Miocene to Early Pleistocene Depositional History and Tectonic Evolution of the Issyk-Kul Basin, Central Tian Shan

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Abstract The Issyk-Kul Basin (Kyrgyzstan), situated in the central Tian Shan Mountains, hosts the largest and deepest mountain lake in Central Asia. Erosion of the surrounding Terskey and Kungey ranges led to the accumulation of up to 4 km of sediment in the adjacent depression. Creation of the basin from regional shortening and uplift likely initiated around the Oligocene-Miocene, yet precise age control is sparse. To better understand the timing of these processes, we obtained magnetostratigraphic age constraints on fossil-poor, fluvio-lacustrine sediments exposed south of Lake Issyk-Kul, that agree well with previous age constraints of the equivalent strata outside the Issyk-Kul Basin. Two 500–650 m thick sections comprised mainly of Chu Group sediments were dated at 6.3–2.8 Ma and 7.0–2.4 Ma (late Miocene to early Pleistocene). Together with reinterpreted magnetostratigraphic constraints from underlying strata, we find that syn-tectonic deposition commenced at ~22 Ma with average sedimentation rates <10 cm/ka. Sedimentation rates increased to 10–30 cm/ka at 7 Ma, concurrent with accelerated uplift in the Terskey Range to the south. A deformation event in one section (Kaji-Say) between 5 and 3 Ma together with concurrent shifts of depositional centers throughout the basin signal the onset of substantial uplift of the Kungey Range to the north at ~5 Ma. This uplift and deformation transformed the Issyk-Kul area into a closed basin that facilitated the formation of a deep lake. Lacustrine facies deposited around 3 Ma mark the existence of Lake Issyk-Kul by that time.

Plain Language Summary In this study, we investigated how and when the sedimentary basin that contains the deepest mountain lake in central Asia (Lake Issyk-Kul) formed. The sediments originated from the surrounding Tian Shan Mountains that were exhumed by tectonic forces related to the collision between the Indian and Eurasian plates. Sediments accumulated in the Issyk-Kul Basin as the nearby mountains eroded. By determining detailed records of sedimentation ages and deposition rates, we found that the oldest sediments stemming from mountain building are 22 Myr old, suggesting that uplift initiated then. Around 7 Ma, sedimentation rates increased 2–3 times, thereby signifying a time of accelerated uplift and erosion. After 5 Ma, sedimentary layers south of the lake were strongly deformed, while sedimentation patterns shifted throughout the basin, likely caused by the uplift of mountains farther north. This transformed the Issyk-Kul area into a closed basin, thereby facilitating the formation of a deep lake. Carbonate-rich facies became widespread around 3 Ma, further confirming the existence of Lake Issyk-Kul.

1. Introduction
1.1. Regional Geology

The Tian Shan Mountains comprise a 2,500 km long orogenic belt in central Asia. Ongoing uplift of the range is driven by the India-Asia collision. Although located 1,500 km north of the India-Asia plate boundary, the Tian Shan currently accommodate about 20 mm/yr of north-south shortening, which is equivalent to nearly two-thirds of the total convergence between India and Asia (Zubovich et al., 2010). Mountain building in central Asia initiated along reactivated Paleozoic structures in the late Oligocene, creating vast basins that were subsequently dissected by younger ranges (Buslov et al., 2003; Macaulay et al., 2014; Sobel & Dumitru, 1997).
The Issyk-Kul Basin is one of the largest intermountain basins in the Tian Shan realm, bounded by the Kun-gey Range to the north and the Terskey Range to the south (Figure 1) with maximum peak heights of 4.8 and 5.2 km, respectively. The basin contains up to 4 km of Cenozoic sediments (Buslov et al., 2003; Turchinskii, 1970) that record the uplift and erosion history of the surrounding mountain ranges. Unroofing of the Terskey range commenced around the Oligocene-Miocene boundary between 26 and 20 Ma based on thermochronologic cooling ages (De Grave et al., 2013; Macaulay et al., 2013, 2014) and on the onset of sediment deposition in the adjacent Issyk-Kul Basin (Wack et al., 2014). The initial uplift phase was followed by a second phase of rapid basement cooling after 10 ± 5 Ma when deformation of the Terskey range propagated northward, creating the Issyk-Kul Broken Foreland (Macaulay et al., 2013, 2014). Uplift of the youngest ranges initiated in the Plio-Pleistocene. Unroofing of the Kungey Range that led to the closure of the Issyk-Kul Basin is loosely estimated to ca. 7–4 Ma based on sediment provenance data (Selander et al., 2012).

To better resolve the uplift history of the central Tian Shan around the Issyk-Kul Basin, we collected Cenozoic sediments at two sections, Ak-Terek and Kaji-Say (Figure 1), in the southern rim of the basin in 2016 and 2017 to constrain the age, sedimentation rate and the depositional environment. Here, we describe the geologic setting, the rock magnetism and magnetostratigraphy of the sections. We then discuss the new and existing magnetostratigraphic age constraints from the Issyk-Kul Basin, and place our results in the larger context of the tectonic evolution of the area.

1.2. Local Geology and Stratigraphy

Cenozoic sediments in the central Tian Shan can be divided into four main lithologic groups. These are, from oldest to youngest, the Kokturpak, Shamsi, Chu, and Sharpylak groups (Abdrakhmatov et al., 2001). All four groups are exposed in the southern Issyk-Kul Basin, where we mapped their extent with satellite images (Bing Maps and Sentinel 2, Bands 12-4-2) using QGIS software (Figure 1). Outside our study area, we also referred to Soviet geological maps (Pomazkov, 1971; Turchinskii, 1970) and the PhD thesis of Burgette (2008).

