**INHERITED STRIKE-SLIP FAULTS AS AN ORIGIN FOR BASEMENT-CORED
UPLIFTS: EXAMPLE OF THE KUNGEY AND ZAILISKEY RANGES, NORTHERN
TIAN SHAN**

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A thesis submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Master of Science in the Department of Geological Sciences.

Chapel Hill
2008

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ABSTRACT

**JACOB SELANDER: Inherited strike-slip faults as an origin for basement-cored uplifts:
Growth of the northern Tian Shan, Kyrgyzstan and Kazakhstan
(Under the direction of Michael Oskin)**

Reactivation of strike-slip faults and formation of new faults in the surrounding crust may be a common origin for high-angle reverse faults characteristic of basement-cored uplifts. This relationship is explored here by examining the growth of the Kuney and Zailiskey Ranges, the northernmost of the Kyrgyz and Kazakh Tian Shan. These ranges are cored by the inherited, ENE-striking Kemin-Chilik fault. Range growth in response to the northward propagation of the Tian Shan has taken place along a network of steeply-dipping faults surrounding the Kemin-Chilik fault. Structural relief is recorded by the deformation of a previously planar unconformity separating Paleozoic basement from Neogene strata. Late Quaternary deformation inferred from deformed river terraces is consistent with the long-term pattern of range growth. Interpretations of cross-sectional fault geometries are consistent with predictions from a mechanical model of slip partitioning developed by an obliquely-slipping, steeply-dipping, reactivated fault at depth.

ACKNOWLEDGEMENTS

I would like to thank Ray Weldon and Reed Burgette for introducing me to the Tian Shan, and all the members of the 2004 NSF-supported Tian Shan Field Camp for mapping in the western Kungey Range and Kok-Moynok basin. I am especially grateful to my colleagues from the Kyrgyz Institute of Seismology, Cholponbek Ormukov and Kanatbek Abdrakhmatov, for invaluable help both organizing logistics and out in the field. Also thanks to Michael Oskin and Joseph Goode for mapping assistance.

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1. Introduction

Basement involved thrust belts (BITB), here defined as belts of shortening characterized by high-angle, reverse fault-bounded uplifts, are common on the margins of many orogenic belts (Tapponnier and Molnar, 1979; Jordan and Allmendinger, 1986; Rogers, 1987; Bump, 2003; Hilley et al., 2005) or plateau “pop-up” style structures (Bilham and England, 2001). Individual “thick-skinned” structures within these deformation belts typically absorb only minor amounts of shortening (Erslev, 1991; Narr and Suppe, 1994), thus significant shortening accommodated in BITB must involve slip on multiple structures. This is in contrast with “thin-skinned” thrust belts, where thrust sheets or wedges are detached from basement that is subducted beneath a gently dipping, long-lived, large-offset thrust fault (e.g. Hubbert and Rubey, 1959; Chapple, 1978; Davis et al., 1983; Burchfiel et al., 1999; Scharer et al., 2004). Though the amount of shortening across BITB is typically low (<200 km) the rates of deformation in presently active BITB can be a significant portion of the total shortening rate across an orogen (Jordan and Allmendinger, 1986; Abdrakhmatov et al., 1996; Molnar and Ghose, 2000; Meade and Hager, 2001).

Development of BITB requires repeated through-going failure of the basement to initiate new or reactivate pre-existing reverse faults. However, initiation of slip on high-angle reverse faults in BITB poses two problems: development of new high-angle reverse faults violates the prediction from Mohr-Coulomb mechanics that thrust faults will form with $\sim 30^\circ$ dip (Anderson, 1951) and motion on high-angle structures is kinematically

unfavorable to absorb shortening (e.g. Sibson, 1985). One explanation for the development of BITB is the re-activation of an older structural grain. Many studies have shown that inherited faults exert a strong influence on the loci of deformation in intracontinental orogens (e.g. Holm and Cloud, 1990; Allen and Vincent, 1997; D'Lemos et al., 1997; Holdsworth et al., 1997; Darby and Ritts, 2002; Bump, 2003; Mouthereau and Lacombe, 2006; Butler et al., 2006; Webb and Johnson, 2006). Inheritance of older structures may be favored where reactivation of pre-existing faults requires significantly less work than initiation of new, optimally oriented faults (Cowie and Scholz, 1992; Scholz, 2002). Pre-existing high-angle faults may also become mechanically favorable when pore fluid pressure within the crust surrounding such faults approaches lithostatic loading and sufficiently decreases friction along the fault surface (Hubbert and Rubey, 1959; Sibson et al., 1988; Hilley et al., 2005). However, both of these conditions cannot explain the generation of new high-angle faults in BITB. Thus, either all faults in these settings are reactivated, mechanically favorable high-angle faults or there exists a poorly understood process that initiates new high-angle reverse faults, despite their mechanical shortcomings.

In this study, we explore the possible role of oblique deformation in the origin of high-angle reverse faults in BITB. Commonly, reverse faults present in BITB are oriented oblique, rather than orthogonal, to overall compression (Tapponnier and Molnar, 1979; Jordan and Allmendinger, 1986; Ding et al., 2004). In regions of complex structural history, a pre-existing structural grain is unlikely to be oriented optimally to absorb compression; nonetheless these weaker areas of crust may be preferentially reactivated (Webb and Johnson, 2006). Re-activation of these high-angle structures at

depth in a compressional regime can cause deformation to propagate upwards as a partitioned system of reverse and obliquely slipping faults (Molnar, 1992; Bowman et al., 2003). This partitioning can possibly represent a lowest energy condition for motion (Michael, 1990), potentially required for the re-activation of pre-existing faults. Stress conditions at the margins of an orogen may also be critical to this reactivation process. The irregular distribution of topographic loads introduces variations in horizontal stress that could locally change the direction of principal stresses such that strike-slip faulting is locally favored over reverse faulting (Cowgill et al., 2003).

Once initiated or re-activated, strike-slip faults can accommodate shortening in an orogen via transform motion and outward horizontal extrusion of material (Molnar and Tapponnier, 1975). Alternatively, major strike-slip faults may be entirely embedded within an orogen, requiring that all slip along the fault must eventually be absorbed by local thickening or shortening structures (e.g. Kirby et al., 2007). Because high-angle strike-slip faults may evolve into oblique-reverse faults with continued deformation (Sibson et al., 1985), the development and overprinting of such faults provides a possible origin of the ubiquitous high-angle reverse faults in BITB. Thus, there may exist a fundamental, but poorly characterized, relationship between strike-slip faults and the propagation of BITB.

To explore the role of inherited strike-slip faults in the formation of high-angle reverse faults, we study the Tian Shan of central Asia (Fig. 1a). The Tian Shan are a BITB formed as a result of Indo-Eurasian convergence (Burtman, 1975; Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1979; Avouac et al., 1993; Abdrakhmatov et al., 2001; Thompson et al., 2002), and are dominated by north-south convergence along

Figure 1. (A) Map of central Asia showing the location of the Tian Shan, highlighting major tectonic provinces and strike-slip faults of the India-Eurasia convergence. Fault locations and names from Molnar and Tapponnier (1975), image courtesy of WSI Earth. **(B)** Generalized geology of the Kungey and Zailiskey Ranges, northern Tian Shan, noting major structures, Paleozoic basement, and location of preserved Cenozoic deposits. Locations of detailed maps in Figures 3, 7, and 9 are shown. Mapping overlain on shaded relief generated from Shuttle Radar Topography Mission data (Farr et al., 1997).

east-west striking high-angle reverse faults (Abdrakhmatov et al., 1996; Burbank et al., 1999; Korjenkov, 2000; Mikolaichuk et al., 2000; Molnar and Ghose, 2000; Abdrakhmatov et al., 2001; Bullen et al., 2001; Meade and Hager, 2001; Thompson et al., 2002; Bullen et al., 2003; Mikolaichuk et al., 2003; Bowman et al., 2004; Sobel et al., 2006; De Grave et al., 2007; Korjenkov et al., 2007). Strike-slip faulting is also prevalent in the Tian Shan (Figure 1), ranging in scale from the ~600-km long Talas Fergana fault that bisects the entire orogen (Burtman et al., 1996) to somewhat shorter strike-slip faults that are embedded within the orogen (Delvaux et al., 1999; Mikolaichuk, 2000; Buslov et al., 2003). The objective of this study is to determine the role of these embedded strike-slip faults in accommodating north-south shortening and northward propagation of the Tian Shan.

We focus in detail on the example of the Kungey and Zailiskey Ranges in the northern Tian Shan. These ranges are separated by the Kemin-Chilik fault, a 240 km-long inherited, active sinistral fault (Delvaux et al., 1999) (Fig. 1b). Analysis of synorogenic Neogene stratigraphy shows that the Kungey and Zailiskey Ranges formed in response to northward propagation of the Tian Shan. Preservation of a pre-orogenic unconformity as a low-relief upland surface (Fig. 2) provides an unusually extensive structural marker from which we can measure integrated deformation. The temporal evolution of uplift and

Figure 2. (A) Slope map overlain on a hillshade model showing examples of the preserved unconformity surface present in the central Kungey Range. Approximate extent of the preserved surface is noted. Note that horizontal striping in slope data highlights an artifact common in Shuttle Radar Topography Mission data from this area. (B) Photo taken looking west at point B (location shown in (A)) of the preserved unconformity surface. The extent of the surface is outlined in the foreground; ridgetops in background are also portions of the preserved surface.

reactivation of structures in building these ranges is inferred from comparison of this deformed marker surface to rates and styles of late Quaternary fault activity. The geometry of faulting at depth is constrained from folding and faulting of the unconformity surface, and from folding of Neogene strata and Quaternary fluvial terraces. Though the Kemin-Chilik fault is inherited, we argue that range growth took place along newly generated, steeply dipping reverse faults emanating from the strike-slip fault at the core of the ranges. The distribution of active shortening shows that range growth occurs via integrated shortening and strike-slip faulting, with gradients in deformation rates that result from trade off between strike-slip and reverse-slip fault systems. These observations are consistent with the development of new high-angle reverse faults in a BITB through interaction of regional compression with a re-activated, obliquely oriented strike-slip fault.

2. Setting

The Tian Shan is composed of a series of east-west striking basement uplifts commonly reaching elevations of 5 km with a maximum of 7 km in the central portion of the orogen, and is bounded on the north and south by the Kazakh Platform and Tarim Basin, respectively (Fig. 1a). Although 1000-1500 km north of the collisional plate boundary between India and Eurasia, the Tian Shan have been built as a direct result of this collision (Burtman, 1975; Molnar and Tapponnier, 1975; Tapponnier and Molnar, 1979; Avouac et al., 1993) and have absorbed $\sim 200 \pm 50$ km of crustal shortening (Avouac et al., 1993). Current shortening rates for the western Tian Shan are approximately 20 mm/yr, roughly equal to shortening across the Himalaya and almost half of the total Indo-Eurasian convergence (Abdrakhmatov et al., 1996; England and Molnar, 1997a,b; Larson et al., 1999; Meade and Hager, 2001; Reigber et al., 2001). Fault-plane solutions (Molnar and Ghose, 2000) and slip-rate studies (Abdrakhmatov et al., 2001; Thompson et al., 2002) show this shortening is being accommodated via thrust or oblique-slip transpressional motion distributed throughout the western Tian Shan, not confined to its margins.

The basement rocks of the Tian Shan are a part of the Central Asian Orogenic Belt, a series of accreted microcontinents, accretionary wedges, continental margin and volcanic arcs which were sutured onto the edge of the Siberian craton to form the Kazakh Platform from $\sim 540 - 250$ Ma (Sengor et al., 1993; Mossakovsky et al., 1994; Carroll et al., 2001; Windley et al., 2007). Evidence of minimal Mesozoic tectonism in the western Tian Shan is preserved as deposition of Jurassic shales in a few minor basins. The Cretaceous and early

Cenozoic were dominated by erosion, beveling down the Paleozoic rocks to form a quasi-planar erosional surface (Makarov, 1977; Sadybakasov, 1990). This low-relief unconformity surface separates basement from overlying late Cenozoic pre- and synorogenic deposits (Chediya, 1986) and is widely preserved as a relict landform throughout uplifted basement ranges in the Tian Shan (Fig. 2), thus providing an excellent structural and geomorphic marker (e.g. Burbank et al., 1999; Abdrakhmatov et al., 2001; Thompson et al., 2002; Mikolaichuk et al., 2003; Oskin and Burbank, 2005; Sobel et al., 2006; Oskin and Burbank, 2007).

Orogenic growth initiated in the eastern and southern Tian Shan circa 25-20 Ma, based on thermochronologic and magnetostratigraphic studies (Hendrix et al., 1994; Sobel and Dumitru, 1997; Yin et al., 1998; Dumitru et al., 2001; Heermance et al., 2007). Deformation appears to have propagated northwards as a series of east-west striking basement uplifts. Examination of pre-and syn-orogenic stratigraphy and thermochronology from the Kyrgyz Range in the northwestern Tian Shan demonstrate a history of Miocene burial prior to exhumation starting at ~11 Ma (Bullen et al., 2001; Bullen et al., 2003; Sobel et al., 2006), consistent with northward propagation into a former foreland basin.

