshly weathered material.

The observation provides support for the hypothesis of Zachos et al. (2010) who suggested that the long eccentricity variations in the global carbon cycle are controlled by seasonality of precipitation on land. More year-round precipitation favours the areal spread of humid conditions and wetlands during times of long eccentricity minima, which in turn led to increased terrestrial carbon sequestration. More seasonal precipitation, instead, supports monsoonal and dry climates and increased steppe and dry grasslands. Abels et al. (2014) observed a well-developed cyclicity in fluvial sediments of the lower Eocene Willwood Formation of the Bighorn Basin in North America and showed precessional control for overbank avulsion. Furthermore, at the 100 kyr and 405 kyr scales, the bundling of well-developed simple pedofacies cycles can be linked to eccentricity maxima and, thus, to intervals of mature palaeosol development. The 405 kyr cyclicity may have originated from subsequent relatively wet conditions related to high amplitude precession cycles during eccentricity maxima. Such a pattern is also similar to that observed in the Bastau succession. Although it is not possible to discuss phase relationships in terms of the orbital solution, based on the observed pattern, it is possible to suggest that arid to semi-arid terrestrial mudflat sedimentation in the mid-Miocene Ili Basin in Central Asia was strongly controlled by seasonal changes in moisture availability paced by long eccentricity.

**Mid-Miocene palaeoenvironment**

Proxy records from various basins provide evidence that Central Asia’s climate was warmer and wetter in the mid-Miocene in comparison to the long-term Cenozoic average that displayed pronounced aridity and desertification from the Oligocene to early Miocene (Guo et al., 2002; Sun & Windley, 2015; Zheng et al., 2015). Sedimentary facies in the northern Junggar Basin (Fig. 12) comprise fluvial and lacustrine deposits between 17.5 and 13.5 Ma with the onset of aeolian red clay deposition after 13.5 Ma (Sun et al., 2010). Evidence for the presence of perennial fluvial drainage and lakes comes also from the southern Junggar Basin with the development of modern-like desert vegetation after 13.5 Ma (Tang et al., 2011b). Charreau et al. (2012). South of the Tian Shan, reddish mudstones of the Jidike Formation indicate the prevalence of arid conditions since 13.5 Ma (Sun et al., 2015), and palynological evidence from basins in the north-eastern Tibetan Plateau, such as Qaidam and Tianshui, argue for a warmer, moister period between 14 and 15 Ma with substantial cooling and drying afterwards (Hui et al., 2011; Miao et al., 2011). These findings are consistent with the assumption that on longer timescales mid-Miocene warming and late Miocene cooling correspond to the global climate evolution (Zachos et al., 2008; De Vleeschouwer et al., 2017).

Results from climate modelling with Miocene boundary conditions and lower than present topography suggest significant warming in Inner Asia compared to today (Henrot et al., 2010; Tang et al., 2011a). Climate warming is most pronounced in the winter with more zonal climate and increased moisture supply by westerly winds. Strong low-level westerlies were generated as a result of a strong N-S pressure gradient between atmospheric high pressure above the Tibetan Plateau and a low-pressure cell above the northern lowlands (Tang et al., 2011a; Fig. 12). Westerly wind-driven moisture supply is documented for many sites in Inner Asia based on the oxygen isotopic composition of pedogenic carbonates (Caves et al., 2015). In addition, the lack of oxygen isotopic fractionation along the trajectories argues for a high degree of regional moisture recycling by evapotranspiration (Caves et al., 2015).

The palynological results from the Bastau Formation presented here describe an open landscape covered by steppe vegetation with small riparian forests around smaller ponds typical of semi-arid climates. The geochemical data show a strong sedimentary response to regional surface and subsurface water availability relative to orbital
extremes. Insolation changes affect the length of the seasons and, thus, the intensity of winter precipitation. Most of the precipitation is probably trapped by the low-relief mountain ranges of the Tian Shan, which served as a regional source for runoff, aquifer recharge and detrital sediment supply. The intensity of westerly winter winds are assumed to have responded sensitively to orbital forcing, hence controlling the amount of moisture available for regional recycling in both the catchment area and the aquifers. In times of pronounced regional evapotranspiration, a stronger summer–winter gradient of westerly wind intensity probably reduced the amount of precipitation within the basin and additionally increased the probability for heavy rain storms and flash flood deposition due to more intense precipitation events in the catchment area.