The Kokturpak Group represents pre-orogenic sediments. It comprises deeply weathered paleosols, thin lacustrine deposits and reddish sandstones that formed in shallow, low-relief areas above the Paleozoic basement or above locally preserved Jurassic deposits (Fortuna et al., 1994). In the Issyk-Kul Basin, the Kokturpak Group reaches up to 100 m in thickness (Selander et al., 2012). The age is loosely constrained as late Cretaceous to Eocene (Fortuna et al., 1994; Sobel & Arnaud, 2000). Kokturpak and Jurassic sediments were combined in our geologic maps (Figure 1, J-Pg); these are identified as white and yellow layers that cover basement rocks and/or by resistant red horizons that crop out in the cores of anticlines (Figures 1d and 1e).

The Shamsi Group represents the basal, syn-orogenic sediments (locally called the Kyrgyz or Dzhety Oguz Formation) overlying the Kokturpak Group. In the Issyk-Kul Basin, these deposits consist of poorly sorted sandstone and conglomerate with a characteristic red pigment near the base that fades toward the top. In the vicinity of the Terskey Range (CK and JO in Figure 1a), the ~1 km thick sections were magnetostratigraphically dated between 26 and 11 Ma (Wack et al., 2014). We mapped the Shamsi unit in Figure 1 based on its distinctive red color and strong reflectance in the Sentinel bands 12 and 4. In the eastern part of the basin, the Shamsi Group can be subdivided into a lower (N1-S1, red) and upper (N1-S2, light red) unit based on a characteristic decrease in red pigment (Figure 1e). The similar appearance of lower Shamsi and upper Kokturpak groups made it sometimes ambiguous to distinguish them on the aerial images.

The Shamsi Group grades upward into lighter, more fine-grained strata of the Chu group, which consists of white to tan sandstone and siltstone, intercalated with conglomerate. The Chu Group is often described as the main basin-filling unit, with thicknesses up to 2.5 km reported in the Naryn Basin (Goode et al., 2011), 1.5 km in the Chu Basin (Bullen et al., 2001) and 3 km in the At-Bashi Basin (Abdrakhmatov et al., 2001). In the latter two, the Chu Group was magnetostratigraphically dated between 7.5 and 3.0 Ma (Abdrakhmatov et al., 2001; Bullen et al., 2001). Selander et al. (2012) reported a maximum thickness of 600 m in the northern Issyk-Kul Basin. This unit was mapped based on its tan color at the base that fades toward the top and possesses alternating lighter and darker horizons. Where possible, we differentiated between lower Chu (dominantly darker tones; mapped as N1C1) and upper Chu (highly reflective, grayish beds; mapped as N1C2; Figures 1b–1d).
Figure 1. Geologic overview of the study area at Lake Issyk-Kul (Central Tian Shan, Kyrgyzstan). (a) General location map. Names and abbreviations in white boxes denote locations of new and previously studied stratigraphic sections as follows: (c) Chu, (AB) At-Bashi, (K1) Toru-Aygir, (K2) Cholpon-Ata, (AT) Ak-Terek, (KS) Kaji-Say, (CK) Chon Kyzylsuu and (JO) Jeti-Oguz. (b) Geology of the southern Issyk-Kul Basin with mapped sedimentary units (see legend and text for details), major faults (thick lines) and folds (thin lines, anticlines dashed, synclines dotted). Geologic and structural information were mapped from satellite images, a digital elevation model, Burgette (2008), Macaulay et al. (2013; 2014; 2016) and Korzhennkov and Deev (2017). Rectangles show locations of maps (c)–(e); units corresponding to the legend: Q, Quaternary; N, Neogene; 1, lower, 2, upper; Pg, Paleogene; J, Jurassic; Pz, Paleozoic basement. Filled circles in (c) and (d) indicate paleomagnetic sample locations of this study (black = normal polarity and white = reversed polarity). Circles in (e) show sample locations from Wack et al. (2014). Projection (b)–(e): Pulkovo 1942/Gauss-Kruger zone 14. (f) Cross-section through the western (W-W’) and eastern transect (E-E’) at Kaji-Say (2:1 vertical exaggeration); bedding attitudes outside the magnetostratigraphic section from Burgette (2008). Camera symbols show locations where the field photos in Figure 2 were taken.
Poorly sorted, coarse conglomerates of the Sharpyldak Group overlie the Chu group, with the contact being sometimes gradual and sometimes unconformable, indicating that locally, deformation has occurred prior to deposition of the conglomerates. The basal age of the Sharpyldak Group was dated to ca. 5–3 Ma in adjacent basins (Abdrakhmatov et al., 2001; Bullen et al., 2001). We mapped the Sharpyldak deposits (N2-Q1) based on their bright gray appearance without visible bedding structures. The Sharpyldak conglomerates are locally covered by lacustrine deposits and river terraces that formed in response to lake level variations and glaciation events during the Quaternary (Burgette et al., 2017). We did not map these youngest features (Q in Figures 1c–1e) in detail. The distinction between Sharpyldak conglomerates and Quaternary terraces in Figure 1 was primarily based on topography.

The major tectonic structures in Figure 1 were adapted from Burgette (2008), Macaulay et al. (2013, 2014, 2016), and Korzhenkov and Deev (2017) and mapped on a 30″ (arcsec) digital surface model (Tadono et al., 2015) that is shown as topographic shading in all maps. The two major thrust faults are the north-vergent South Issyk-Kul Fault and the Main Terskey Fault. The Issyk-Kul Broken Foreland, north of the Main Terskey Fault, is dominated by secondary south-vergent reverse faults that thrust Cenozoic sediments over basement rocks (Burgette, 2008; Korzhenkov & Deev, 2017; Macaulay et al., 2014), thereby producing E-W striking folds in the southern Issyk-Kul Basin. Anticlines with gently tilted northern and steep southern limbs are typically thrust up along reverse faults (Buslov et al., 2003; Figure 1f).