Basement ranges are separated by basins filled with Cenozoic syn-orogenic deposits (Butman, 1975, Burbank et al., 1999; Abdrakhmatov et al., 2001; Thompson et al., 2002). Quaternary deformation is concentrated within these basins where faults and folds deform Cenozoic sedimentary and alluvial deposits. Active shortening structures are often located kilometers from the basement-bounding structures (Thompson et al., 2002). Surface expressions of faults and folded strata define a shallow ramp-style geometry at depth which

transfers deformation on to steep crustal-scale faults at the range fronts (Molnar et al., 1994; Burbank et al., 1999; Burchfiel et al., 1999; Thompson et al., 2002).

The majority of range fronts and river networks in the Tian Shan contain a regionally correlative suite of alluvial fans and fluvial terraces. Previous studies correlate and group these terraces on the basis of morphology and geomorphic position into four main divisions, Q1, Q2, Q3 and Q4 (Grigorienko, 1970; Makarov, 1977 as cited by Thompson et al., 2002). These terraces and fans provide planar, ideal markers with which to measure modern deformation amount and style across active structures (e.g. Weldon and Sieh, 1985; Avouac et al., 1993; Molnar et al., 1994; Lave and Avouac, 2000; Abdrakhmatov et al., 2001; Thompson et al., 2002).

2.1 The Issyk-Kul basin

The Issyk-Kul basin in northeastern Kyrgyzstan is the largest intermontane basin in the Tian Shan (~230 km east-west and ~80 km north-south) (Fig. 1b). The basin is deepest along its southern margin, where the south-dipping pre-Cenozoic unconformity surface is overlain by ~4km of sedimentary fill (Mikolaichuk, 2000; Buslov et al., 2003). The south side of the basin is bounded by the Terskey Range, where over 7 km of structural relief has been developed, evidenced by preservation of the unconformity surface at high elevations (~4 km) within the Terskey Range. The 700 m-deep Issyk-Kul (Kul = lake) with a surface elevation of ~1600 m currently occupies the majority of the basin (Buslov et al., 2003).

The Kungey and Zailiskey Ranges are the northernmost ranges of the Tian Shan and bound the northern margin of the Issyk-Kul basin. These ranges are juxtaposed by the historically active north-northeast striking sinistral Kemin-Chilik fault (Delvaux et al., 1999, 2001; Crosby et al., 2007). Fission track studies of the Kungey Range indicate an absence of

reset ages (DeGrave et al., 2007). This observation, along with the widespread preservation of the pre-Cenozoic unconformity surface at high elevations, supports relatively recent uplift with little incision when compared to the adjacent Kyrgyz Range (Sobel et al., 2006). The margins of the Kungey and Zailiskey ranges are bounded by active fold and thrust belts where deformation is accommodated by slip along north- and south-vergent thrust and reverse faults as well as by slip on obliquely oriented strike-slip faults.

2.2 Neogene-Quaternary Stratigraphy

Pre- and syn-orogenic Neogene and Quaternary strata of the northern Tian Shan can be regionally correlated despite facies changes along strike of the range fronts (Fig. 3). Syn-orogenic strata consist of a wedge of fluvial sediments derived from more southerly portions of the Tian Shan. This wedge is overlain by a coarsening-upward series of sandstones and conglomerates that records erosion of the growing Kungey and Zailiskey Ranges.

The basal Neogene unit is the Kokturpak (Suluterek) formation (Korjenkov, 2000; Mikolaichuk, 2000; Abdrakhmatov et al., 2001; Povolotskaya et al., 2006) which unconformably overlies the Paleozoic basement and varies from 10 to 80 m in thickness. The base of the Kokturpak Fm. consists of thin paleosols with carbonate nodules, minor gypsiferous sandstones, and thin local lacustrine carbonate deposits. Locally in the western Issyk-Kul basin basal layers of the Kokturpak Fm. are overlain by interbedded red siltstones and sandstones with abundant gypsum beds. Basalts flows present in the Kokturpak Fm. near Toru-Aygir have been dated at 53 ± 1 Ma (Sobel and Arnaud, 2000). However, the age of its uppermost strata is likely to just predate the onset of foreland basin sedimentation at any given site.

Figure 3. Cenozoic stratigraphy of the western and central Kungey Range front. Thicknesses determined from conformable dip sections and cross-section interpretations. Rose diagrams show paleocurrents from the Chu Fm. near Toru-Aygir ($n = 52$) and near Cholpon-Ata ($n = 68$). Azimuths measured from cross-bedding exposures and imbricated clasts. See Appendix A for paleocurrent measurements and locations.

A conformable, gradational contact separates the Kokturpak Fm. from the overlying Shamsi Fm. Oldest of the syn-orogenic stratigraphy, the Shamsi Fm. consists of massive red sandy clay units interbedded with paleosols and minor gravel conglomerates. Basal layers contain gypsiferous horizons which become absent higher in the column. Along the southern margin of the Kungey Range, the Shamsi Fm. is absent in the east, thickening to ~500 m in the west. In adjacent intermontane basins thickness of correlative Shamsi Fm. has been measured at several hundred meters (Abdrakhmatov et al., 2001). Paleomagnetic data from the exposures fringing the nearby Kyrgyz Range places a depositional time of ~12 – 8 Ma (Abdrakhmatov et al., 2001; Bullen et al., 2001).

The widespread basin-filling unit is referred to as the Chu Fm. (Korjenkov, 2000; Mikolaichuk, 2000; Abdrakhmatov et al., 2001) and locally noted as the Issyk-Kul Fm. (Bowman et al., 2004; Korjenkov et al., 2007). We divide the Chu Fm. into two members

based on clast lithology indicative of source area. The Terskey member consists of sandstones, gravels and gravel conglomerates interbedded with massive silt and sand layers. Individual clasts include metavolcanic rocks, metasedimentary rocks, gneiss, low-grade schists, and felsic plutonic rocks. Bedded layers display abundant low-angle cross bedding with paleocurrent indicators that support south-to-north transport (Figure 3). On the basis of paleocurrent directions and diversity of clast lithology, the Terskey member is inferred to be syn-tectonic with the growth of the Terskey Range south of the Issyk-Kul basin. The Kungey member of the Chu Fm. is composed of locally derived granitic material forming massive grus layers with interbedded sandstones and gravel conglomerates. Cross-bedding in sandstone and conglomerate layers indicates a north-to-south transport direction (Fig. 3). Flanking the western Kungey Range, the >600 m-thick Terskey member of the Chu Fm. conformably overlies the Shamsi Fm. The Kungey member is preserved only locally at the top of the section. In outcrops along the central Kungey Range, as little as 10 m to as much as 200 m of the Terskey member conformably overlies the Kokturpak Fm. and is in turn conformably overlain by the Kungey member.

The conglomerates of the Sharpyldak Fm. overlie the Kungey member of the Chu Fm. with a gradational coarsening-upward contact. These conglomerates are composed of locally-derived, dominantly granitic clasts, are >700 m thick, and record erosion of the Kungey Range and consequent progradation of coarse material into the Issyk-Kul basin. Where present proximal to the Kungey Range, the Sharpyldak Fm. is purely granitic in composition containing clasts up to 2m in diameter supported by a grus matrix. Correlation with Sharpyldak Fm. in other basins places the onset of deposition at mid-Pliocene or ~4 Ma (Abdrakhmatov et al., 2001). However, because the coarse-grained

facies of the Sharpyldak Fm. are linked to the uplift and erosion of local source areas, its age may be significantly younger or older locally.

Reconnaissance investigations indicate that the Neogene stratigraphy of the Zailiskey Range consists of similar Kokturpak and Shamsi Fm. equivalents that are overlain by coarser Chu and Sharpyldak Fm. equivalents that record range uplift and erosion. An exposure of a tilted, north-dipping section lying atop the unconformity surface east of Chilik shows that the Kokturpak equivalent is ~80 m thick, Shamsi equivalent ~400 m thick, and Chu equivalent >500 m thick.

Late Quaternary deposition in the northern Tian Shan is recorded by a regionally correlative, well-preserved suite of fluvial terraces and alluvial fans. Composition of clasts composing these deposits in the northern Issyk-Kul basin is predominantly granitic, reflecting the composition of the Kungey Range source area. These surfaces can be classified using morphology and geomorphic position (Grigorienko, 1970; Makarov, 1977; as cited by Thompson et al., 2002) and additional criteria we define in this study (Table 1). Subdivisions of major terrace groups are defined by surface morphology, pavement development, soil development, and clast characteristics to 50 cm depth. We divide Q2 into Q2₁ and Q2₂, Q3 into Q3₁, Q3₂ and Q3₃, and define recent (likely Holocene) surfaces as Q4. Because Q3₂ is the most widely preserved terrace and fan deposit, the majority of measurements were made where faults displace its surface.

Table 1: Morphology and characteristics of major terrace divisions in the northern Tian Shan

Surface	Surface morphology	Clast weathering	Pavement development	Soil development
Q4	Subdued bar and swale topography (< 1 m local relief)	Subangular to subrounded clasts, poor light brown varnish development	Immature, isolated pavement with large gaps of dust in between clasts	< 5 cm thick AV horizon with minimal stage 1 carbonate development
Q3 ₂	Extensive flat, well-defined surfaces with slight concavity. No preservation of remnant topography, minor frost ridges present	Angular to subrounded clasts, thin varnish development (< 0.25 mm)	Immature, patchy pavement with little dust in between clasts	10 cm thick AV horizon with minor stage 1 carbonate development on clasts to 50 cm depth
Q2 ₂	Flat surfaces with no preservation of remnant topography. Frost ridges are present and oriented sub-parallel to contours	Angular to subrounded clasts, varnish development on non-granitic clasts of 0.5 mm. Significant break-up of larger clasts	Patchy areas of interlocking clasts	10 - 15 cm thick AV horizon with stage 1 to stage 2 carbonate development to 50 cm depth
Q2 ₁	Ridge and ravine topography with areas of flat, preserved surfaces. Low-amplitude frost ridges present.	Angular to subrounded clasts, granitic clasts have advanced granular attrition. 0.75 - 1.5 mm thick varnish development on non-granitic clasts	Patchy pavement development in areas of small, angular clasts	15 - 17 cm thick AV horizon with stage 2 to minor stage 3 carbonate development to 50 cm depth

3. Structures of the Kungey and Zailiskey Ranges

Neogene and Quaternary geology of the Kungey and Zailiskey Ranges was mapped on aerial photography, LANDSAT imagery, and 1:25,000 topographic maps. Structural measurements were taken in deformed Neogene strata to determine fold and fault geometries. Deformed terrace surfaces were identified; vertical and lateral offsets were measured with a Trimble GeoXT differential GPS to determine displacement.

3.1 Western Kungey Range

The western Kungey Range consists of a wedge shaped basement uplift bounded by sinistral-oblique faults with reverse faults at its western end (Mikolaichuk, 2000; Delvaux et al., 1999; 2001; Povolotskaya et al., 2006) (Fig. 4 and Plate 1). The unconformity surface has been folded and faulted over the range crest with >3 km of structural relief. The northwest side of the range is bounded by the sinistral Kemin-Chilik fault, and the southeast side of the range by the sinistral Toguz-Bulak fault. These faults are linked at the western end of the Kungey Range by a set of reverse faults that bound the intensively deformed Kok-Moynok basin. This basin lies between the Kungey Range and the Kyrgyz Range to the west. A series of east-west striking, south-vergent reverse faults step southward from the eastern end of the Toguz-Bulak fault. The range front also steps south from here to form the central Kungey Range. In this area, at high elevations within the range, additional east- to southeast-striking reverse faults are inferred from offset of the low-relief relict unconformity surface.

Figure 4. (A) Geologic map emphasizing Neogene and Quaternary strata of the western Kungey Range. See Fig. 1 for map location. Locations of Figs. 5 and 6 shown. Mapping overlain on shaded relief map as in Fig. 1. (B) Detailed Neogene and Quaternary geology of the Toru-Aygir River valley. Locations (i), (ii), and (iii) (in A) are locations of detailed fault scarp surveys, shown in Fig. 6. N-S line notes the location of a long survey profile of the Ak-Teke and Tekren anticlines shown in Fig. 7. X-X' notes the cross-section line in Fig. 15. Due to the density of structural measurements, not all are shown in this figure. See Appendix B for all structural data and locations.

Structures exposed along the Toru-Aygir River reveal a pattern of deformation stepping southward from the Kungey Range (Bowman et al., 2004). In the Ak-Teke hills, along the lower Toru-Aygir River the Chu (Terskey) is deformed into an anticline in the hanging wall of the north-dipping Ak-Teke fault (Korjenkov, 2000; Mikolaichuk, 2000; Bowman et al., 2004; Korjenkov et al., 2007). The Ak-Teke anticline is ~3 km in width and extends at least 30 km east-west. The anticline is asymmetric with a backlimb dip of 30° north, a broad flat crest, and overturned beds in the southern limb where the Ak-Teke thrust fault outcrops at the surface. Morphology and geometry of the fold lead to the interpretation that the Ak-Teke anticline is a fault-propagation fold formed synchronously with slip on the Ak-Teke fault (Suppe, 1983; Suppe and Medwedeff, 1990). North of the Ak-Teke anticline lies the Kyzyl-Kultor basement uplift and the Jai-Lo syncline. The Kyzyl-Kultor hills consist of Paleozoic rocks folded and uplifted along the south-vergent Kyzyl-Kultor fault. The Jai-Lo syncline deforms both the Paleozoic bedrock and overlying Neogene sediments. Faults rooting into bedrock within the Jai-Lo syncline are responsible for local shortening near the syncline axis.

