ALONG STRIKE VARIATION AND THE ROLE OF FAULT PROPAGATION FOLDING IN GENERATION OF STRUCTURAL RELIEF IN THE KOCHKOR VALLEY, TIEN SHAN, KYRGYZSTAN

by

KATHRYN TERESA PAULSON

A THESIS

Presented to the Department of Geological Sciences
and the Graduate School of the University of Oregon
in partial fulfillment of the requirements
for the degree of
Master of Science

September 2013

THESIS APPROVAL PAGE

Student: Kathryn Teresa Paulson

Title: Along Strike Variation and the Role of Fault Propagation Folding in Generation of Structural Relief in the Kochkor Valley, Tien Shan, Kyrgyzstan

This thesis has been accepted and approved in partial fulfillment of the requirements for the Master of Science degree in the Department of Geological Sciences by:

Samantha Hopkins	Chair
Ray Weldon	Advisor
Marli Miller	Member

and

Kimberly Andrews Espy	Vice President for Research and Innovation; Dean of the Graduate School

Original approval signatures are on file with the University of Oregon Graduate School.

Degree awarded September 2013

THESIS ABSTRACT

Kathryn Teresa Paulson

Master of Science

Department of Geological Sciences

September 2013

Title: Along Strike Variation and the Role of Fault Propagation Folding in Generation of Structural Relief in the Kochkor Valley, Tien Shan, Kyrgyzstan

The southern margin of the Kochkor Basin in the Kyrgyz Tien Shan is actively shortening. The South Kochkor Fault, a reverse fault that places Paleozoic granite on Neogene sediments, varies in displacement from 0-2 km while the structural relief across the basin margin is 4 km. North of the fault, a 2 km thick panel of steeply-dipping to overturned sediments exhibits flexural shearing. This steep section is bounded by limbs of gently-dipping beds to the north and south. Northward, Neogene section is thrust over late Quaternary deposits in two younger episodes of faulting: the Akchop Hills Fault and the Aigyrdzal Hills Fault. Through 1:25,000 scale mapping I have demonstrated that of structural relief in the area is shared by fault propagation folding and faulting on a steep, reverse fault that shallows into a detachment.

A complete geologic map of Kochkor, Kyrgyzstan is included with this thesis as a supplemental file.

CURRICULUM VITAE

NAME OF AUTHOR: Kathryn Teresa Paulson

GRADUATE AND UNDERGRADUATE SCHOOLS ATTENDED:

University of Oregon, Eugene
University of Washington, Seattle

DEGREES AWARDED:

Master of Science, Geology, 2013, University of Oregon
Bachelor of Science, Geology, 2011, University of Washington

AREAS OF SPECIAL INTEREST:

Structural Geology

PROFESSIONAL EXPERIENCE:

Graduate Teaching Fellow, University of Oregon, Sept 2011-Sept 2013

Teaching Assistant, University of Washington, Jan 2010-Jun 2011

GRANTS, AWARDS, AND HONORS:

Travel Grant, Masters field work, University of Oregon, 2012

North Seattle Lapidary and Mineral Club Scholarship, University of Washington, 2010

A. Woolley and J.W. Crooks Scholarship, University of Washington, 2010

University of Washington Dean's List
Annual Dean's List: 2006 – 2007 academic school year
Spring 2008
Winter/Spring/Summer 2010

ACKNOWLEDGMENTS

I would like to acknowledge and thank the Kyrgyz aids who helped me in the field, Kanatbek Abdrakhmatov, Imankulov Segyn, Atyr Djumabaeva and Azat Said; they made my time in Kyrgyzstan run smoothly and feel like home. Thank you to Nyle Weldon, for his help in the field and great attitude. I thank my committee members, Samantha Hopkins, Marli Miller and advisor Ray Weldon for feedback, support and encouragement. Special thanks to my cohorts and office mates, Ashley Streig, James McNabb and Lauren Austin, who helped with brainstorming, technology concerns and emotional support and encouragement. This project was a pleasure to be a part of and everyone who has contributed made it that much better.

TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

The Tien Shan mountain range ("Heavenly Mountains" in Chinese) is an actively deforming zone within the Eurasian plate (Figure 1). This intercontinental orogeny is caused by the collision of India with Eurasia and currently accommodates about half of the shortening generated by the plate boundary (Abdrakhmatov et al. 1996; Holt et al. 2000). The Tien Shan consists of alternating uplifting ranges, built by thick-skinned faulting and basement-involved folding and intermontane basins filled with syntectonic sediments. Faults along the South Kochkor Basin margin account for around 15% of this total shortening within the central Tien Shan (Abdrakhmatov et al. 2001).