2. Sections and Sampling

2.1. Ak-Terek Section

The Ak-Terek section was sampled on the west side of the Ak-Terek river valley, spanning 500 m in stratigraphic height (Figures 1c, 2a, and 3a). Figure 3a includes a stratigraphic column of the section that can be subdivided into three lithologic units (AT-1 to AT-3). The lower part (AT1) contains alternating sand and silt layers intercalated with conglomerate. Above ∼230 m, fine massive sandstones become dominant (AT2). Above 324 m, the number of conglomerate layers, sporadic calcareous deposits and paleosols increase (AT3). A 30 cm-thick gypsum layer was found at 430 m. Massive conglomerates above ∼500 m mark the conformable transition from Chu to Sharpyldak deposits. Bedding dips gradually flatten from 21° at the base to 5° at the top, reflecting regional scale folding or growth strata. No major discontinuity, unconformity, or fault was observed in the section.

We collected two oriented paleomagnetic cores per horizon (302 in total), generally selecting fine-grained mud or silt layers. The lower 200 m of the section were sampled along the Ak-Terek river valley in ∼2 m intervals. The coarser grained upper 300 m of the section were sampled every 7 m on average, following tributaries away from the river valley. Samples were obtained using a battery-powered, water or air-cooled drill; poorly lithified strata were sampled with a handheld push corer that we manufactured for this purpose. The corer injects the extracted, oriented sediment directly into plastic cylinders of the same dimension as standard paleomagnetic specimens (2.5 cm diameter, 2.2 cm height). All samples were oriented with a magnetic and, when possible, with a sun compass using a Pomeroy orientation tool. The average anomaly from 58 sun compass readings was 4.0° ± 2.5°, in good agreement with the International Geomagnetic Reference Field (IGRF) declination anomaly of 4.6°, which we used to correct the declination azimuths of all samples.

2.2. Kaji-Say Section

The Kaji-Say section is located 10 km northeast of Kaji-Say village and spans 650 m in stratigraphic height. We sampled the section along two transects, west and east (Figures 1d and 1f). Bedding dips in the eastern transect are ∼25° (N) at the base of the section (0 m) and flatten to horizontal at around 225 m height. After 245 m the beds abruptly dip ∼75° (N), defining an asymmetric anticline with its axis striking E-W (Figure 2b). The beds remain steeply dipping (∼75°) until the top of the eastern transect at 464 m. Farther north along these sites, the steeply dipping beds disappear under Sharpyldak conglomerates. Following 1 km along strike to the west (western transect), the Chu beds dip more gently around 30° (N) (Figure 2d) shallowing to ∼15° (N) toward the top of the section. The beds thicken to the northwest and pinch out to the southeast, which could indicate the presence of growth strata.
We could not follow individual beds between the eastern and western transects. The change in dip from \( \sim 75^\circ \) in the eastern section to \( \sim 30^\circ \) in the western section could signal an unconformable surface thereby suggesting the section was folded prior to the deposition of the upper unit, with a hiatus between the two. The postulated unconformable surface likely strikes E-W, parallel to the strike of the strata, which would explain why we did not identify it on the ground or in aerial images. An alternate interpretation that we cannot rule out is that a syncline observed between the two transects (Figure 2c) connects the steeply dipping (\( \sim 75^\circ \)) units in the east to the shallow-dipping (\( \sim 30^\circ \)) units in the west.

Fluvial deposits of alternating sand, silt, and mudstone layers intercalated with conglomerates characterize the lower, eastern part of the section (Figure 3b, KS-1). At the top of this transect, between 440 and 460 m, we identified two, \(<0.5 \text{ m} \) thin calcareous interbeds. Along the western transect, the sediments consist mostly of fine-grained calcareous silt, and carbonates that alternate with laminated silt or mudstone, and rippled or cross-bedded sandstone (Figure 3b, KS-2). The up to 9 m thick calcareous, partially laminated beds indicate lacustrine deposition. The number and thickness of interbedded coarse conglomerates increases above \( \sim 550 \text{ m} \), marking the transition between Chu and Sharpylak style deposits (Figure 2d); above 600 m the section is dominated by Sharpylak conglomerates.

Paleomagnetic samples were collected in approximately 2 m intervals, taking two oriented cores per horizon (312 in total) and selecting fine grained mud or silt when possible. In contrast to Ak-Terek, most strata
in this section were poorly lithified. We obtained drill cores from 15 horizons, while 297 horizons were sampled with the push corer. Therefore, samples from Kaji-Say were predominantly contained within plastic cylinders. The average anomaly from 156 Sun compass readings was $4.2° \pm 2.3°$, again in good agreement with the IGRF declination anomaly of $4.5°$.

### 3. Paleo and Rock Magnetic Characterization

#### 3.1. Laboratory Methods

Because the majority of the samples were contained in plastic cylinders that prevented thermal treatment, we subjected one sample of each horizon to stepwise alternating field (AF) demagnetization. In case of unstable trajectories, or if polarity intervals were defined by a single specimen, a second sample was AF demagnetized. In addition, samples from all 15 drilled horizons from Kaji-Say and from 23 of the drilled sites from Ak-Terek were thermally demagnetized using 14 heating steps to compare against the AF demagnetization data. AF demagnetization (16 steps up to 90 mT) and magnetic moment measurements were conducted inside a magnetically shielded room ($\sim 500$ nT) using an automated measurement system (SushiBar) based on a 2G Enterprises, three-axis superconducting magnetometer (Wack & Gilder, 2012). Characteristic remanent magnetizations were determined by principal component analysis (Kirschvink, 1980) and mean directions were calculated with Fisher statistics (Fisher, 1953) using the software PaleoMac (Cogné, 2003).