Figure 5. (A) Aerial photograph of sinistrally offset Q3₂ fan along the Toguz-Bulak fault north of Balikche. Location shown in Fig. 3. Numbers (1) and (8) indicate offset fan edges, (2) – (7) note heads and outlets of channels used for restoration. (B) Restoration of 125 ± 8 m of sinistral offset. Gap in the center is accommodated by minor oblique motion along the Toguz-Bulak fault.

Figure 6. Sinistral offset along the Toguz-Bulak fault east of the Balikche fault. Location shown in Fig. 4. Offset was measured from: (1) channel offset, measured from abandoned paleochannel to the present-day thalweg; (2) offset of eastern channel edge; (3) offset of Q₃₂ deposit edge. 95 ± 8 m of offset is present in the channel and Q₃₂ edge.

Most of the range-bounding structures of the western Kungey Range show abundant evidence of late Quaternary activity. Two sites along the Toguz-Bulak fault sinistrally offset Q₃₂ alluvial fans. These sites are separated by the Balikche fault, a northwest-striking reverse fault that branches southward from the Toguz-Bulak fault into the Issyk-Kul basin. West of the Balikche fault, the Toguz-Bulak fault sinistrally displaces a Q₃₂ alluvial fan and several inset channels by 125 ± 8 m (Fig. 5). East of the Balikche fault, the fault displaces the margins of a channel inset into Q₃₂ by 95 ± 8 m (Fig. 6). The Balikche fault itself shows evidence of Holocene activity, with a northeast-facing scarp and displacement of a Q₄ fan by 7 ± 2 m. Strike-slip on the Toguz-Bulak fault feeds into active, east-west striking thrust faults and folds along the Toru-Aygir River valley (Korjenkov, 2000; Bowman et al., 2004; Korjenkov et al., 2007). The Ak-Teke fault is the most active and largest spatially of these and displaces and warps preserved Q₂₁, Q₂₂, Q₃₁, Q₃₂, Q₃₃ and Q₄ surfaces (Fig. 7). Displacement along the Ak-Teke fault was measured at 48 ± 4 m in Q₂₂ and 32 ± 3 m in Q₃₂. A scarp in Q₄ shows a vertical offset of ~ 2 m (Korjenkov, 2000). East of Toru-Aygir slip on the Ak-Teke fault decreases to 21 ± 2 m in Q₃₂ (Fig. 7).

Figure 7. (A) Top: Surveyed profile of the Ak-Teke and Tekren anticlines. Profile rotated 5° to remove river gradient. Vertical exaggeration $\sim 9\times$. Center: Photo mosaic of the Ak-Teke anticline, looking west. Bottom: Detailed surveys across the Ak-Teke fault on the west side of the Toru-Aygir River. Surveys made in location (i) in Fig. 4. Vertical exaggeration = $5\times$. **(B)** Scarp profiles from locations (ii) and (iii) in Fig. 4. Vertical exaggeration = $5\times$.

South of the Ak-Teke fault, the Tekren anticline deforms Q_{2_2} , Q_{3_2} and Q_4 surfaces with only a minor amount of shortening, 10 ± 4 m, measured from the deflection of Q_{2_2} . Thrusting in the core of the Jai-Lo syncline also deforms Q_{3_2} , Q_{3_3} and Q_4 surfaces with an offset of 30 ± 6 m in Q_{3_2} (Fig. 7).

3.2 Central Kungey Range

Basement uplift across the central Kungey Range is accomplished by a series of north- and south-vergent reverse faults (Fig. 8 and Plate 2). North of the town of Cholpon-Ata, these faults displace the unconformity surface. Where preserved at the range front, this surface dips uniformly south $\sim 25^\circ$. South of the range front, the south-vergent Cholpon-Bosteri fault bounds an open, east-west trending syncline developed in Neogene strata. Paleozoic rocks are locally exposed on the south limb of the syncline, thus the basement is presumably folded similar to the Neogene strata. Conformable Neogene strata on the north limb of the syncline are locally overturned on the south limb in the Svalka anticline. East of Cholpon-Ata the unconformity surface and overlying Neogene strata uniformly dip $\sim 25\text{-}30^\circ$ south near the range front. South-vergent faulting with minor displacements disrupts the overlying Neogene and Quaternary deposits, but likely roots into basement at shallow depths. Evidence of faulting disappears east of the Chon-Aksu River and exposure of the Neogene strata defines a south-dipping homocline overlying the unconformity surface.

Figure 8. Detailed Neogene and Quaternary geology of the central Kungey Range, location noted in Fig. 1. Line Y-Y' indicates cross-section line in Fig. 16. Locations (i) and (ii) show where detail fault scarp surveys were made, shown in Fig. 9.

Figure 9. (A) Photo of Q₃₂ offset along the Cholpon-Bosteri fault at location (i) from Fig. 8. Photo is looking east. (B) Surveyed profiles across fault scarps at locations (i) and (ii) from Fig. 8. Vertical exaggeration = 5x.

Active deformation in the central Kuney Range is expressed by slip along the Cholpon-Bosteri fault system. Unlike the western Kuney Range, all late Quaternary deformation along the central Kuney Range front occurs via thrust or reverse faulting. Where bounding the southern limb of the Neogene syncline, the Cholpon-Bosteri fault dips

~55° north as calculated by local topographic expression of the fault trace. In the town of Cholpon-Ata, this fault displaces Q2₂, Q3₂ and Q4 surfaces. Slip in Q3₂ measured at 16 ± 2 m (Fig. 9). East of Cholpon-Ata, north-facing scarps in deformed terraces indicate a change of fault geometry and decrease of deformation rate. Deformation appears to transfer from the Cholpon-Bosteri fault to north-vergent back-thrusts near the town of Korumdu. Older, inactive back-thrusts deform Q2₂ surfaces, younger back-thrusts are expressed via small scarps and hanging-wall anticlines in Q3₂. Slip measured across the scarp and back limb of an anticline on one of these back-thrusts is 6 ± 2 m in Q3₂ (Fig. 9). Further east, fault scarps in Q2₂ and Q3₂ surfaces indicate a return to south-vergent, shallow structures. These scarps diminish eastward and disappear entirely near the Chon-Aksu River.

3.3 Chon-Kemin and Chon-Aksu Valleys

The east-northeast striking Kemin-Chilik fault zone runs longitudinally through the Chon-Kemin river valley, separating the Kungey Range from the Zailiskey Range. The Kemin-Chilik fault is a re-activated Paleozoic-Mesozoic sinistral fault zone with offset basement terranes (Delvaux et al, 1999, 2001). Late Quaternary sinistral motion is evidenced by sinistral offset in undifferentiated fluvial terraces along strands of the fault, while historical ruptures along the fault zone show both sinistral and reverse motion (Tapponnier and Molnar, 1979; Molnar and Ghose, 2000; Delvaux et al., 2001; Crosby et al., 2005, 2007).

The Chon-Aksu valley cuts east-west through the Kungey Range northeast of Cholpon-Ata. Running through this valley is the 45°-60° northeast-dipping Chon-Aksu fault (Delvaux et al., 2003; Crosby et al., 2005). Trenching along the Chon-Aksu fault shows ~4 major events within the past 12 kyr, the most recent being the 1911 Kemin earthquake (Delvaux et al., 1999; Delvaux et al., 2001; Arrowsmith et al., 2004; Crosby et al., 2005).

The 1911 event also ruptured segments of the Kemin-Chilik fault with sinistral-oblique motion expressed at the surface (Delvaux et al., 1999). Ruptures along the Chon-Aksu fault associated with this event display both reverse and normal motion with vertical displacements of 2-8 m (Arrowsmith et al., 2004).

3.4 Northern Zailiskey Range

The basement uplifts of the Zailiskey Range are bounded on the north by a system of north-verging thrust and reverse faults (Fig. 10). Where preserved, the Cenozoic unconformity surface is north-dipping and generally overlain by a conformable Neogene sedimentary section. Along the eastern range front near Chilik, basement is upthrust above a series of south-vergent reverse faults that step progressively northward (Tibaldi et al., 1997).

Near Almaty, the Neogene section is buried by a loess deposit of unknown thickness. Based upon topographic expression and limited exposures of Neogene strata, the range front east of Almaty appears to have been warped into a series of east-west-trending anticlines (Fig. 10). Further east, the loess cover diminishes and outcrops of Neogene sedimentary units are common. South of Chilik, these sediments have been uplifted and warped into east-west-trending, east-plunging anticlines. East of Chilik the Neogene section is exposed in a 6° - 17° north-dipping conformable section on top of the Cenozoic unconformity surface.

Quaternary deformation along the Zailiskey Range front is expressed by fault scarps and folding of a regional terrace sequence that appears correlative to the terrace sequence in the Issyk-Kul basin. Unnamed faults that displace the terraces have reverse and minor oblique-slip geometries. Analogous Q4 surfaces along the range front that cross reverse faults have scarps ~3-5 m in height, Q3 and Q2 surfaces have progressively more deformation. South of Chilik the range front shows evidence for Quaternary activity along

two north-vergent thrust faults. Displacement of Q2 surfaces was measured at 40 ± 20 m along the southern fault proximal to the range, and 72 ± 30 m on the northern fault (Fig. 11).

Figure 10. (A) Generalized geology of the northern Zailiskey Range, showing major structures, preserved Cenozoic deposits and locations where the Cenozoic unconformity surface is exposed. Location noted in Fig. 1. (B) Detailed Neogene and Quaternary geology near Chilik. Locations (i) and (ii) show where fault surveys were made, shown in Fig. 11.

Figure 11. Detailed fault scarp surveys from the northern Zailiskey Range near Chilik. Locations of (i) and (ii) are noted in Fig. 10, vertical exaggeration = 5x.

4. Geochronology

We selected a well-preserved chronosequence of alluvial terraces along the Toru-Aygir River for cosmogenic ^{10}Be exposure age dating. Samples for analysis were collected from depth profiles to simultaneously determine terrace age and account for ^{10}Be inherited during erosion, transport, and deposition of sediment (Anderson et al. 1996; Repka et al., 1997; Perg et al., 2001).

Cosmogenic ^{10}Be ($t_{1/2} = 1.36$ m.y.) is produced in quartz from the spallation of O and Si when exposed to high-energy cosmic rays (Cerling and Craig, 1994). For a stable, non-eroding surface, in-situ ^{10}Be accumulation can be described by the exponential equation (after Lal, 1988; Perg et al., 2001):

$$C_d = C_i + P_o t e^{(-z/z^*)} \quad (1)$$

where C_d is the concentration of ^{10}Be at depth (atoms/g), inherited ^{10}Be C_i (atoms/g), production rate P_o (atoms/g/yr), age of the surface t (yr), depth of sample z (cm), and z^* the characteristic attenuation length scale for unconsolidated alluvium calculated from a mean-free path of 165 g/cm^2 (Brown et al, 1992). For unconsolidated alluvium we use a bulk sediment density of 2.0 g/cm^3 , yielding z^* value of 82.5 cm. Decay of ^{10}Be may be ignored on time scales much shorter than its half-life (Lal, 1991)

To solve for inheritance and terrace age, we convert equation (1) into a linear expression by the substitution

$$z' = e^{(-z/z^*)} \quad (2)$$

Thus equation (1) can be represented as

$$C_d = C_i + P_o t z' \quad (3)$$

Using this linear relationship, measured C_d and calculated P_o and z' , equation (3) is solved for values of inheritance, C_i and terrace age, t .

Samples were taken from flat terrace surfaces well away from convex, actively eroding edges. Pits were dug into Q2₁, Q2₂ and Q3₂ terraces to a depth of 170 cm. Quartz-rich clasts ranging in size from 1 to 10 cm were taken by hand from depths of 170, 100, 50, 25 and 10 cm and from the surface of the terrace proximal to each pit. Samples were crushed and sieved to isolate a 250-500 μ m fraction. Standard quartz separation techniques were followed, and targets of ¹⁰Be were prepared for analysis at the University of Minnesota Cosmogenic Lab. Analysis was performed at the Lawrence Livermore National Laboratory accelerator mass spectrometer.

Production rates (P_o) for ¹⁰Be in the western Kungey Range were calculated using methods described by Pigati and Lifton (2004). Time-averaged production rates vary with altitude, and to a lesser extent, with terrace age. We find P_o values of 26.0, 24.8 and 24.3 atoms ¹⁰Be/g/yr for Q2₁, Q2₂ and Q3₂, respectively and use equation (3) to solve for the age of each surface. The depth profiles are exceptionally well behaved (Fig. 12). Our model ages, cited with a 95% confidence interval, are 139.9 ± 6.5 ka for Q2₁, 126.4 ± 10.8 ka for Q2₂ and 85.6 ± 7.6 ka for Q3₂ (Fig. 12 and Table 2).