Throughout the central Tien Shan, similar structural basins have been studied (Figure 2). The three we will discuss here are the Chu Basin (Bullen et al. 2003), Naryn Basin (Burbank et al. 1999) and the Issyk-Kul Basin (Burgette, 2008). These basins are all basement-bounded and contain steep reverse faults, but accommodate shortening with slight variations in structures and structural relationships (Figure 2).

The relatively young Tersky Ala-Too range forms the southern margin of the Kochkor Basin (Figure 2) bounding a thick (~3.5-4 km) section of Neogene synorogenic sediments associated with earlier episodes of mountain building. West of the Djuanarik River, there is a 2 km wide panel of sub-vertical to overturned sedimentary beds (Figure 3). The sedimentary section is bounded by the South Kochkor Fault to the south and the

Akchop Hills Fault to the north. North of the Akchop Hills, a third zone we will call the Aigyrdzal Hills Fault Zone is actively uplifting Neogene and Quaternary sediments. The goal of this thesis is to determine the structural mechanisms of relief generation in the Kochkor Basin and analyze along-strike variability between local structures.

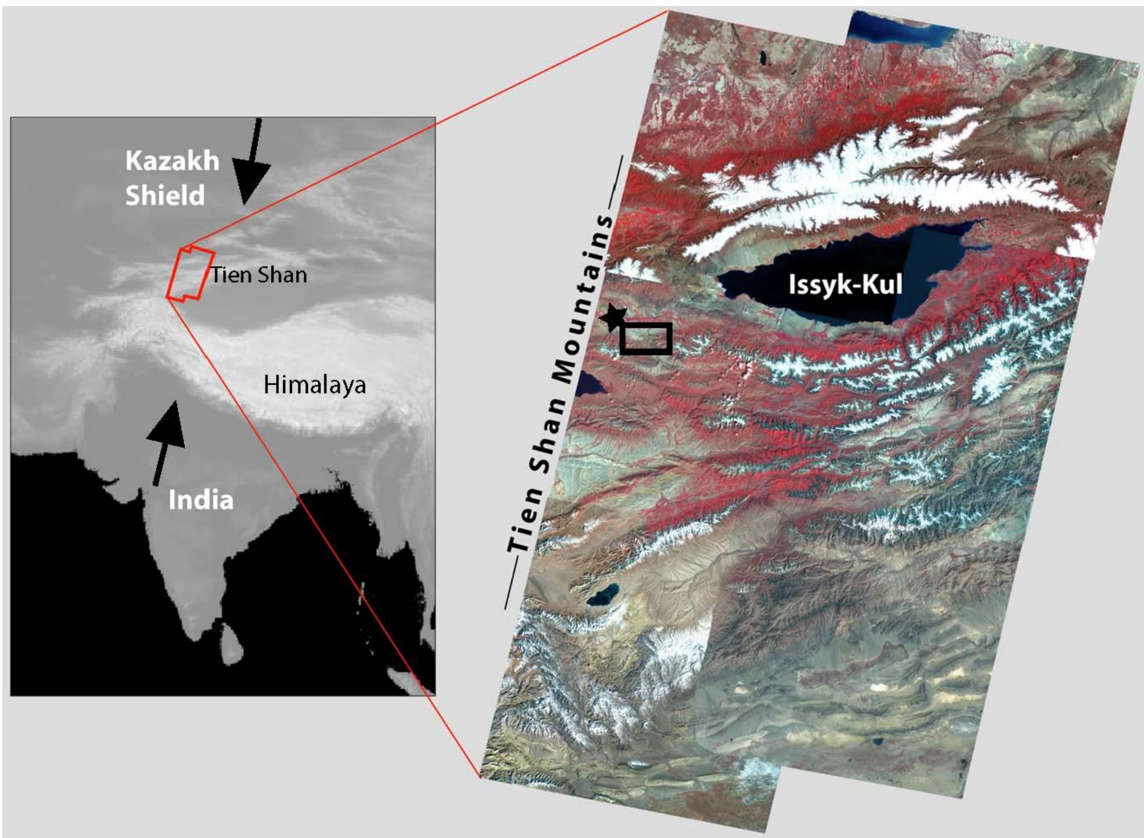

Figure 1- (Left): Map of India-Eurasia boundary indicating direction of relative plate motion. Box shows location of Central Tien Shan. (Right): Landsat image of the Issyk-Kul region of the central Tien Shan, starred box shows area of study.