Rock magnetic parameters were measured on at least one sample per horizon to determine magnetic mineralogy and grain size variations throughout both sections. We measured magnetic susceptibility ($\chi$), anhysteretic remanent magnetization (ARM) with a peak alternating field of 90 mT and a 0.1 mT bias field and calculated the ARM/$\chi$ ratio as a proxy for grain size and/or mineralogic changes (King et al., 1982). Subsequently, a 1 T isothermal magnetic remanence (IRM) followed by a back field IRM of $-0.3$ T were measured in order to calculate the S-ratio (Bloemendal et al., 1992), which is a proxy for the relative hematite to magnetite concentration. We further determined the low coercivity component (IRM$_{0.1T}$) and the high coercivity component (HIRM) representative of the magnetite and hematite concentrations, respectively (e.g., Liu et al., 2012).
3.2. Rock Magnetic Analyses

Thermal demagnetization experiments indicated that both sections contain two magnetic phases: one that unblocks between 300°C and 580°C, suggestive of magnetite with variable titanium concentrations and another whose magnetic remanence persists to ~680°C, indicative of hematite (Figures 4a, 4b, S1 and S2). At Ak-Terek, the magnetic mineralogy changes midsection, as indicated by an increase in the S-ratio from an average of 0.65 below 200 m (AT1) to 0.82 above 300 m (AT3) (Figure 3a), signifying a decrease in relative hematite contribution with increasing stratigraphic height. HIRM and IRM0.3T show that this trend is linked to a decrease in hematite concentration above 200 m and an increase in magnetite above 350 m.

At the Kaji-Say section, IRM0.3T and HIRM indicate that hematite and magnetite concentrations are significantly lower above the hypothetical unconformity at 464 m (KS-2) compared to below (KS-1) (Figure 3b). In unit KS-2, the magnetic properties correlate with lithology, where calcareous lacustrine horizons have an order of magnitude lower IRM0.3T and HIRM than coarser grained, fluvial deposits. Substantially lower...
magnetite and hematite concentrations in the lacustrine sediments likely reflect the dilution of detrital particles by diamagnetic carbonate. Sharpyldak conglomerates are characterized by elevated HIRM and low S-ratios, reflecting higher proportions of hematite. A slightly reddish color of the Sharpyldak Group at Kaji-Say (Figure 2c) further suggests the presence of hematite pigment in these layers.

### 3.3. Paleomagnetic Analyses

AF demagnetization removed 70%–80% of the natural remanent magnetization (NRM) on average, suggesting that at least 20%–30% of the NRM is carried by hematite. Most samples had a single magnetization component that decayed toward the origin or close to it, and demagnetization trajectories from thermal and AF treatment of samples from the same horizon yielded compatible demagnetization components (Figures 4a, 4b, and S2).

Best-fit directions from AF demagnetized samples were derived using an average of nine steps between 20 and 80 mT, and thermally demagnetized samples were mostly fit between 400°C and 680°C. For Ak-Terek, we retained 188 magnetization directions out of 216 demagnetized samples (Figure 4c). For Kaji-Say, 163 magnetization directions were retained from 235 demagnetized samples (Figure 4d). At both sections, the McFadden and McElhinny (1990) reversals test is negative. For Ak-Terek, the angle between the two polarity populations is 6.3°, which exceeds the critical angle of 4.3°; for Kaji-Say, the angle between the two means is 7.9° with a critical angle of 6.7° (Table 1 and Figures 4c and 4d). The bootstrap reversals test of Tauxe (2010) shows that the Y and Z components overlap at 95% confidence but not X for Ak-Terek and overlap for the X and Z components but not Y for Kaji-Say. Incompletely removed recent field components can explain the differences between the two polarities. For Kaji-Say, the fold test is positive at 95% confidence limits McFadden (1990) (Xicrit95: 14.85, Xicrit1g: 23.27, Xicrit1s: 6.39), with the Fisher (1953) precision parameter (k) being maximized at 96 ± 32% unfolding when considering no uncertainty on bedding attitudes or at 90 ± 18% unfolding with 5° uncertainty on bedding attitudes (Watson & Enkin, 1993). Only minor differences in bedding attitudes at Ak-Terek lead to an insignificant change in k, hence an inconclusive/indeterminate fold test.

### 4. Magnetostratigraphy

To establish a magnetic polarity sequence for each section we converted the magnetization component directions into virtual geomagnetic poles (VGPs; Figures 5a and 5b). At least two successive horizons of the same VGP polarity were used to define polarity intervals. The obtained polarity sequence was then correlated to the Neogene geomagnetic polarity time scale (GPTS2012) of Gradstein et al. (2012). Because both sections mostly contain Chu Group sediments, our correlations assumed the sections must be younger than...

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### Table 1

| Section          | All samples | Reversed-only | Normal-only |
|------------------|-------------|---------------|-------------|
|                  | n           | Dg            | Ig          | k   | α95 | Ds  | Is   | k   | α95 |
| Ak-Terek (42.2°N, 76.7°E) | 188 | 341.6         | 67.0        | 24.9 | 2.1 | 352.4 | 56.0 | 24.3 | 2.1 |
|                  | 110 | 157.5         | −68.8       | 29.5 | 2.5 | 170.3 | −58.3 | 30.8 | 2.5 |
|                  | 78  | 346.5         | 64.2        | 21.5 | 3.5 | 355.0 | 52.6 | 19.8 | 3.7 |
| Kaji-Say (42.2°N, 77.3°E) | 163 | 335.2         | 85.7        | 5.9  | 5.0 | 2.9   | 48.0 | 11.5 | 3.4 |
|                  | 83  | 42.4          | −80.5       | 4.7  | 8.1 | 178.0 | −50.3 | 10.5 | 5.0 |
|                  | 80  | 10.2          | 76.2        | 11.0 | 5.0 | 7.4   | 45.5 | 13.4 | 4.5 |

Note. Precise GPS coordinates are given for each sample in the on-line data. Abbreviations: n, number of samples; D, declination; I, inclination; g, geographic (in-situ) coordinates, s, stratigraphic (tilt-corrected) coordinates; k, best estimate of the precision parameter; α95, radius that the mean direction lies within 95% confidence.
the top of the underling Shamsi Group, which was previously dated to 11 or 13 Ma (Wack et al., 2014) in the Issyk-Kul Basin. We therefore took 13 Ma as the maximum possible age for both sections.