Figure 12. Concentrations of ¹⁰Be at depth for Q3₂, Q2₂, and Q2₁ terrace surfaces along the Toru-Aygir River valley. Depth profiles and inheritance (equivalent age) values are presented with 95% confidence interval. Data used in plots is presented in Table 2.

Table 2: ^{10}Be data for samples taken from terraces along the Toru-Aygir River. Data is also presented in Fig. 11.

Sample	Depth (cm)	Surface	$^{10}\text{Be}^a$ (atoms/g $\times 10^6$)	error ($\pm$) (atoms/g $\times 10^6$)	Surface	Latitude ($^\circ\text{N}$)	Longitude ($^\circ\text{E}$)	Elevation (m)	Inheritance ^{b,c} (yr $\times 10^3$)	Age ^{b,c} (yr $\times 10^3$)
TA-05-01	0	Q3 ₂	2.44615	0.37639	Q3 ₂	42.57962	76.39908	1906	13.8 $\pm$ 5.2	85.6 $\pm$ 7.6
TA-05-03	-170		0.65925	0.10496	Q2 ₂	42.58058	76.39449	1937	23.1 $\pm$ 7.3	126.4 $\pm$ 10.8
TA-05-04	-100		1.03905	0.51449	Q2 ₁	42.59036	76.39064	2003	17.8 $\pm$ 4.4	139.9 $\pm$ 6.5
TA-05-05	-50		1.37808	0.21112	modern	42.56818	76.40527	1829		
TA-05-06	-25		1.70586	0.32937	stream					
TA-05-07	-10		2.34742	0.35041						
TA-05-02	0	Q2 ₂	3.96822	0.68267						
TA-05-09	-170		1.03869	0.21742						
TA-05-10	-100		1.64984	0.23115						
TA-05-11	-50		2.12051	0.69755						
TA-05-12	-25		2.90166	0.6718						
TA-05-13	-10		3.15091	1.10335						
TA-05-08	0	Q2 ₁	4.08747	0.50764						
TA-05-14	-170		1.10524	0.26645						
TA-05-15	-100		1.4174	0.30206						
TA-05-16	-50		2.44587	0.36077						
TA-05-17	-25		3.13277	0.49242						
TA-05-18	-10		3.80088	0.62007						
TA-05-19	0	modern	0.631482	0.14444						
		stream								

^a samples processed at the University of Minnesota with analyses performed at

Lawrence Livermore National Laboratory accelerator mass spectrometer

^b values calculated using equations (2) and (3) described in the text

^c errors reported with 95% confidence

5. Late Quaternary deformation rates

Late Quaternary deformation expressed as folded and faulted fluvial terraces was studied to determine styles and rates of deformation (Table 3 and Fig. 13). Fault scarps in preserved terrace surfaces were field mapped on aerial photography and surveyed with a differential GPS to determine offset and fault geometry. Lateral offsets of terrace edges and ephemeral stream channels were measured to determine strike-slip displacement, where present. Amount of slip along thrust faults was calculated from scarp profiles using the methodology of Thompson et al. (2002, Appendix A) taking into account uncertainty in the dip of hanging wall and footwall terrace surfaces and backlimb shortening, where applicable. Fault dip was measured from topographic exposure of scarp faces, estimated from similarly deforming areas with known fault dip, or based on cross-section interpretations. Slip rates were calculated using ^{10}Be ages for offset surfaces. Monte Carlo simulations with 10,000 calculations give slip rates with a 95% confidence interval.

Fault slip rates are highest in the western Kungey Range where sinistral motion along the Toguz-Bulak fault feeds into a series of east-west trending faults and folds along the Toru-Aygir river valley (Fig. 13). An overall gradient in slip rates, decreasing from west to east, is observed along the range front. Along the Toguz-Bulak fault, sinistral slip rates decrease from 1.4 ± 0.2 mm/yr to 1.1 ± 0.2 mm/yr across the intersection with the Balikche fault. Total north-south shortening rate along parallel east-west trending faults and folds in the Toru-Aygir river valley is approximately 1 mm/yr. Slip rates along the Ak-Teke fault diminish slightly along strike from west to east from ~ 0.4 mm/yr to <0.3 mm/yr. Late

Figure 13. Summary of late Quaternary fault slip rates for the northern Tian Shan. Faults where detailed studies were made are noted in bold, slip rates are presented in mm/yr with a 95% confidence interval. Slip rate data is presented in Table 3.

Table 3: Slip rates and fault data from the Kungey and Zailiysky Ranges.

Fault	Location	Fault dip	Surface ¹	Offset (m)	Slip rate (mm/yr) ²
Toguz-Bulak ^a	West of Balikche	n/a	Q3 ₂	125 ± 8 ^a	1.5 ± 0.2 ^a
	North of Balikche	n/a	Q3 ₂	95 ± 8 ^a	1.1 ± 0.2 ^a
Ak-Teke	Toru-Aygir river valley	30 ± 2°	Q3 ₂	32 ± 3	0.37 ± 0.04
			Q2 ₂	48 ± 4	0.38 ± 0.04
	East of Toru-Aygir	30 ± 5°	Q3 ₂	21 ± 3	0.24 ± 0.04
Un-named	Jai-Lo syncline	11 ± 2°	Q3 ₂	30 ± 6	0.35 ± 0.07
Cholpon-Bosteri	North of Cholpon-Ata	55 ± 10°	Q3 ₂	16 ± 2	0.19 ± 0.03
	North of Korumdu	30 ± 5°	Q3 ₂	6 ± 2	0.07 ± 0.02
Un-named northern	Chilik	45 ± 10°	Q2*	72 ± 30	0.8 ± 0.5
Un-named southern	Chilik	30 ± 10°	Q2*	40 ± 20	0.43 ^{+1.0/-0.3}

¹ Ages: Q3₂: 85.6 ± 7.6 ka; Q2₂: 126.4 ± 10.8 ka

² Errors reported with 95% confidence interval

^a Sinistral strike-slip displacement

* Assumed age of Q2: 100 ± 30 ka to encompass Q2 ages of Thompson et al. (2002), Bowman et al. (2004), and this study

Quaternary deformation rates continue to decrease to the east, where dip-slip reverse motion along the Cholpon-Bosteri fault diminishes from ~ 0.25 mm/yr to <0.1 mm/yr (Fig. 13).

Slip rates were estimated along two thrust faults in the eastern Zailiskey Range front near Chilik (Fig. 13). Offset was measured from deformed Q2 surfaces. We assume an age of 100 ± 30 ka for this terrace, which encompasses ages for Q2 elsewhere in the Tian Shan from this study, Thompson et al. (2002), and Bowman et al. (2004). For the southern fault we find a rate of 0.43 ± 0.3 mm/yr. The slip rate of the northern fault is about twice this amount, 0.8 ± 0.5 mm/yr.

6. Discussion

Within the context of the northward propagation of the Tian Shan, the growth history of the Kungey and Zailiskey Ranges is discussed in relation to the central, inherited Kemin-Chilik fault. By interpreting the structural evolution of these ranges in map-view and in cross-section, it is inferred that these have grown as a mega-flower structure, with the Kemin-Chilik fault at its core. This pattern of active shortening is shown to be incompatible with a transform fault model for the Kemin-Chilik fault. Rather, the pattern of faulting is shown to be consistent with the mechanical model of oblique fault reactivation of Bowman et al. (2003). Because inherited strike-slip faults are common within the basement-cored uplifts of the Tian Shan, the generation of high-angle reverse faults via reactivation of nearby, obliquely oriented, inherited faults may be a general feature of the orogen (Burtman, 1975; Sengor et al., 1993; Delvaux et al., 1999; Burtman et al., 1996; Mikolaichuk et al., 2000; Abdrakhmatov et al., 2001; Buslov et al., 2003).

6.1 Stratigraphic evidence for uplift history

Preceding uplift, a foreland flexural basin occupied the region of the Kungey and Zailiskey Ranges. Facies of the Shamsi formation in the Chu Basin (Bullen et al., 2001), western Kungey Range, and Terskey Range (Thomas et al., 1993; Bazhenov et al., 1994) record subsidence of the foreland basin and burial of the northern Tian Shan prior to 7 Ma (Bullen et al., 2001, 2003; Sobel et al., 2006). Absence of the Shamsi formation in present-day eastern Kungey Range stratigraphy defines the lateral extent of this flexural basin.

Expansion of this flexural basin is recorded by the Chu (Terskey) Fm., present in outcrops along both the western and eastern Kungey Range front.

Inception of uplift of the Kungey Range and initial closure of the Issyk-Kul basin occurred during deposition of the Chu Fm., ostensibly between 7 and 4 Ma. This transition is indicated by a reversal of paleocurrents and a change in clast lithology. Paleocurrent indicators in the Chu (Terskey) Fm. record a south-to-north transport of distally derived sediments. This transitions upsection to locally-derived *grus* of the Chu (Kungey) Fm. Production of *grus* via erosion of exposed bedrock typically occurs at rates of <0.01 mm/yr (Small et al., 1997), thus it is interpreted that the thick section (400-600 m) of *grus* and thin gravel conglomerates records initial slow uplift and erosion of the Kungey Range.

Upward-coarsening of the Chu (Kungey) Fm. into the conglomerates of the Sharpyldak Fm. signifies increasing relief of the Kungey Range source area. Within the Sharpyldak Fm., the absence of observed growth strata (e.g. fanning dips) indicates deposition of these conglomerates prior to the inception of folding along the present southern margin of the growing Kungey Range. Stratigraphy present along the Zailiskey Range front displays similar attributes as the Kungey Range stratigraphy. The Zailiskey Chu Fm. equivalent also exhibits a coarsening-upward sequence into equivalent Sharpyldak conglomerates. Likewise, these locally derived conglomerates suggest a south-to-north growth of the Zailiskey Range from the Kemin-Chilik fault into the Kazakh Platform. The timing of influx of coarse detritus into these flanking basins is poorly understood, as the depositional age of the Sharpyldak Fm. is unlikely to be the same as in the better-studied Chu basin section of Bullen et al. (2001). The best estimate for the age of onset of significant

uplift of the Kungey and Zailiskey Ranges is sometime after the Shamsi-Chu transition, circa 7 Ma (Abdrakhmatov et al., 2001; Bullen et al., 2001).

6.2 Structural evolution

Subsurface geometries of faults responsible for the uplift of the Kungey and Zailiskey Ranges are inferred from structural measurements of Neogene stratigraphy and exposures of the deformed unconformity surface. The Kungey Range front and portions of the Zailiskey Range front are dominated by uniformly south- and north-dipping spatially extensive panels of the exhumed unconformity surface. While there are numerous ways to produce such a dip panel (e.g. Suppe, 1983; Erslev, 1986; Johnston and Yin, 2001), the subsurface fault geometries of the Kungey and Zailiskey Ranges must account for a steeply dipping, active fault at the core of the range (Tapponnier and Molnar, 1979; Tibaldi et al., 1997; Molnar and Ghose, 2000; Delvaux et al., 1999, 2001; Crosby et al., 2005, 2007). Rough seismicity of the northern Tian Shan shows events approximating a steeply-dipping feature extending to ~20 km depth in the region of the Kemin-Chilik Fault (Zubovich et al., 2001).

Reverse faults responsible for growth of the Kungey and Zailiskey Ranges have roughly linear map traces, especially where exposed high within the ranges, consistent with relatively steep fault dips near the surface. Only the Ak-Teke fault, which appears to detach the Neogene section from Paleozoic basement, shows clear evidence of a gentle (~30°) dip where it breaks the surface.

Based on these observations of the deformed unconformity surface and steep fault dips near the surface, the Kungey and Zailiskey Ranges are described using a positive flower structure fault geometry (Woodcock and Fischer, 1986) (Fig. 14) with curvilinear reverse faults that steepen at depth (e.g. Erslev, 1986) to root into the Kemin-Chilik fault. To

investigate the overall structure of the Kungey Range, balanced cross-sections through the Toru-Aygir River valley (Fig. 15) and Cholpon-Ata syncline (Fig. 17) were constructed south of the Kemin-Chilik fault. Though these structural cross-sections are not unique, through presentation of these sections and their key structural observations insights are gained into overall range structure and its relation to the inherited strike-slip fault at the range core.

Figure 14. Schematic block diagram of a positive flower structure with reverse faults steepening at depth (After Erslev, 1986; Woodcock and Fischer, 1986) rooting into a central strike-slip fault. This geometry allows for simultaneous motion on all members of the fault network.

6.2.1 Western Kungey Range

A cross-section through the western Kungey Range was constructed along the Toru-Aygir river valley and north through the range (Fig. 15). Steeply-dipping reverse faults within the range proximal to the Kemin-Chilik fault are responsible for basement uplift but account for only minor amounts (<1 km) of shortening. To the south, the unconformity surface is preserved on both limbs of the Jai-lo syncline, where shortening is being accommodated via active faulting involving both Neogene sedimentary units and Paleozoic bedrock.

Figure 15. (A) Balanced cross-section through the Toru-Aygir River valley and Kungey Range along X-X', shown in the inset and Fig. 4. Major structures are labeled, no vertical exaggeration. Detail of the Ak-Teke fault and tri-shear model is shown in Fig. 16. Inset map shows the location of the cross-section, star indicates the approximate AFT sample location from De Grave et al. (2007) where no reset ages were found. (B) Partial restoration of the section, showing block rotation and minor shape changes. (C) Fully restored section.