The three fault zones are the primary means of shortening and relief generation along the south Kochkor margin. Fault slip rate studies along the margin have measured around 3 mm/yr on the Akchop Hills Fault at the Djuanarik River and at least 0.2 mm/yr

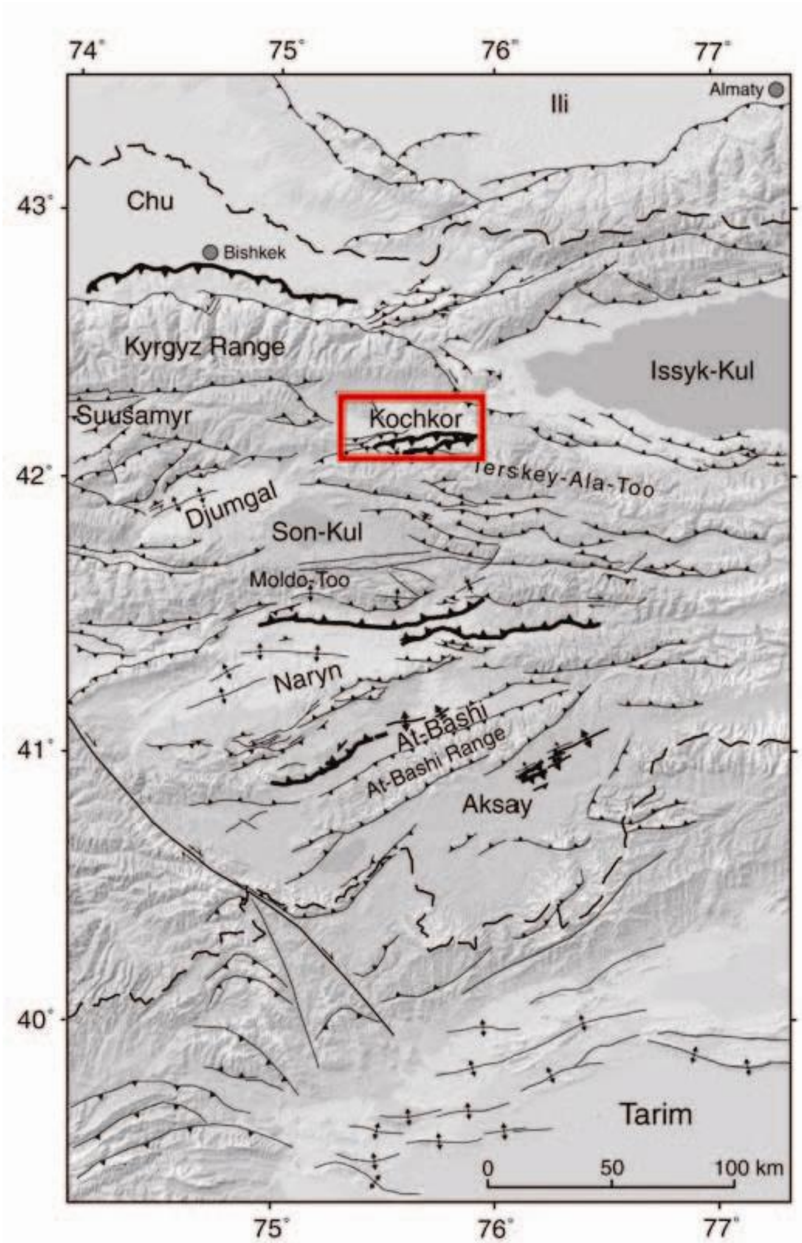

Figure 2- Major faults of the central Tien Shan. Akchop Hills and South Kochkor Faults are outlined in red box. Chu Basin is to the northwest, Naryn to the south and Issyk-Kul to the east. The Tersky Range forms the southern boundary of both the Kochkor and Issyk-Kul Basins. Modified from Thompson et al. 2002 (Figure 2). Bold faults indicate faults included in their study.

on the South Kochkor Fault (Thompson et al. 2002; Abdrakhmatov et al. 2001). The shallower basin faults are lower angle and have frequent splays that, in some instances, have created secondary propagation folds within the Neogene sediments. Abdrakhmatov et al. (2001) constructed a small scale cross section of the southern Kochkor Basin margin and how it relates to larger structures to the south (Figure 4). The faults in the Kochkor Basin are connected at depth to a steep (~40 degrees) fault that continues into the mid crust beneath the Tersky Ala-Too Range.