4.1. Ak-Terek

Based on 188 tilt-corrected VGP directions, we established 15 polarity intervals for Ak-Terek (Figure 5a). Visual correlation of the polarity sequence with the GPTS yields the best match between 6.3 and 2.8 Ma (Figure 5c). This correlation includes a missing normal polarity subchron (C2An.2n) at ca. 3.2 Ma (450 m) and a normal polarity interval at 5.9 Ma (60 m) that has no equivalent with the reference scale. The former lasted ca. 90 ka, which corresponds to about 10 m in thickness. With an average sampling interval of 7 m in this part of the section, the subchron could have been missed given fluctuations in the sedimentation process. The normal polarity interval at ∼60 m is restricted to a 2.5 m thin conglomerate layer of anomalously high IRM values (Figure 4a), so it likely represents an isolated aberration in the magnetic recording process.

4.2. Kaji-Say

The magnetic polarity sequence for Kaji-Say was based on 165 tilt-corrected directions (Figure 5b), which identified 13 polarity intervals. A normal polarity interval spans ∼150 m across the potential unconformity between the eastern and western transect. However, the base of the upper section contains a single reversed and two transitional samples, which may indicate that a reversed polarity interval lies below. Two possibilities were considered when correlating the obtained polarity sequence with the global reference scale. Option 1 assumes continuous sedimentation between the eastern and western transects, where a correlation can be found between 12.7 and 9.5 Ma (Figure 5c). This solution includes one reversed polarity interval at ∼100 m that does not exist in the reference scale and misses two short subchrons at the top of the section (580–620 m). Option 2 assumes a hiatus exists between the eastern and western transects at 464 m. The stratigraphically higher, western section spans ∼200 m in thickness but contains only two polarity intervals. However, assuming the sedimentation rates are similar in the lower unit, restricts the possible correlations with the GPTS. Moreover, the transition between Chu and Sharpyldak deposits between 550 and 600 m can serve as a tentative tie point to the equivalent transition at the Ak-Terek section. When respecting these criteria, the 160 m normal polarity interval, followed by a 50 m reversed polarity interval of the upper section, best match the reference scale between 3.0 and 2.4 Ma (Figure 5c).

Correlating the lower part of the section (eastern transect) individually to the GPTS yields two plausible matches. One possibility is to correlate the lower section in the same way as in Option 1, from 12.7 to 10.9 Ma (Figure 5c). However, this correlation results in an 8 Myr hiatus within the section and a ∼4 Myr age gap between the Chu Group at Kaji-Say and Ak-Terek. The other possible correlation to the reference scale lies between 7.0 and 5.1 Ma, which overlaps our age estimate for the base of the Ak-Terek section and reduces the hiatus to 2 Myr (Figure 5c). This correlation involves two normal polarity zones around 320 and 400 m height that are not matched to the reference scale. Considering their short duration, the unmatched intervals are likely explained by local magnetic recording aberrations in our sections but could also represent true subchrons that were too short to be recognized in the global polarity scale.
5. Depositional History of the Issyk-Kul Basin

5.1. Depositional Age at Ak-Terek

The magnetostratigraphic correlation of the 500 m thick Ak-Terek section yields a robust correlation to the reference scale, suggesting that the Chu sediments were deposited between 6.3 and 2.8 Ma with an average sedimentation rate of 14 cm/ka. The conformable transition to conglomerate at the top of the section dates the Chu-Sharpyldak transition at 2.8 Ma. We did not observe a lithologic transition at the base of the section; however, along strike to the east, Shamsi deposits are exposed by a reverse fault (Figure 1c). Together with the observation of slightly reddish layers at the base of the section (Figure 2a) that are rich in hematite (Figure 3a), this points to a Shamsi-Chu transition close to 6.3 Ma at Ak-Terek.

5.2. Depositional Age at Kaji-Say

Of the two plausible magnetostratigraphic correlations for Kaji-Say, Option 1 assumes quasi-continuous sedimentation between the eastern and western transects, thereby dating the ca. 650 m thick section to between 12.7 and 9.5 Ma, with an average sedimentation rate of 25 cm/ka and places the Chu-Sharpyldak transition at ca. 10 Ma. Based on more reddish strata south of the sampled section, suggestive of Shamsi type deposits (Figure 1d), we assume that the base of our section represents approximately the base of the Chu Group at Kaji-Say. A basal age of ca. 13 Ma for the Chu Group is consistent with previous age estimates from the eastern Issyk-Kul Basin that dated the top of the Shamsi Group to 13–11 Ma (Wack et al., 2014). On the other hand, this age model implies a 4 Myr hiatus between the Chu sediments deposited at Kaji-Say and Ak-Terek. It also suggests that the stratigraphic boundary between the Chu and Sharpyldak groups at Kaji-Say predates the equivalent transition at Ak-Terek by more than 7 Myr.

Option 2 dates the lower unit to 7.0–5.1 Ma and the upper unit to 3.0–2.4 Ma with average sedimentation rates of 23 and 30 cm/ka, respectively. This places the Shamsi-Chu transition at around 7 Ma and the Chu-Sharpyldak transition at 2.8–2.6 Ma, which agrees well with the stratigraphic boundaries inferred for Ak-Terek. Although average sedimentation rates of the two age models are similar, Option 2 involves less variability within the section (20–30 cm/ka, Figure 7a) compared to Option 1 (16–43 cm/ka). The presence of calcareous lacustrine deposits in the upper part of Kaji-Say (Figure 3b) yields an additional age constraint that points to the younger age of Option 2, as it implies the existence of a lake (Lake Issyk-Kul) at the time of deposition. A precondition for lake formation was the closure of the Issyk-Kul Basin, caused by uplift of the Kungey Range, which was estimated to post-date 7 Ma (Macaulay et al., 2014; Selander et al., 2012).