Deformation involving Paleozoic basement ceases south of the Kyzyl-Kultor fault, with shortening occurring only in overlying Neogene strata. The Ak-Teke anticline is asymmetric with a broad, flat crest, well documented structural geometry, and overturned bedding on its southern limb. The dip of the north limb of this fold matches the dip of the Ak-Teke fault measured from scarp exposure where the fault displaces multiple generations of fluvial terraces. This coincidence of fault and backlimb dip indicates that the fault soles into a horizontal detachment, which is interpreted to be the gypsum-rich Kokturpak Fm. Because locally overturned beds were observed surrounding the propagating tip of the fault, a trishear model (Erslev, 1991; Allmendinger, 1998) was applied to analyze the geometry of the forelimb of the Ak-Teke fold and fault at depth (Fig. 16). This model results in ~550 m of slip and, because the fault soles into a horizontal décollement, an equivalent amount of shortening across the structure.

Shortening and uplift estimates across the Western Kungey Range can be calculated from restoring the cross-section using the unconformity surface as a deformation marker. Shortening and uplift estimates have been made relative to the present position of the unconformity in the footwall of the Ak-Teke fault at ~500m elevation (Fig. 15). Area-balancing was used to model the minor changes in shape of basement blocks required to accommodate faulting at depth. Uplift calculated for the core of the range adjacent to the Kemin-Chilik fault is a minimum because the unconformity surface is not preserved at the

Figure 16. Detailed cross-section of the Ak-Teke anticline constructed using a tri-shear model (Erslev, 1991; Allmendinger, 1998) allowing for the gypsum-rich Kokturpak Fm. (Tk) to act as a basal decollement. No vertical exaggeration.

range crest. Restoration of the cross-section and including folding across the Ak-Teke anticline shows that 5 ± 1 km of shortening has been accommodated across the western Kungey Range. Uplift of the range is highest closest to the Kemin-Chilik Fault, where >5 km of rock uplift relative to the undeformed unconformity surface beneath the Ak-Teke anticline has taken place. This amount decreases to the south, where the basement-cored Kyzyl-Kultor hills have only experienced ~ 2 km of rock uplift.

6.2.2 Central Kungey Range

A second cross-section was constructed through the central Kungey Range east of the town of Cholpon-Ata (Fig. 17). The cross-section was balanced using the same techniques applied to the western Kungey Range. Fault geometries are estimated from well-exposed Neogene strata and exposures of tilted unconformity surface both at the range front and high within the range. With the exception of the southern limb of the Cholpon-Ata syncline, the exhumed unconformity surface dips south $25-30^\circ$, indicating a major concave-down fault at

Figure 17. (A) Balanced cross-section through the central Kungey Range, line Y-Y' noted in the inset and Fig. 8. Major structures are labeled, no vertical exaggeration. Inset map shows the location of Y-Y' and AFT sample locations from De Grave et al. (2007). (B) Fully restored section, no vertical exaggeration. (C) Detailed cross-section through the Cholpon-Ata syncline. No vertical exaggeration.

depth (Erslev, 1986). Rooting into this fault is a set of north-vergent backthrusts bounding the northern limb of the Cholpon-Ata syncline.

The unconformity surface is again used as a deformation marker to restore the cross-section through the Central Kungey Range. Because it is not directly possible to measure the position of the unconformity surface in the footwall of the central Kungey Range, the same position as the footwall unconformity surface in the western Kungey Range is assumed at ~500 m elevation. Restoration of the cross-section indicates 4 ± 1 km of shortening across the Central Kungey Range. Although this amount is less than the shortening in the Western Kungey Range, higher topographic elevations indicate that a greater amount of uplift is likely to have taken place. From restoration of the cross-section ~6 km of uplift is estimated relative to the inferred position of the unconformity surface at the northern margin of the Issyk-Kul basin. Fission track studies of the Kungey Range (De Grave et al., 2007) (Figure 17) show an absence of reset ages between the western and central Kungey cross-sections. Assuming a closure temperature of 110°C for apatite fission tracks and a geotherm of 25-30°C/km (Sobel et al., 2006; De Grave et al., 2007), a maximum of ~4 km of incision into the unconformity surface is allowed. This places an upper limit on the amount of rock uplift at the range crest.

6.2.3 Range growth

The Kemin-Chilik fault is one of many inherited structures that play a role in the growth of the Tian Shan (e.g. De Grave et al., 2007). Inheritance of the Kemin-Chilik fault is

demonstrated by offset of Paleozoic basement terranes (Delvaux et al, 1999). Minor late Cenozoic motion is of the same sense as these Paleozoic offsets, and thus does not by itself accomplish range uplift. Growth of the northern Tian Shan has instead taken place via a newly formed reverse fault network that surrounds the inherited strike-slip fault. Evidence that these faults are newly formed includes basement offsets that are consistent with late Quaternary deformation, and no juxtaposition of contrasting Paleozoic terranes across members of this fault network.

The cross-sections (Fig. 15 and Fig. 17) demonstrate the pattern of structural growth characteristic of the Kungey Range. Using the pre-Cenozoic unconformity surface as a deformation marker, there is a north-to-south decrease in rock uplift developed on reverse faults within the range. Steeply-dipping reverse faults in the core of the range display the greatest amount of slip, which corresponds to the regions of maximum topography and little preservation of the unconformity surface in the landscape. Faults at the southern margin of the Kungey Range display smaller amounts of slip, though the majority of horizontal shortening has taken place along these faults. This pattern of greater uplift in the range core and shortening along the margin is most consistent with a network of concave-down faults rooting into a steeply-dipping shear zone coincident with the Kemin-Chilik fault at depth.

Comparison of net structural growth to the distribution of active structures illustrates a complex, but overall southward-stepping pattern of deformation in the western Kungey Range. The most denuded portions of the range lie in its core, adjacent to the Kemin-Chilik fault. These areas are likely also the earliest-formed parts of the range, providing granitic sediments that make up the Kungey member of the Chu Fm. in exposures uplifted along the range margin. The Kyzyl-Kultor Fault that bounds the southern limb of the Jai-Lo syncline

does not deform any member of the preserved terrace chronosequence. This indicates that the fault has not been active in the past ~140 ka. In this area deformation has largely stepped southward into the Issyk-Kul basin, where the Ak-Teke fault and Tekren anticline deform Neogene strata and late Quaternary alluvial surfaces. However, some active deformation also occurs in the Jai-Lo syncline, showing that some active out-of-sequence deformation accommodates overall growth of the Kungey Range.

Deformation in the central Kungey Range displays a similar pattern of north-to-south propagation, although here active faults are also recognized within the range. Stratigraphic evidence shows that prior to deposition of the Sharpyldak Fm. deformation occurred proximal to the Kemin-Chilik fault. Later deformation has stepped southward to the range front. Active faults today include both the Kemin-Chilik fault and Chon-Aksu faults within the range (Delvaux et al., 2001; Arrowsmith et al., 2004; Crosby et al., 2005, 2007), and the range-bounding Cholpon-Bosteri fault.

6.3 Comparison of long-term and late Quaternary deformation

Comparison of late Quaternary deformation rates to net shortening further illustrates the pattern of uplift that formed the Kungey and Zailiskey Ranges. Using structural shortening estimates and the stratigraphic interpretation that growth initiated between 7 and 4 Ma gives long-term shortening rates between 0.5 and 1.4 mm/yr for the western Kungey Range and 0.4 to 1.2 mm/yr in the central Kungey Range. Summing north-south late Quaternary shortening rates along the Toru-Aygir river valley in the western Kungey Range and allowing for minor shortening on additional structures in the Jai-Lo syncline adds to modern shortening of $\sim 1.2 \pm 0.1$ mm/yr, similar to the long-term rate. Since not all faults in the western Kungey Range are currently active and the shortening rate appears to have

remained approximately constant over time, shortening in the western Kungey Range is interpreted to be partitioned on to separate sets of faults with activity that varies over ~100 ka timescales. In contrast to the western Kungey Range, long-term and late Quaternary shortening rates may not agree in the central Kungey Range. Although modern shortening at the central Kungey Range front is $\sim 0.3 \pm 0.1$ mm/yr, activity along the Chon-Aksu fault (Delvaux et al., 1999) could account for the discrepancy between modern and long-term shortening rates.

Opposing gradients in deformation rate are observed along the Kungey and Zailiskey range fronts. Shortening rates in the Kungey Range are highest in the west and decrease to essentially zero in the east. Though thick loess cover obscures much of the Quaternary record along the central and eastern Zailiskey Range front, deformation rates inferred from deformed terrace markers and exposures of Neogene strata appear highest in the eastern half of the range front.

6.4 The role of strike-slip faulting in shortening of the northern Tian Shan

Intracontinental strike-slip faults in convergent orogens have generally been thought to act as transform faults, shunting deformation from one part of the orogen to another (e.g. Molnar and Tapponnier, 1975). Major strike-slip faults bounding the Tibetan plateau, such as the Altyn-Tagh and Karakorum faults have been held as type examples, though fierce debate surrounds this interpretation (Fig. 1) (e.g. Lacassin et al., 2004; Chevalier et al., 2005; Cowgill, 2007). The pattern of shortening in the Kungey and Zailiskey Ranges is geometrically opposite of what would be expected for the absorption of slip at the ends of a sinistral transform fault (Fig. 18a). Instead, shortening is absorbed via east-west striking reverse faults located along and stepping outward from the axial strike-slip fault. Thus,

rather than acting as a transform, it appears that the Kemin-Chilik fault acts as a central member of a dominantly north-south contractional system. Because the Kemin-Chilik fault remains embedded within the Kungey and Zailiskey Ranges, what sinistral motion does take place along the fault must be absorbed somehow along its length. We suggest that instead of shortening at the fault tips, sinistral motion is absorbed by rotation and oroclinal folding of the fault trace, commensurate with gradients in shortening along the range margins (Fig. 18b).

Figure 18. (A) Schematic diagram showing expected faulting at the tips of a sinistral strike-slip fault acting as a transform. Material is moved along the fault into fold and thrust belts that emanate outward from the fault tips. (B) Observed fault geometry of the northern Tian Shan. Shortening is accomplished along roughly east-west striking reverse faults that are sub-parallel to the Kemin-Chilik fault and located on the opposite side than is expected for a transform fault. Sinistral strike-slip deformation plays a larger role in the western Kungey Range where the Kemin-Chilik fault is oriented $\sim 60^\circ$ to north-south convergence. At $\sim 76^\circ 15'$ E the Kemin-Chilik fault bends to become almost orthogonal to overall convergence and reverse motion rather than strike-slip motion plays a larger role in range growth.

The pattern of reverse faulting surrounding an inherited strike-slip fault we observe in the Kungey and Zailiskey Ranges appears elsewhere in BITB with embedded strike-slip faults. For example, numerous strike-slip faults embedded within the Zagros Plateau absorb

shortening via networks of reverse faults that have developed surrounding the axial strike-slip fault (Allen et al., 2006). Another example is the Kunlun fault, where a slip rate study by Kirby et al. (2007) showed that slip is absorbed gradually along strike through formation of shortening structures.

6.5 Implications for the development of high-angle basement-involved reverse faults

The reactivation of pre-existing, steeply dipping faults oriented oblique to the shortening direction could be a common mechanism for the production of new high-angle reverse faults in basement-involved thrust belts (BITB). A pre-existing, high-angle fault zone in the crust may preferentially re-activate despite non-optimal orientation to overall compression (Webb and Johnson, 2006). Following initial re-activation, a network of high-angle reverse faults rooting into the central steeply dipping fault may develop to accommodate continued shortening. This geometry is commonly observed in transpressional regimes where restraining bends along major strike-slip faults produce steeply dipping reverse fault networks (e.g. Cunningham et al., 1996; Ding et al., 2004; Vassallo et al., 2007). However, this geometry has not been proposed in regions where lateral motion along the strike-slip fault only plays a minor role. Within the framework of the northern Tian Shan, sinistral motion along the Kemin-Chilik fault has not played a major role in the shortening of the Kungey and Zailiskey Ranges. What little late Cenozoic slip along the Kemin-Chilik fault that has occurred is absorbed along its length. The more important role of the Kemin-Chilik fault zone appears to be that it acts as a nucleation point for the numerous high-angle reverse faults responsible for range growth and shortening.

The pattern of steeply dipping reverse faults emanating outward from a central, inherited strike-slip fault fits very well with the predictions of a mechanical model of slip partitioning (Bowman et al., 2003). Here, the obliquely-oriented Kemin-Chilik fault accommodates transpression at depth, with deformation propagating upwards as a partitioned system in response to convergence. Models developed by Bowman et al. (2003) use a rectangular, oblique elastic dislocation (Okada, 1985) along a steeply-dipping fault at depth. Their model predicts that for oblique motion at depth, deformation will propagate upwards as a partitioned system of strike-slip and oblique-slip faults. Because fault geometries and slip are better understood in the Kungey Range than the Zailiskey Range, the model of Bowman et al. (2003) is compared only to faulting associated with uplift of the Kungey Range. A combination of models with modestly varying ratios of strike-slip to reverse motion fits well with the observed faulting of the western and central Kungey Range (Fig. 19). For the western part of the range, greater strike-slip than reverse motion is inferred where the Kemin-Chilik is oriented $\sim 60^\circ$ oblique to north-south compression. This model accurately predicts sinistral motion along both the Kemin-Chilik and Toguz-Bulak faults. Where the Kemin-Chilik fault is oriented $>60^\circ$ from the north-south compression direction, the reverse component of the modeled slip is greater than the strike-slip component. This model predicts the observed strike and dip of reverse faults within the range and along the range front. The model also successfully predicts the overall cross-section geometry of these faults (Fig. 19). Faults high in the range are steeply dipping, while those further away from the Kemin-Chilik fault dip less and accommodate more shortening. The entire fault network roots concave-downward into a central shear zone co-located with the Kemin-Chilik fault.