Limited recent work has been done in the Kochkor region since the soviet era and advent of modern balanced cross section methodology; primarily by Abdrakhmatov et al. (2001), Thompson et al. (2002) and Park et al. (2003). Both Abdrakhmatov and Thompson used the deformation of Quaternary terrace deposits to calculate slip rate and some fault geometry in a localized area of the Akchop Hills Fault. Park et al. (2003) conducted a magnetotelluric study along the South Kochkor Fault and Akchop Hills Fault just east of my field area. They found that the cumulative shortening across the margin is from 2.5-7.5 km (Park et al. 2003).

In the following sections of Chapter I, I will discuss the geologic setting including an explanation of the units mapped. In Chapter II, I will outline my results. In Chapter III, I will discuss the implications of my structural results and compare them with other studies in the same region. coarse-grained, feldspar-rich granite (Figure 5) and Neogene sediments. The sedimentary package is generally divided into five units, the Kokturpak formation, Bjer formation (equivalent to the Shamsi Formation in the Chu Basin, and will be referred to as such), Djuanarik Formation (equivalent to the Chu Formation, will be referred to as such), Sharpyldak Formation and late Quaternary, which includes fluvial terraces, colluvium and alluvium.

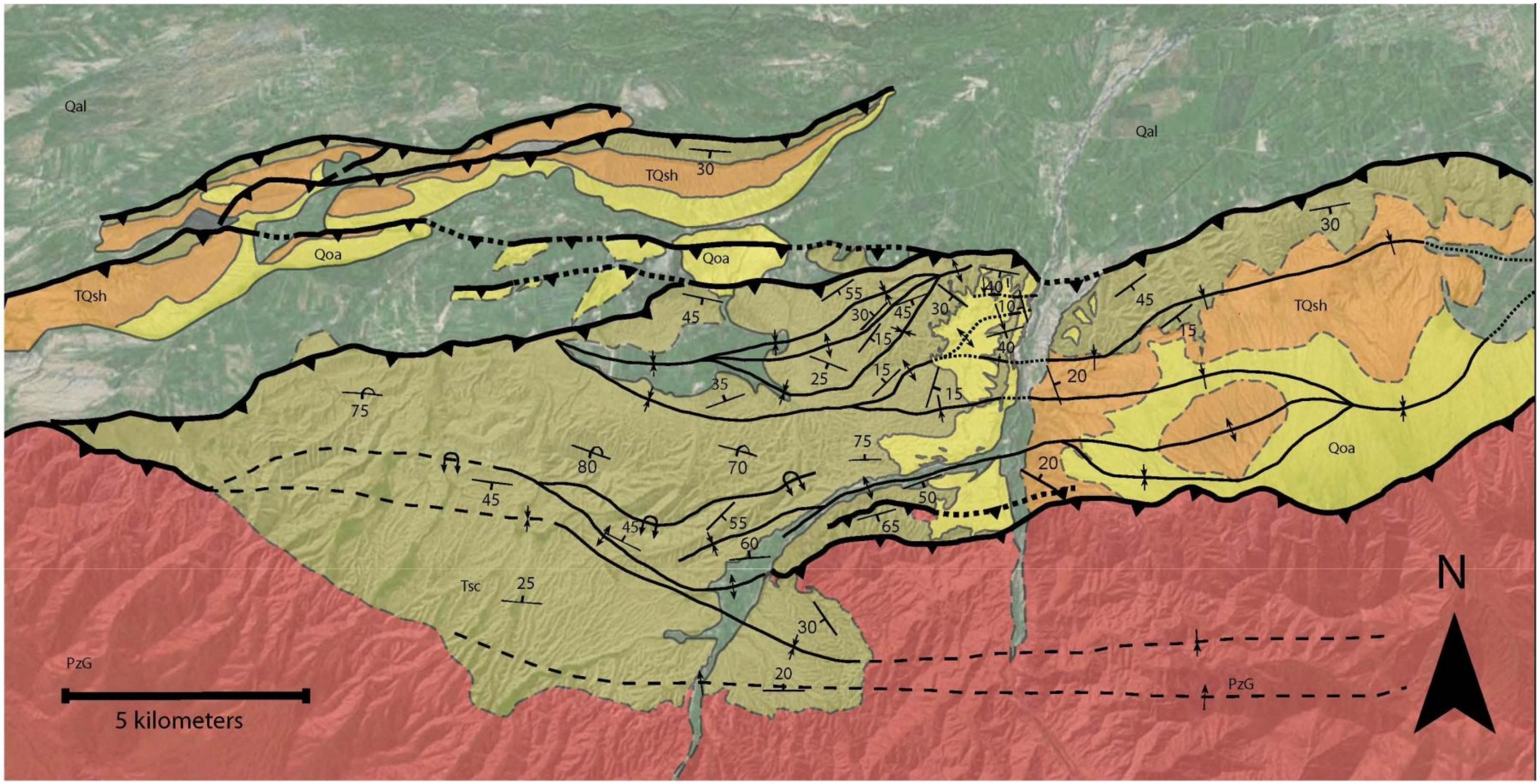