A conformable transition to Sharpyldak conglomerates in the upper section also argues for the younger ages implied by Option 2. Deposition of Sharpyldak-type conglomerates marks a prominent transition from a low to high energy depositional regime, a widely recognized phenomenon throughout the Tian Shan, with Sharpyldak equivalents identified in China as the Xiyu Formation (e.g., Zhou et al., 2020) and the Polizak Formation in Tajikistan (e.g., Dedow et al., 2020). Commonly, these formations are late Plio-Pleistocene in age and have been linked to the onset of northern hemispheric glaciation (e.g., Peizhen et al., 2001; Zhao et al., 2020). However, other authors described the Xiyu conglomerates as a time-transgressive prograding gravel wedge with depositional ages ranging from ca. 15 to 2 Ma (Charreau et al., 2009; Heermance et al., 2007), therefore, regional correlation of the formations should be made with caution.

In the Chu Basin (Nuruz section, 150 km west of AT, Figure 1a), the transition between the Shamsi equivalent (Saryagach Formation) and the 1.5 km thick Chu Formation was dated magnetostratigraphically to ~7.5 Ma, while the Chu-Sharpyldak transition was dated to ca. 3 Ma (Bullen et al., 2001) and 4.5 Ma (Abdrakhmatov et al., 2001; C1 and C2 in Figure 6). Based on similar depositional ages inferred for a ~3.5 km thick Chu Group in the At-Bashi Basin (AB in Figure 6) and on further preliminary magnetostratigraphic studies from the Kochor and Naryn basins, Abdrakhmatov et al. (2001) suggested that the transitions between the main stratigraphic groups occurred coevally from basin to basin in the central Tian Shan. Their proposed Shamsi-Chu and Chu-Sharpyldak transition ages around 8 and 4 Ma, respectively, generally agree with the depositional ages we determined for Ak-Terek and with the age model of Option 2 at Kaji-Say (Figure 6).
Taking into account all local and regional age constrains from the Chu and Sharpyldak-equivalent formations supports Option 2 at Kaji-Say, suggesting a depositional age of ca. 7.0–2.4 Ma, with a hiatus between ca. 5 and 3 Ma.

5.3. The Shamsi Group, Eastern Issyk-Kul Basin

The new age constraints for the Chu Group at Ak-Terek and Kaji-Say with a tentative Shamsi-Chu transition age close to 7 Ma led us to re-evaluate the magnetostratigraphy of the Shamsi Group in the eastern Issyk-Kul Basin (Figure 1e), previously dated between 26 and 11 Ma (Wack et al., 2014). Owing to its lower sedimentation rate and poorer magnetic recording than the Chu group, the magnetizations in the Shamsi Group were less stable and their polarity sequence yielded ambiguously defined polarity intervals, leading to inconclusive magnetostratigraphic age estimates (Wack et al., 2014). The polarity sequence of Chon Kyzylsuu (CK) was assigned to two age models (A) and (B), with model A yielding 26–16 Ma and model B yielding 25–11 Ma. Re-correlating this section with the GPTS2012 (Gradstein et al., 2012) to the period from 26 to 7 Ma, by considering all inconclusive horizons as unknown polarities, yields a plausible match between 17.3 and 7.5 Ma (Figure 6), with an average sedimentation rate of 9 cm/ka.

The polarity sequence of Jeti-Oguz (JO) was originally correlated between ca. 23 and 13 Ma or 23 and 11 Ma (Wack et al., 2014). The lower 400 m of the section are robustly defined as 23–18 Ma in both age models they considered. Polarity intervals were more ambiguously defined above 400 m. However, a tie-point exists between the two sections based on a characteristic change in magnetic properties (up-section increase in ARM) observed at around 550 and 700 m stratigraphic height in the CK and JO sections, respectively (arrows in Figures 6 and 7; Wack et al., 2014). Respecting this tie point, the whole section yields a plausible correlation to the GPTS2012 as well as to the CK polarity sequence between 22.4 and 8.5 Ma with an average sedimentation rate of 8 cm/ka (Figure 6).

Geologic mapping based on satellite images further supports the proposed tie-point between the two sections (Figure 1e). In both sections, the levels characterized by increasing ARM values, reflecting an increase in fine grained magnetite (Figures 7c and 7d), mark a prominent color transition from intense dark red beds below (lower Shamsi) to lighter, pale red beds above (upper Shamsi; Figure 1e), indicating a decrease in pigmented hematite. The difference in basal ages (22.4 Ma vs. 17.3 Ma) of the two sections appears reasonable, considering that the Shamsi deposits extend significantly farther below the base of the CK section. In contrast, the base of JO lies above white (lower) Kokturpak or Jurassic strata (observed on satellite images and in the field) that onlap on up-thrusted basement rocks (Figure 1e). The transition from Shamsi to Chu type deposits is unconformably overlain by Sharpyldak conglomerates at both sections and was therefore not identified in the field. However, our satellite image mapping further supports that the top of both sections lies within the uppermost Shamsi Group (Figure 1e). Good agreement between the here suggested age of the Shamsi group, the new age constraints for the Chu Group, and geologic mapping between the studied sections, leads us to conclude that the Shamsi Group was likely deposited throughout the Miocene, between ca. 22 and 7 Ma in the Issyk-Kul Basin.