Figure 19. (A) Slip partitioning model (using models from Bowman et al. (2003)) for the western and central Kungey Range compared to observed fault geometry. For this model, the Kungey Range was divided into two segments with varying reverse to strike-slip motion ratios to find a best fit. Segment 1 has a 0.6:1.0 reverse to strike-slip ratio, and segment 2 uses a 1.0 : 0.6 reverse to strike-slip ratio. (B) Representations of failure planes using the notation of Bowman et al. (2003). In map view, solid lines indicate intersections of predicted fault planes with the surface. For reverse motion, blue lines note the predicted fault strike. Blue and red dots indicate hanging walls for south- and north-verging faulting, respectively. Red and blue lines for strike-slip motion represent predicted fault traces, with red indicating sinistral motion and blue dextral motion. In cross-section view, solid lines indicate intersections of predicted fault planes with the vertical section line. Strike-slip motion is indicated by a single line with a red dot indicating sinistral motion into the plane of section. Reverse motion is denoted by red and blue lines showing predicted fault orientations. (C) Cross-section slip partitioning model along cross-section line X-X', shown in Fig. 14. For this comparison, a 1.0 : 0.6 reverse to strike-slip ratio model was used with a 75° dipping fault at depth, the tip of which is co-located with the Kemin-Chilik fault at 20km depth. The re-activated Kemin-Chilik fault is colored orange in the figure.

7. Conclusions

The development of high-angle reverse faults commonly found in basement-cored uplifts poses problems, as these faults violate mechanical predictions for the initiation of thrust or reverse faults, and absorbing shortening on high-angle structures is kinematically unfavorable (Anderson, 1959; Sibson, 1985). Reactivation of pre-existing strike-slip faults and the initiation of new faults in the surrounding crust may provide an explanation for the existence of these high-angle reverse faults. Inherited strike-slip faults can act as nucleation points, where oblique deformation at depth can propagate upwards as a partitioned system of reverse and obliquely-slipping faults (Molnar, 1992; Bowman et al., 2003). This network of neoformed faults can be described as a positive mega-flower structure with concave-down faults emanating from a central shear zone.

The Kungey and Zailiskey Ranges of the northern Tian Shan are dominated by curvilinear reverse and oblique faults whose dips increase at depth to root into the central Kemin-Chilik fault zone. Mechanical models of slip partitioning (Bowman et al., 2003) accurately predict the observed fault geometries at depth and on the surface. Growth of the ranges, deduced from structural and stratigraphic evidence, took place as these fault networks developed, propagating outward from the Kemin-Chilik fault. At present, the geometry of the northern Tian Shan can be described using a mega-flower structure, with active deformation in the core of the range and at its margins. Because many other ranges within the Tian Shan are cored by inherited strike-slip faults, this growth model may apply

elsewhere within the orogen, and provide an explanation for the origin of high-angle reverse faults in basement-involved uplifts.

Appendix A: Paleocurrent measurements

Easting ^a	Northing ^a	Unit ^b	transport azimuth*	Easting ^a	Northing ^a	Unit ^b	transport azimuth*
Toru-Aygir				Toru-Aygir			
615395	4716412	Tc(t)	353	615915	4715316	Tc(t)	334
615411	4716404	Tc(t)	323	615935	4715325	Tc(t)	309
615382	4716410	Tc(t)	332	616046	4715215	Tc(t)	310
615335	4716359	Tc(t)	18	616373	4714948	Tc(t)	13
615354	4716351	Tc(t)	22	616415	4714899	Tc(t)	25
615340	4716341	Tc(t)	342	616327	4714853	Tc(t)	348
615322	4716339	Tc(t)	350	616281	4714663	Tc(t)	350
615315	4716340	Tc(t)	35	616294	4714065	Tc(t)	13
615268	4716320	Tc(t)	14	616246	4714135	Tc(t)	22
615263	4716309	Tc(t)	5	616207	4714228	Tc(t)	354
615263	4716280	Tc(t)	25	616082	4714154	Tc(t)	25
615304	4716259	Tc(t)	351	616060	4714166	Tc(t)	16
615320	4716250	Tc(t)	4	615969	4714254	Tc(t)	355
615323	4716235	Tc(t)	306	615995	4714193	Tc(t)	351
615357	4716193	Tc(t)	325	615929	4714156	Tc(t)	248
615406	4716156	Tc(t)	336	615882	4714128	Tc(t)	334
615394	4716149	Tc(t)	5	615906	4714115	Tc(t)	36
615404	4716124	Tc(t)	15	615847	4714160	Tc(t)	6
615906	4716033	Tc(t)	12	615826	4714177	Tc(t)	360
615876	4715992	Tc(t)	23	615879	4714195	Tc(t)	2
615868	4715985	Tc(t)	210	615923	4714232	Tc(t)	348
615750	4715997	Tc(t)	9	615845	4715387	Tc(t)	215
615733	4715969	Tc(t)	317	615846	4715387	Tc(t)	313
615728	4715948	Tc(t)	325	Cholpon-Ata			
615623	4715600	Tc(t)	330	676391	4726736	Tc(t)	340
615631	4715601	Tc(t)	15	676382	4726740	Tc(t)	327
615632	4715562	Tc(t)	355	676383	4726737	Tc(t)	6
615656	4715538	Tc(t)	320	707144	4737788	Tc(t)	281
615634	4715474	Tc(t)	346				

^a Coordinate system: WGS 1984 UTM zone 43 N

^b Units: Tc(t) (Chu Fm., Terskey); Tc(k) (Chu Fm., Kungey)

* Measurements taken from dipping beds and then rotated to flat using an equal-angle stereographic projection

Appendix A (continued)

Easting ^a	Northing ^a	Unit ^b	transport azimuth*	Easting ^a	Northing ^a	Unit ^b	transport azimuth*
Cholpon-Ata				Cholpon-Ata			
691767	4730155	Tc(t)	346	673221	4725575	Tc(k)	192
691767	4730156	Tc(t)	341	673207	4725632	Tc(k)	160
691767	4730139	Tc(t)	5	673196	4725665	Tc(k)	168
691765	4730134	Tc(t)	1	674281	4724910	Tc(k)	206
691765	4730127	Tc(t)	13	674309	4724934	Tc(k)	163
691683	4730266	Tc(t)	356	674408	4725023	Tc(k)	200
691514	4730413	Tc(t)	355	674442	4725060	Tc(k)	218
691512	4730404	Tc(t)	17	674457	4725075	Tc(k)	224
691483	4730457	Tc(t)	340	674460	4725071	Tc(k)	224
691479	4730462	Tc(t)	310	674422	4725102	Tc(k)	210
691422	4730505	Tc(t)	20	674432	4725117	Tc(k)	214
691483	4730655	Tc(t)	348	674429	4725117	Tc(k)	239
691488	4730660	Tc(t)	352	674432	4725116	Tc(k)	210
691483	4730668	Tc(t)	355	674464	4725133	Tc(k)	232
691490	4730653	Tc(t)	320	674445	4725148	Tc(k)	193
691597	4730621	Tc(t)	300	674447	4725155	Tc(k)	236
691670	4730550	Tc(t)	345	674386	4725361	Tc(k)	200
691697	4730562	Tc(t)	19	674391	4725432	Tc(k)	186
691691	4730527	Tc(t)	25	674402	4725455	Tc(k)	168
673541	4725529	Tc(k)	199	674396	4725454	Tc(k)	186
673517	4725567	Tc(k)	161	674406	4725478	Tc(k)	168
673512	4725591	Tc(k)	191	674420	4725523	Tc(k)	222
673499	4725626	Tc(k)	164	674415	4725529	Tc(k)	191
673457	4725671	Tc(k)	127	674234	4725949	Tc(k)	239
673460	4725673	Tc(k)	174	672958	4725249	Tc(k)	200
673467	4725685	Tc(k)	167	673234	4725568	Tc(k)	201
673333	4725766	Tc(k)	194	691770	4730166	Tc(t)	350
673323	4725766	Tc(k)	175	691771	4730159	Tc(t)	6
673282	4725721	Tc(k)	207	691778	4730170	Tc(t)	12
673235	4725562	Tc(k)	170	691775	4730167	Tc(t)	315

^a Coordinate system: WGS 1984 UTM zone 43 N

^b Units: Tc(t) (Chu Fm., Terskey); Tc(k) (Chu Fm., Kungey)

* Measurements taken from dipping beds and then rotated to flat using an equal-angle stereographic projection

Appendix B: Structural measurements from the Kungey Range front

Easting ^a	Northing ^a	Elevation	Unit ^b	Azimuth ^c	Dip ^c
Boom Gorge					
568420	4720330	1473	Tk	315	25
568229	4720418	1478	Tk	300	18
568305	4720150	1468	Ts	136	22
567838	4720079	1566	Ts	255	40
567790	4720003	1575	Ts	230	75
567710	4719993	1560	Ts	225	22
567700	4720188	1625	Ts	210	25
567517	4719860	1520	Tk	244	31
567540	4719913	1541	Ts	261	32
567738	4720079	1523	Ts	250	18
567430	4720224	1568	Ts	101	25
567450	4720414	1581	Ts	315	10
567366	4720543	1591	Ts	76	27
567376	4720574	1603	Ts	91	43
567365	4720595	1621	Ts	82	56
567247	4720554	1604	Ts	80	65
567500	4720625	1629	Tk	88	90
567167	4719908	1534	Ts	250	35
566575	4720000	1566	Ts	90	68
566678	4719997	1560	Ts	260	68
566750	4719930	1558	Ts	105	46
566012	4719540		Ts	94	82*
Kok-Moynok basin					
562927	4701619		Tc(t)	90	62
562809	4702000		Tc(t)	91	88
563089	4701916		Tc(t)	100	33
562759	4702162		Tk	115	80
563067	4702325		Ts	91	26
563386	4702286		Tk	120	22
Kok-Moynok basin					
564473	4701910		Ts	98	46
564748	4701412		Tc(t)	88	37
565432	4701299		QTs	60	28
565207	4701075		QTs	88	31
564983	4700773		QTs	90	20
564978	4702398		Ts	118	21
565174	4702022		Tk	70	28
565628	4702230		Ts	101	49
566384	4701821		Ts	95	59
567113	4701899		Tk	60	50
567578	4702045		Tk	55	57
567376	4703468		Ts	285	33
567600	4704045		Tc(t)	145	12
569000	4703457		Tc(t)	120	37
569287	4703356		Tc(t)	117	34
569304	4703726		Tc(t)	351	4
569522	4703563		Tc(t)	11	7
569954	4701350		Tc(t)	35	67
569915	4703636		Tc(t)	90	11
569147	4704292		Ts	118	12
568166	4704701		Tc(t)	350	8
566311	4704454		Tk	9	55
566631	4704505		Ts	10	15
566776	4704662		Tc(t)	45	20
566933	4704886		Ts	95	12
566054	4704959		Tk	15	35
566020	4705144		Tk	5	37
566300	4705289		Ts	72	22
566222	4705900		Tk	80	20

^a Coordinate system: WGS 1984 UTM zone 43 N

^b Units: Tk (Kokturpak Fm.); Ts (Shamsi Fm.); Tc(t) (Chu Fm., Terskey); Tc(k) (Chu Fm., Kungey); QTs (Sharpyldak Fm.); Q₂, Q₃ (terrace gravels); Ql (lake beds)

^c All measurements noted using right hand rule

* Overturned bedding

Appendix B (continued)