In times of wetter conditions, a lower summer–winter gradient of westerly intensity increased the amounts of year-round surface runoff and activated mudflat aggradation.

The overall successions of both sedimentary facies and geochemical data of the Bastau Formation represent enhancement of aridity on longer time scales. The establishment of alkaline palustrine conditions marks a transition in the Miocene evolution of the Ili Basin when hypersaline conditions prevailed in the basin with limited runoff. Incoming water from floods evaporated and as the brine concentrates gypsum precipitated either directly from solution or by forming pedogenic crystallites and crusts on top of the playa floor. The appearance of gypsum occurred rather abruptly and could be explained either by the formation of endorheic conditions or by climate change. Since endorheic conditions were already prevalent from the onset of mudflat deposition in the Bastau Formation, the first accumulation of gypsum is related to a severe change in the regional climate system from wetter semi-arid conditions to more pronounced aridity. A dry climate persisted from this time onwards.

The sudden appearance of gypsum in the Miocene Ili Basin is difficult to explain and the source of the sulphur is questionable since gypsum is completely absent in the succession below the palustrine GB horizon. There are no local sulphur sources in the catchment area since it consists entirely of rhyolitic and andesitic volcanic rocks (Jahn et al., 2000, 2004). It is possible that the sulphur originated from a marine source. Deposition of Bastau Formation sediments lasted for about 1·0 to 1·2 Myr with the biostratigraphic data indicating a middle Miocene, possibly Langhian age (Fig. 3). At this time, extensive evaporites were deposited at the margins of the Eastern Paratethys (Rögl, 1999; Popov et al., 2004; Bruch et al., 2007). Although, this area is located more than 500 km
CONCLUSIONS

Middle Miocene mudflat and marginal playa lake sediments were deposited at the margin of low-gradient alluvial systems in the endorheic Ili Basin, south-east Kazakhstan within the Tian Shan mountain system. The 91 m thick Bastau Formation exposed in the Aktau Mountains was studied for its bulk-sediment geochemistry, MS and sediment colour to characterize its composition and to determine changes in weathering, pedogenesis and alluvial fan activity. A positive correlation between weathering indices (CIA, CPA) and the Mg/Al ratio documents evaporative enrichment and authigenic Mg fixation by clay mineral formation in the vadose zone in highly alkaline/saline settings. Four major periods of arid soil formation and one palustrine interval represent the highest degrees of weathering in periods when pedogenesis exceeded sedimentary discharge. Periods of higher moisture availability and higher rates of hinterland precipitation are indicated by successive mudflat accretion by higher alluvial fan activity recorded by elevated Ti/Al ratios and MS.

Time series analysis of chemical weathering indices, MS and sediment colour data show cycle-to-frequency ratios typical of Milankovitch cyclicity, with dominant periodicities interpreted as representing short and long eccentricity cycles. In particular, the Ti/Al ratio demonstrates a pacing of pedogenic mottling and detrital mudflat accretion by long eccentricity, thus suggesting an orbital control on regional moisture availability and mudflat deposition. It is assumed that more frequent bundling of sheet flood deposition and subsequent pedogenic alteration correspond to long eccentricity maxima, and longer lasting periods of elevated fan activity to long eccentricity minima. However, a better-constrained age model is necessary to relate these changes to the orbital solution.

The overall sedimentary succession shows a long-lasting increase in aridity in the studied area. Of particular interest is the abrupt onset of gypsum formation at the time the GB horizon was deposited. The sudden appearance of gypsum beds indicates a climate and possibly orbital trigger analogous to the initiation of the Messinian salinity crisis in the Mediterranean. Such a trigger could have been the transition to the mid-Miocene cooling. On longer timescales, the closure of the eastern gateway of the Mediterranean to the Indian Ocean enhanced restriction within Eastern Tethys, providing the necessary boundary conditions.

In light of the results above, the quasi-continuous, terrestrial Miocene succession of the Aktau Hills emerges as a sensitive recorder of changes in atmospheric moisture supply. This makes it a highly promising terrestrial archive for palaeoclimate research, ideally located in order to address the role of Central Asia in the global climate evolution during the Miocene.

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# Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Data S1. Magnetic susceptibility, geochemistry and colour data of Bastau Formation sediments.