Figure 6. Magnetostratigraphic correlations of sections from the central (Krygyz) Tian shan. Abbreviations above the polarity sequences indicate name and location of the sections from Figure 1. New and reinterpreted magnetostratigraphies from the Issyk-Kul Basin are shown in color (this study). Polarity sequences of CK and JO after Wack et al. (2014); arrows indicate tie points based on a prominent change in magnetic properties (see also Figure 8). C1 and C2 represent the Naryn section from the Chu Basin after Bullen et al. (2001) and Abdrahmatov et al. (2001), respectively; AB is from the At-Bashi Basin (Abdrakhmatov et al., 2001). CK, Chon Kyzylsuu; JO, Jeti-Oguz.
6. Tectonic Implications of the Syn-orogenic Sedimentary Record

6.1. Uplift of the Terskey Range

Taken together, the age constraints from four different sedimentary sections yield a nearly complete record of the Neogene to early Pleistocene depositional history of the southern Issyk-Kul Basin. These sediments accumulated in response to the exhumation and successive erosion of the Terskey Range (Macaulay et al., 2016), thus the sedimentation rate and lithologic characteristics of these units hold information concerning the uplift- and climate-history of the area. The Shamsi group, deposited between 22.4 and 7.5 Ma, consists dominantly of coarse-medium sized sandstone (Figure 7a) with relatively low sedimentation rates of 4–11 cm/ka (Figure 7b). A prominent increase in fine grained magnetite (higher ARM and ARM/Sus, Figures 7c and 7e) and a decrease in pigmented hematite mark the transition from lower to upper Shamsi...
Group at ca. 12 Ma and coincide with a grain size fining from coarse to medium sand (Figure 7a). Assuming that the oldest sediments from the Jeti-Oguz section represent the base of the Shamsi Group, implies that syn-tectonic sedimentation in the Issyk-Kul Basin, and therefore uplift in the Terskey range, commenced by 22.4 Ma, which is compatible with the estimated onset of deformation in the range at 26-20 Ma (Macaulay et al., 2013, 2014). Relatively constant and low sedimentation rates throughout the Shamsi Group imply that erosion rates were comparatively low and did not change significantly until 7.5–7.0 Ma. However, changes in magnetic mineralogy may indicate a change in source material around 12 Ma. The timing of these changes generally coincides with the onset of global cooling after the mid-Miocene climate optimum (Figure 7f); consequently, a climatically driven change in erosion cannot be excluded. Exhumation rates inferred from thermochronologic data (Figure 7g) point to a slight increase in exhumation during the early to middle Miocene from <0.08 to <0.12 km/Myr (Macaulay et al., 2013), which is, however, not mirrored by an increase in sedimentation rate.

The transition from Shamsi to Chu-type deposits between 7.5 and 7.0 Ma is linked to a fining in grain size from medium sand to dominantly fine sand and silt deposits and an overall increase in sedimentation rates (Figures 7a and 7b). Up to three-fold higher sedimentation rates of the Chu compared to the Shamsi Group indicate an increase in erosion rate after 7 Ma. Thermochronologic data point to accelerated unroofing of the Terskey Range after 10 Ma with exhumation rates of 0.1–0.4 km/Myr and of >0.2 km/Myr between 8 and 7 Ma (Figure 7g) (Macaulay et al., 2013, Figure 7f). A good agreement between the increase in exhumation and sedimentation rates suggests that the stratigraphic boundary between the Shamsi and Chu groups at ca. 7 Ma marks the onset of accelerated uplift of the Terskey Range.

Based on local and temporal variations in lithology and sedimentation rates, the Chu Group can be subdivided into two distinctly different deposition stages. Stage 1, between 7 and 5 Ma, is characterized by comparatively high sedimentation rates (on average 23 cm/ka) in the central part of the basin (at Kaji-Say) and low sedimentation rates (∼13 cm/ka) at Ak-Terek further west. It comprises the lithologic units KS-1 and AT-1. Stage 2 between 5 and 3 Ma is characterized by a hiatus at Kaji-Say, while sedimentation rates nearly doubled at Ak-Terek between 5 and 4 Ma (AT-2, Figure 7b) and the lithology changed to more massive and uniform sandstone beds (Figure 3a). After ca. 4 Ma sedimentation rates decreased again, and a more frequently changing lithology includes sporadic carbonates and a gypsum layer that indicate still water deposition (AT-3), while laminated limestones deposited after 3 Ma imply lacustrine deposition (KS-2). After ca. 4 Ma sedimentation rates decreased again, and a more frequently changing lithology includes sporadic carbonates and a gypsum layer that indicate still water deposition (AT-3), while laminated limestones deposited after 3 Ma imply lacustrine deposition (KS-2). The hiatus together with strongly folded strata (dip > 70°) of the lower Chu Group at Kaji-Say likely reflect the onset of deformation and uplift within the foreland basin, which shifted the local depocenter farther north. The concurrent changes in sedimentation rates, lithology and magnetic mineralogy at Ak-Terek (Figures 7c and 7e) may signal a change of source material in the western side of the basin at ca. 4.5 Ma. The transition from Stage 1 to 2, between 4.5 and 5.0 Ma, therefore, marks a prominent change in the deposition dynamics in the Issyk-Kul Basin. The associated northward propagation of the locus of deformation at Kaji-Say indicates that the formation of the Issyk-Kul Broken Foreland initiated around 5 Ma.

Uplift of the mountain ranges to the north may have influenced the depositional dynamics throughout the basin. Thermochronologic data suggest an onset of exhumation of the northern Tian Shan (Zaili Range) between 29 and 15 Ma (De Grave et al., 2013). However, paleocurrent and provenance data from the Kungey Range in the northern Issyk-Kul Basin attest that sediments from the Terskey Range in the south persisted until ca. 7–4 Ma, suggesting that substantial uplift north of the lake commenced only after 7 Ma (Selander et al., 2012).

### 6.2. Uplift of the Kungey Range and Formation of Lake Issyk-Kul

A shift in sediment provenance within the Chu Group exposed north of Lake Issyk-Kul, from the lower Terskey member to the upper Kungey member, marks the onset of substantial uplift in the Kungey Range (Selander et al., 2012). Although no precise age constraints are available for the sediments in the northern part of the basin, our new age constraints for the Chu Group at Ak-Terek and Kaji-Say (7.0–2.8 Ma) likely apply to the entire Issyk-Kul Basin, yielding an average sedimentation rate of 14 cm/ka for the up to 600 m thick Chu Group in the northern basin. Assuming a constant sedimentation rate dates the transition from the Terskey member (up to 200 m thickness) to the Kungey member (up to 400 m thickness) to ca. 5.5 Ma. Consideration of the evidence for major spatio-temporal shifts of depocenters during this time interval in
the southern and in the northern part of the Issyk-Kul Basin points to a link between the change in deformation style around 5 Ma in the southern basin and the shift from Terskey to Kungey-sourced Chu deposits in the northern basin. We therefore propose that the unconformity at Kaji-Say and the doubling of sedimentation rates at Ak-Terek at ca. 5 Ma coincide with the initiation of substantial uplift in the Kungey range.