Easting ^a	Northing ^a	Elevation	Unit ^b	Azimuth ^c	Dip ^c
Kok-Moynok basin					
567774	4704275		Tc(t)	150	5
567925	4704432		Tc(t)	300	17
568004	4704947		Tc(t)	160	9
567864	4705541		Ts	115	11
567813	4705967		Ts	8	17
567662	4706147		Ts	20	15
566681	4706096		Ts	319	35
566799	4706298		Ts	45	10
567006	4706287		Ts	130	12
567186	4706472		Ts	90	7
567281	4706606		Ts	18	16
567331	4706718		Ts	320	35
566564	4706970		Ts	278	42
567017	4707150		Tc(t)	325	16
566283	4707525		Ts	345	20
566642	4707632		Tc(t)	310	23
566435	4707957		Tc(t)	330	22
565874	4707850		Tk	27	38
566233	4708282		Ts	5	38
566592	4708141		Tc(t)	290	18
566227	4708562		Ts	348	60
566132	4708679		Ts	8	40
566065	4708943		Ts	352	49
566429	4708696		Tc(t)	35	15
566676	4709408		Ts	132	25
566586	4709806		Ts	151	21
566552	4710120		Ts	117	12
565247	4708786		Ts	16	10
564860	4709251		Ts	60	7
562988	4709935		Ts	215	22
Kok-Moynok basin					
563756	4711324		Ts	120	50
563969	4711050		Tk	355	15
570506	4706021		Ts	265	16
571060	4706267		Tk	182	24
573167	4706357		Tk	330	54
573526	4706217		Ts	178	16
572585	4703107		Ts	95	5
573599	4703622		Ts	152	17
571014	4703404		Ts	112	63
563487	4701641		QTs	92	59
563762	4701899		Ts	90	49
564148	4701596		Tc(t)	95	56
564300	4701361		QTs	94	55
564232	4701249		Tc(t)	100	48
567118	4705043		Ts	63	12
567281	4705104		Ts	12	35
567398	4705160		Tc(t)	310	25
567533	4705289		Tc(t)	28	21
567651	4704628		Tc(t)	165	5
563504	4701972		Ts	91	56
565572	4704931		Tk	330	45
563577	4710136		Tk	220	5
563263	4710187		Ts	238	22
562865	4710445		Ts	7	10
563414	4710461		Ts	235	20
563454	4711431		Ts	162	60
563779	4711027		Ts	135	18

^a Coordinate system: WGS 1984 UTM zone 43 N

^b Units: Tk (Kokturpak Fm.); Ts (Shamsi Fm.); Tc(t) (Chu Fm., Terskey); Tc(k) (Chu Fm., Kungey); QTs (Sharpyldak Fm.); Q_{2s}, Q_{3s} (terrace gravels); Ql (lake beds)

^c All measurements noted using right hand rule

* Overturned bedding

Appendix B (continued)

Easting ^a	Northing ^a	Elevation	Unit ^b	Azimuth ^c	Dip ^c
Kok-Moyonok basin					
574232	4703398		Ts	117	61
572478	4701644		Tc(t)	150	3
574574	4701106		Tc(t)	83	5
584527	4701361	1628	Ql	270	5
584769	4701250	1634	Ql	295	7
584710	4701338	1624	Q3 ₂	278	11
584661	4701324	1626	Q3 ₂	270	8
584650	4701186	1630	Q3 ₂	269	4
584574	4700939	1650	Q3 ₂	95	10
584724	4701334	1623	Ql	270	4
571223	4703868	1544	Ts	115	30
567626	4708959	1527	Ts	90	16
567837	4709027	1535	Ts	82	24
584613	4700940	1647	Q3 ₂	flat	
567505	4703580		Tc(t)	flat	
567443	4704124		Tc(t)	flat	
573487	4701257		Tc(t)	flat	
574255	4701129		Tc(t)	flat	
567426	4703165		Tk	121	83*
567141	4703406		Tk	112	87*
567715	4703664		Tk	135	90
565835	4704734		Tk	321	90
566059	4705547		Tk	173	90
Toru-Aygir River valley					
615417	4716710	1962	Tc(t)	85	5
615402	4716416	1993	Tc(t)	241	31
615319	4716316	1955	Tc(t)	263	22
615273	4716293	1939	Tc(t)	266	19
615284	4716147	1930	Tc(t)	269	18
Toru-Aygir River valley					
615523	4716184	1948	Tc(t)		15
615706	4715865	1935	Tc(t)	295	3
615665	4715207	1894	Tc(t)	85	2
616244	4714154	1892	Tc(t)	110	11
615927	4714204	1872	Tc(t)	50	15
615890	4714136	1874	Tc(t)	89	27
615888	4714127	1870	Tc(t)	86	24
615814	4714286	1870	Tc(t)	115	10
615892	4714320	1864	Tc(t)	65	3
616633	4714838	1936	Tc(t)	80	4
620127	4712620	1854	Tc(t)	75	8
616471	4713987	1888	Tc(t)	96	13
616069	4714161	1886	Tc(t)	76	15
615858	4714140	1881	Tc(t)	73	32
614355	4718169	1962	Q2 ₂	80	5
613631	4719539	2008	Tk	170	16
613038	4720078	2054	Ts	182	18
612466	4720565	2106	Ts	100	14
612088	4720782	2133	Ts	108	44
611883	4720793	2172	Tc(t)	145	42
611841	4720967	2140	Ts	165	47
611783	4721078	2142	Ts	136	43
611495	4721386	2170	Ts	159	41
610868	4723032	2302	Ts	281	6
615402	4716414	1996	Tc(t)	242	36
615393	4716337	1991	Tc(t)	275	31
615265	4716401	1953	Tc(t)	273	31
615305	4716314	1954	Tc(t)	285	19
615264	4716287	1940	Tc(t)	262	24
615306	4716249	1935	Tc(t)	273	21

^a Coordinate system: WGS 1984 UTM zone 43 N

^b Units: Tk (Kokturpak Fm.); Ts (Shamsi Fm.); Tc(t) (Chu Fm., Terskey); Tc(k) (Chu Fm., Kungey); QTs (Sharpyldak Fm.); Q2₂, Q3₂ (terrace gravels); Ql (lake beds)

^c All measurements noted using right hand rule

* Overturned bedding

Appendix B (continued)

Easting ^a	Northing ^a	Elevation	Unit ^b	Azimuth ^c	Dip ^c
Toru-Aygir River valley					
615364	4716175	1935	Tc(t)	262	9
615386	4716146	1943	Tc(t)	278	14
615412	4716182	1954	Tc(t)	276	15
615441	4716093	1945	Tc(t)	278	8
615627	4715906	1938	Tc(t)	286	5
615817	4715833	1960	Tc(t)	277	4
615367	4715696	1954	Tc(t)	281	3
615655	4715598	1970	Tc(t)	273	2
615631	4715544	1940	Tc(t)	280	1
615920	4714976	1891	Tc(t)	275	2
615618	4715364	1916	Tc(t)	flat	
615638	4715285	1909	Tc(t)	flat	
616284	4714670	1906	Tc(t)	84	1
616406	4714366	1903	Tc(t)	89	5
616514	4714048	1907	Tc(t)	102	24
616228	4714169	1899	Tc(t)	109	17
616200	4714259	1890	Tc(t)	94	9
615928	4714059	1888	Tc(t)	115	53
615639	4711167	1794	Q ₂	94	5
616629	4711158	1792	Q ₂	282	17
616622	4711107	1785	Q ₂	277	10
616614	4710999	1792	Q ₂	275	5
616613	4710978	1799	Q ₂	284	4
616604	4710938	1783	Q ₂	270	2
616614	4710903	1766	Q ₂	290	2
616607	4710881	1781	Q ₂	92	3
616608	4710867	1785	Q ₂	95	7
616627	4710810	1787	Q ₂	92	6
616617	4710786	1814	Q ₂	102	3
613879	4719946	2030	Tk	240	11
Toru-Aygir River valley					
614238	4720422	2043	Tk	275	7
614373	4720716	2068	Tk	108	75
614263	4721023	2084	Tk	245	11
613294	4722546	2209	Ts	272	2
613278	4722973	2168	Ts	flat	
613974	4724683	2246	Ts	85	3
615395	4716412	1997	Tc(t)	281	30
615411	4716404	2000	Tc(t)	267	27
615382	4716410	1998	Tc(t)	270	25
615335	4716359	1971	Tc(t)	259	35
615354	4716351	1959	Tc(t)	265	26
615340	4716341	1964	Tc(t)	261	22
615322	4716339	1962	Tc(t)	265	25
615315	4716340	1960	Tc(t)	285	31
615268	4716320	1951	Tc(t)	278	20
615263	4716309	1950	Tc(t)	260	20
615263	4716280	1940	Tc(t)	270	21
615304	4716259	1941	Tc(t)	260	17
615320	4716250	1946	Tc(t)	271	13
615323	4716235	1937	Tc(t)	270	16
615357	4716193	1949	Tc(t)	268	15
615406	4716156	1942	Tc(t)	276	13
615394	4716149	1945	Tc(t)	268	10
615404	4716124	1944	Tc(t)	270	11
615906	4716033	1963	Tc(t)	275	5
615876	4715992	1967	Tc(t)	265	11
615868	4715985	1970	Tc(t)	flat	
615750	4715997	1964	Tc(t)	flat	
615733	4715969	1952	Tc(t)	275	3
615728	4715948	1944	Tc(t)	274	5

^a Coordinate system: WGS 1984 UTM zone 43 N

^b Units: Tk (Kokturpak Fm.); Ts (Shamsi Fm.); Tc(t) (Chu Fm., Terskey); Tc(k) (Chu Fm., Kungey); QTs (Sharpyldak Fm.); Q₂; Q₃ (terrace gravels); Ql (lake beds)

^c All measurements noted using right hand rule

* Overturned bedding

Appendix B (continued)

Easting ^a	Northing ^a	Elevation	Unit ^b	Azimuth ^c	Dip ^c
Toru-Aygir River valley					
615623	4715600	1924	Tc(t)	275	2
615631	4715601	1927	Tc(t)	272	2
615632	4715562	1921	Tc(t)	flat	
615656	4715538	1912	Tc(t)	98	2
615634	4715474	1918	Tc(t)	flat	
615845	4715387	1934	Tc(t)	85	4
615846	4715387	1938	Tc(t)	85	4
615915	4715316	1931	Tc(t)	278	2
615935	4715325	1932	Tc(t)	84	2
616046	4715215	1931	Tc(t)	flat	
616373	4714948	1914	Tc(t)	283	12
616415	4714899	1921	Tc(t)	278	3
616327	4714853	1913	Tc(t)	flat	
616281	4714663	1916	Tc(t)	100	4
606506	4713921	1895	Tc(t)	282	56*
616294	4714065	1901	Tc(t)	100	20
616246	4714135	1889	Tc(t)	110	24
616207	4714228	1884	Tc(t)	87	14
616082	4714154	1889	Tc(t)	105	34
616060	4714166	1890	Tc(t)	110	22
615969	4714254	1883	Tc(t)	105	12
615995	4714193	1874	Tc(t)	101	20
615929	4714156	1873	Tc(t)	94	23
615882	4714128	1861	Tc(t)	103	26
615906	4714115	1867	Tc(t)	107	31
615847	4714160	1866	Tc(t)	105	34
615826	4714177	1863	Tc(t)	90	26
615879	4714195	1867	Tc(t)	93	20
615923	4714232	1870	Tc(t)	96	15
Chirpikty					
625619	4714292	1851	Tc(t)	294	29
625807	4714421	1840	Q2 ₂	87	8
625822	4714387	1833	Q2 ₂	274	30
625820	4714346	1837	Tc(t)	260	25
625861	4714245	1828	Tc(t)	275	22
625888	4714193	1823	Tc(t)	277	13
625907	4714191	1822	Tc(t)	270	12
625944	4714139	1817	Tc(t)	271	9
626018	4714079	1812	Tc(t)	276	4
Cholpon-Ata					
675215	4730922	2107	Tc(k)	64	12
675220	4731028	2126	Tc(k)	67	25
674889	4731676	2204	Tc(k)	64	26
674108	4730493	2147	Tc(k)	62	25
674131	4730137	2128	Tc(k)	58	21
674528	4729761	2112	Tc(k)	63	29
674379	4729763	2184	Tc(k)	62	21
674262	4729677	2221	QTs	67	21
676090	4727922	1985	QTs	75	6
676090	4727880	1985	QTs	80	3
676071	4727843	2014	QTs	228	11
676096	4727739	1977	QTs	288	8
676375	4726735	1822	Tc(k)	320	23
676346	4726353	1737	Tc(k)	262	20
678467	4733069	2266	Tc(k)	80	4
678282	4732890	2211	Tk	308	14
678717	4732395	2147	Tc(k)	68	22
678546	4732603	2212	Tc(k)	61	21
678899	4729312	1956	Tc(k)	161	14

^a Coordinate system: WGS 1984 UTM zone 43 N

^b Units: Tk (Kokturpak Fm.); Ts (Shamsi Fm.); Tc(t) (Chu Fm., Terskey); Tc(k) (Chu Fm., Kungey); QTs (Sharpyldak Fm.); Q2₂, Q3₂ (terrace gravels); Ql (lake beds)

^c All measurements noted using right hand rule

* Overturned bedding

Appendix B (continued)