To further test this hypothesis, we dated the available stratigraphic columns of the northern side of the Issyk-Kul Basin (Selander et al., 2012; K1 and K2 in Figure 1a), based on the depositional record of the southern basin, by assuming synchronous transitions between equivalent stratigraphic groups (Figure 8). Based on the stratigraphic thicknesses of ca. 500 m for the Shamsi and Sharpyldak groups and ca. 600 m for the Chu Group reported by Selander et al. (2012) and assuming Shamsi, Chu, and Sharpyldak were deposited between ca. 22–7, 7–3, and <3 (Figure 7), we infer a progressive increase in average sedimentation rates over time from \( \leq 3 \) to \( \leq 12 \) to \( \geq 20 \) cm/ka, respectively. Assuming further that the transition from Terskey (10–200 m at K1; 600 m at K2) to Kungey-derived Chu Group sediments (400 m at K1, absent at K2) coincides with the transition from Stage 1 to Stage 2 in the southern side of the basin at \( \sim 5 \) Ma, yields a sedimentation rate of \( \sim 25 \) cm/ka for the Terskey member at location K1 in the northwest and suggests an increase from <8 to \( \sim 20 \) cm/ka after 5 Ma at K2 in the central Kungey area (Figure 8).

The proposed sedimentation rates compare well with the values determined in the southern part of the basin (Figure 8). Comparing Kaji-Say and K2 both located in the central basin, more sediment was deposited at Kaji-Say (up to 28 cm/ka), in proximity to the Terskey Range, than at K2 (<8 cm/ka) between 7 and 5 Ma. However, comparing Ak-Terek and K1, in the western side of the basin, indicates that here sedimentation rates were twice as high at the more distal location K1 (<25 cm/ka) than at Ak-Terek (<13 cm/ka) before 5 Ma. Together, this suggests that between 7 and 5 Ma in the western part of the basin, deposition was located farther north from the Terskey Range than in the central part of the basin. This pattern may be applicable for the entire Miocene, as indicated by the westward thickening of the Shamsi Group in the northern side of the basin (Selander et al., 2012) and an apparent eastward thickening of the Shamsi Group on the southern side (Figure 1b). Uplift of the Kungey Range would shift the deposition of Terskey sourced sediments southward to more proximal areas, which is consistent with the observed doubling of sedimentation rates around 4.5 Ma at Ak-Terek. This uplift event may be associated with a change in the direction of compression from NW-SE to N-S reported for the central Tian Shan around the Miocene-Pliocene transition (Buslov et al., 2003).
Mountain building north of the basin transformed the Issyk-Kul area from a foreland to an intermountain basin, thereby facilitating the formation of a deep lake within it. Two thin limestone layers at the top of the eastern transect at Kaji-Say, corresponding to ~5 Ma according to Option 2, as well as sporadic calcareous horizons and a gypsum layer deposited between 4 and 3 Ma at Ak-Terek, may point to the expansion and retreat of an early lake. Up to 50 m thick sequences of mostly calcareous lacustrine strata in the western section at Kaji-Say signify the existence of Lake Issyk-Kul at 3 Ma.

7. Conclusions

New and reinterpreted magnetostratigraphic age constraints of continental sediments from the Issyk-Kul Basin yield a near-continuous stratigraphic record of the Mio- to early Pleistocene, syn-tectonic depositional history in one of the largest sedimentary basins in the central Tian Shan. From these, we draw the following main conclusions:

(1) The Shamsi group, which represents the basal syn-tectonic unit, was deposited between 22.4 and 7.5 Ma. This unit is found in the southeastern and northwestern parts of the basin, with maximum thicknesses of ca. 1,000 and 500 m, respectively, implying average sedimentation rates of 8–9 cm/ka and ~3 cm/ka, respectively. Slight fining in grain size and changes in magnetic mineralogy after the middle Miocene (ca. 13 Ma) may reflect a gradual shift in sediment source or transport conditions.

(2) A major grain size fining between 7.5 and 7 Ma marks the stratigraphic boundary between the Shamsi and Chu groups. Overall higher sedimentation rates after 7 Ma (11–28 cm/ka) indicate that erosion rates increased, linked to accelerated uplift of the Terskey Range around this time. It is interesting to note the inverse relationship between grain size and sedimentation rate across the Shamsi-Chu transition, which may be related to longer sediment transport or increased subsidence of the basin.

(3) Spatio-temporal shifts in the deposition centers documented north and south of Lake Issyk-Kul indicate that the locus of deformation propagated from the Terskey Range into the basin around 5 Ma, forming the Issyk-Kul Broken Foreland. This change in deformation style likely coincides with the initiation of uplift in the Kungey Range to the north, which led to the closure of the basin, a precondition for the formation of Lake Issyk-Kul. Lacustrine deposits dated at ~3 Ma demonstrate that a substantial lake must have existed by that time.

(4) Equivalent stratigraphic boundaries around 7 and 3 Ma in nearby basins suggest that the driving mechanisms that controlled sediment accumulation and the lithology of the three main syn-tectonic units were regionally synchronized throughout the central (Kyrgyz) Tian Shan.

Data Availability Statement

Data produced during this study are available in the open-access online database Zenodo (https://doi.org/10.5281/zenodo.4548968). The interpreted paleomagnetic directions used for the magnetostratigraphy are provided in the supplementary information. Further data sets for this research are included in Wack et al. (2014), Macaulay et al. (2014), and Zachos et al. (2001).

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