Easting ^a	Northing ^a	Elevation	Unit ^b	Azimuth ^c	Dip ^c
Cholpon-Ata					
685737	4727540	1705	Tk	295	14
685790	4727868	1736	Tc(t)	280	20
685560	4728523	1791	Tc(t)	281	5
674826	4725563	1732	Tc(k)	264	19
674823	4725677	1751	Tc(k)	260	18
674192	4725811	1786	Tc(k)	270	34
674234	4725949	1781	Tc(k)	310	22
674349	4726713	1900	QTs	260	5
686004	4732317	2072	Tc(t)	80	16
686763	4729891	1921	Tc(k)	261	10
686728	4729917	1930	Tc(k)	250	6
686683	4730060	1941	Tc(k)	267	4
686568	4726865	1674	Tk	10	35
686549	4726922	1680	Tk	353	32
686151	4728902	1795	Tc(t)	280	7
686339	4727310	1684	Tc(t)	321	26
687756	4729990	1908	Tc(k)	260	9
688531	4729782	1780	Tc(t)	272	4
707026	4737684	1911	Tk	43	21
707150	4737792	1933	Tc(t)	42	25
694374	4731036	1755	Q2 ₂	272	29
694742	4733780	2128	QTs	86	12
693522	4731153	1772	Tc(t)	265	8
693724	4730873	1795	Tc(t)	75	23
691780	4730156	1724	Tc(t)	86	23
691669	4730255	1753	Tc(t)	265	2
691510	4730409	1762	Tc(t)	97	4
691665	4730631	1748	Tc(t)	280	10
687193	4730235	1885	Tc(t)	270	4
687421	4731142	2031	QTs	84	4
Cholpon-Ata					
687124	4731221	2018	QTs	87	3
687150	4731100	2023	QTs	88	1
687088	4731026	2011	QTs	270	1
687143	4730578	1905	Tc(k)	260	4
667506	4726907	1976	QTs	68	28
667389	4727091	1977	QTs	50	25
667420	4727139	1998	QTs	82	16
667489	4727217	1970	Tc(k)	75	20
668281	4728452	1986	Tc(k)	75	14
668206	4728140	1969	Tc(k)	60	12
668332	4727340	1979	QTs	59	7
672958	4725249	1730	Tc(k)	192	23
672939	4725233	1730	Tc(k)	190	19
672920	4725157	1742	Tc(k)	156	14
672920	4725136	1752	Tc(k)	103	22
672914	4725318	1732	Tc(k)	268	23
672965	4725510	1738	Tc(k)	249	20
673105	4725634	1772	Tc(k)	255	30
674087	4725349	1719	Tc(k)	281	22
674136	4725261	1730	Tc(k)	95	14
681846	4730421	1940	Tc(k)	275	10
682096	4729672	1930	Tc(k)	279	12
682789	4729153	1897	Tc(k)	260	14
686004	4732317	2072	Tc(t)	80	16
686763	4729891	1921	Tc(k)	261	10
686728	4729917	1930	Tc(k)	250	6
686683	4730060	1941	Tc(k)	267	4
673541	4725529	1723	Tc(k)	290	7
673517	4725567	1729	Tc(k)	265	17
673512	4725591	1727	Tc(k)	274	22

^a Coordinate system: WGS 1984 UTM zone 43 N

^b Units: Tk (Kokturpak Fm.); Ts (Shamsi Fm.); Tc(t) (Chu Fm., Terskey); Tc(k) (Chu Fm., Kungey); QTs (Sharpyldak Fm.); Q2₂, Q3₂ (terrace gravels); Ql (lake beds)

^c All measurements noted using right hand rule

* Overturned bedding

Appendix B (continued)

Easting ^a	Northing ^a	Elevation	Unit ^b	Azimuth ^c	Dip ^c
Cholpon-Ata					
673499	4725626	1729	Tc(k)	231	32
673457	4725671	1745	Tc(k)	240	21
673460	4725673	1740	Tc(k)	250	24
673467	4725685	1741	Tc(k)	260	39
673333	4725766	1746	Tc(k)	260	39
673323	4725766	1749	Tc(k)	265	38
673282	4725721	1753	Tc(k)	262	20
673235	4725562	1741	Tc(k)	255	21
673234	4725568	1739	Tc(k)	260	26
673221	4725575	1736	Tc(k)	245	33
673207	4725632	1743	Tc(k)	244	36
673196	4725665	1744	Tc(k)	258	24
674281	4724910	1687	Tc(k)	90	35
674309	4724934	1689	Tc(k)	110	24
674408	4725023	1703	Tc(k)	278	11
674422	4725102	1696	Tc(k)	125	57
674432	4725117	1692	Tc(k)	135	70
674429	4725117	1695	Tc(k)	145	64
674432	4725116	1700	Tc(k)	135	40
674464	4725133	1705	Tc(k)	142	35
674445	4725148	1709	Tc(k)	125	36
674447	4725155	1712	Tc(k)	133	28
674386	4725361	1713	Tc(k)	285	18
674391	4725432	1719	Tc(k)	270	31
674402	4725455	1733	Tc(k)	280	24
674396	4725454	1739	Tc(k)	271	35
674406	4725478	1744	Tc(k)	279	33
674420	4725523	1750	Tc(k)	276	26
674415	4725529	1755	Tc(k)	263	23
676391	4726736	1823	Tc(t)	254	20
Cholpon-Ata					
676382	4726740	1815	Tc(t)	260	14
676383	4726737	1818	Tc(t)	259	19
707144	4737788	1918	Tc(t)	50	24
676134	4727743	1991	QTs	flat	
676096	4727739	1977	QTs	flat	
694493	4731216	1819	Q2 ₂	flat	
694742	4732780	2050	QTs	flat	
674148	4725296	1720	Tc(k)	flat	
687073	4732270	1972	QTs	flat	
686506	4731362		QTs	flat	
674442	4725060	1695	Tc(k)	310	80*
674457	4725075	1696	Tc(k)	313	85*
674460	4725071	1701	Tc(k)	316	82*

^a Coordinate system: WGS 1984 UTM zone 43 N

^b Units: Tk (Kokturpak Fm.); Ts (Shamsi Fm.); Tc(t) (Chu Fm., Terskey); Tc(k) (Chu Fm., Kungey); QTs (Sharpyldak Fm.); Q2₂, Q3₂ (terrace gravels); Ql (lake beds)

^c All measurements noted using right hand rule

* Overturned bedding

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PLATE 1:
Toru-Aygir River
valley

(A) Geologic map emphasizing Neogene and Quaternary strata and deposits of the western and central Kunyey Range. Locations of Plate 1B, Plate 2, and Figures 4, 5, 6 and 8 in text are shown, as well as cross-section lines X-X' (Figure 15 in text) and Y-Y' (Figure 17 in text). Mapping overlain on a hillshade model created from SRTM topography.

(B) Detailed Neogene and Quaternary geology along the Toru-Aygir River valley. Locations (i), (ii), and (iii) show where detailed fault scarp surveys were made, see Figure 6 in text. N-S line notes the location of the long profile of the Ak-Teke and Tekren anticlines shown in Figure 7 in the text.

QUATERNARY

Explanation of map units

Symbol	Surface morphology	Climat/weathering	Fluvium development	Soil development
Qal	Subsided flat and wide topography (< 1 m local relief)	Sedimentation in advanced clasts, poor light Brownish brown development	Irrregular, isolated pavement with large gaps of dirt in between clasts	< 5 cm thick Bf horizon with minimal stage 1 carbonate development
Ql	Extensive flat, well defined surfaces with slight concavity. No preservation of remnant topographic, minor from ridges present	Angular to subrounded clasts, thin vertical development (< 0.25 m)	Irrregular, patchy pavement with little dust in between clasts	35 cm thick Bf horizon with minor stage 1 carbonate development on depth less than 30 cm depth
Q4	Fair surfaces with no representation of remnant topography. First ridges are present and covered by soil to combine	Angular to subrounded clasts, various development on non-granitic clasts of 0.2 m. Sharp crest break up granitic clasts	Patchy areas of interlocking clasts	10 - 15 cm thick Bf horizon with stage 1 stage 2 carbonate development to 20 cm depth
Q3z	Ridge and spurs topography with areas of flat, grooved surfaces. Low amplitude broad ridges present.	Regular to subrounded clast, granitic clasts have abundant grayish drinites, 0.75 - 1.5 m thick wedge development on non-granitic clasts	Patchy pavement development in areas of small, angular clasts	17 - 18 cm thick Bf horizon with stage 1 minor stage 3 carbonate development to 30 cm depth

TERTIARY

Sedimentary units

- Om** Undifferentiated moraines and till deposits
- O(u)** Undifferentiated Quaternary deposits
- QtS** **Sharpyldak Fm.** Locally-derived conglomerates with clast size to >2m diameter supported in a gus matrix. Thickness of the Sharpyldak Fm. is >700m.
- Tc(k)** **Chu Fm., Kungey member** Massive grus layers with interbedded sandstones and gravel conglomerates composed entirely of locally-derived granitic material. Paleocurrent indicators support a north-to-south transport direction. Thickness of the Kungey member is ~400m in the central Kungey Range, while only minor beds are preserved at the top of the Chu Fm. in the western Kungey Range.
- Tc(t)** **Chu Fm., Terskey member** Sandstones, gravels and gravel conglomerates interbedded with massive silt and sand layers. Individual clast include metavolcanic rocks, metasedimentary rocks, gneisses, low-grade schists, and felsic plutonic rocks. Abundant low-angle cross-bedding displays paleocurrent indicators that support south-to-north transport. Thickness of the Terskey member is >600m.
- Ts** **Shamsi Fm.** Massive red sandy clays interbedded with paleosols and minor gravel conglomerates. Basal layers contain gypsum horizons which become absent higher in the column. Thickness of the Shamsi Fm. is ~500m. The Shamsi Fm. is absent in central Kungey Range stratigraphy.
- Tk** **Kakturpak Fm.** Thin paleosols, gypsiferous sandstones, and local lacustrine carbonates overlain by red siltstones and sandstones with abundant gypsum beds.
- N(u)** Undifferentiated Neogene deposits

PALEOZOIC

- Pz(s)** Aleatic expanse of preserved unconformity surface
- Pz** Paleozoic bedrock, undifferentiated

Explanation of map symbols

* terrace surfaces mapped only along the Toru-Aygir River and Ak-Teke hills

Datum: WGS84
Projection: Universal Transverse Mercator, Zone 43 North

QUATERNARY		Alluvial deposits			
		Qal	Active alluvium		
		Q4	Terrace deposits		
		Q3 ₃			
		Q3 ₂			
		Q3 ₁			
		Q2 ₂			
		Q2 ₁			
Surface	Surface morphology	Clast weathering	Pavement development	Soil development	
Q4	Subdued bar and swale topography (< 1 m local relief)	Subangular to subrounded clasts, poor light brown varnish development	Immature, isolated pavement with large gaps of dust in between clasts	< 5 cm thick AV horizon with minimal stage 1 carbonate development	
Q3 ₃	Extensive flat, well-defined surfaces with slight concavity. No preservation of remnant topography, minor frost ridges present	Angular to subrounded clasts, thin varnish development (< 0.25 mm)	Immature, patchy pavement with little dust in between clasts	10 cm thick AV horizon with minor stage 1 carbonate development on clasts to 50 cm depth	
Q2 ₂	Flat surfaces with no preservation of remnant topography. Frost ridges are present and oriented sub-parallel to contours	Angular to subrounded clasts, varnish development on non-granitic clasts of 0.25 mm. Significant break-up of larger clasts	Patchy areas of interlocking clasts	10-15 cm thick AV horizon with stage 1 to stage 2 carbonate development to 50 cm depth	
Q2 ₁	Ridge and swine topography with areas of flat, preserved surfaces. Low amplitude frost ridges present	Angular to subrounded clasts, granitic clasts have advanced granular attrition, 0.75-1.5 mm thick varnish development on non-granitic clasts	Patchy pavement development in areas of small, angular clasts	15-17 cm thick AV horizon with stage 2 to minor stage 3 carbonate development to 50 cm depth	

Explanation of map units and symbols

TERTIARY		Sedimentary units	
		QTs	Sharpyldak Fm. Locally-derived conglomerates with clast size to >2m diameter supported in a grus matrix. Thickness of the Sharpyldak Fm. is >700m.
		Tc(k)	Chu Fm., Kungey member Massive grus layers with interbedded sandstones and gravel conglomerates composed entirely of locally-derived granitic material. Paleocurrent indicators support a north-to-south transport direction. Thickness of the Kungey member is ~400m in the central Kungey Range, while only minor beds are preserved at the top of the Chu Fm. in the western Kungey Range.
		Tc(t)	Chu Fm., Terskey member Sandstones, gravels and gravel conglomerates interbedded with massive silt and sand layers. Individual clast include metavolcanic rocks, metasedimentary rocks, gneisses, low-grade schists, and felsic plutonic rocks. Abundant low-angle cross-bedding displays paleocurrent indicators that support south-to-north transport. Thickness of the Terskey member is >600m.
		Tk	Kokturpak Fm. Thin paleosols, gypsiferous sandstones, and local lacustrine carbonates overlain by red siltstones and sandstones with abundant gypsum beds.
PALEOZOIC		Pz(s)	Aerial extent of preserved unconformity surface
		Pz	Paleozoic bedrock, undifferentiated

- contact
- anticline
- syncline
- strike-slip fault
- thrust or reverse fault
- symbols solid where certain dashed where inferred
- orientation of unconformity surface
- town
- Orientation of strata
 - 42° inclined
 - ⊕ flat
 - ↑ vertical
 - 67° overturned

Detailed Neogene and Quaternary geology of the central Kungey Range, also shown in Figure 8 in the text. Location noted in Figure 1 in the text and Plate 1. Locations (i) and (ii) correspond to detailed fault scarp surveys, shown in Figure 9 in the text. Line Y - Y' indicates the cross-section line in Figure 16 in the text.

PLATE 2: Cholpon-Ata and Central Kungey Range

Jacob Selander
2008

Datum: WGS84
Projection: Universal Transverse Mercator, Zone 43 North