Figure 3- Simplified map of field area showing primary faults and fold hinges. Distinct dip panels are indicated by representative attitudes averaged over the area. The southernmost fault is the South Kochkor Fault, emplacing Paleozoic Granite of the Tersky Ala-Too range over Neogene sediments. The central fault strands are the Akchop Hills Fault and the northernmost series of faults are the Aigyrdzal Hills Fault Zone. The Akchop Hills and Aigyrdzal Hills faults uplift Neogene over Quaternary alluvium.

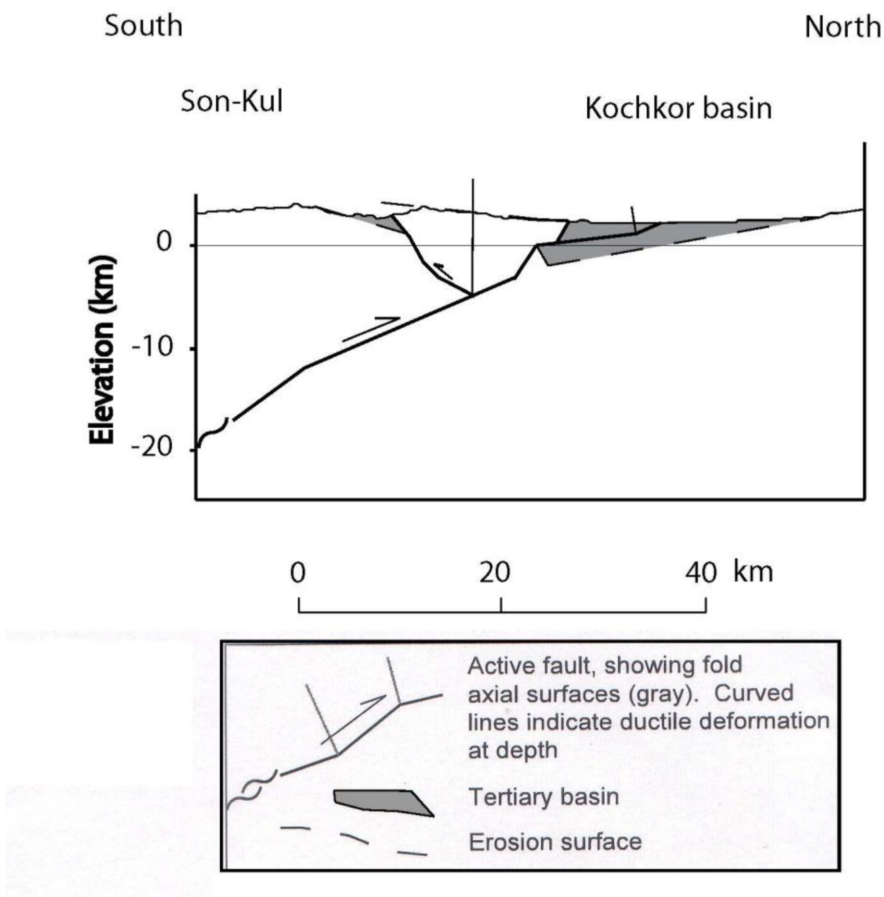

Figure 4- Small scale cross section adapted from Abdrakhmatov et al (2001). This cross section suggests a theory for the origin of the deep crustal fault. The section also shows a backthrust to form the Tulek Basin that is located farther south than my study area. In this section, the basement dips about 8 degrees to the south under the Kochkor Valley.

Geologic Setting

Lithology

The goal of this project is to interpret the local structure and I did not measure or describe section so I am relying on the stratigraphic interpretations of past studies. For the map we used previously established units and have briefly described them here. The southern margin of the Kochkor Basin contains two primary lithologies, Paleozoic

Figure 5- Coarse grained, feldspar-rich Paleozoic granite that comprises the basement of the Kochkor region. This photo is from the hanging wall of the South Kochkor Fault. Notice visible foliated texture.

The unconformity between Paleozoic basement and Neogene sediments is marked by an erosional surface, a small part of which is preserved within the study area. In shallow low-lying areas the Kokturpak formation is deposited directly on this surface. The Kokturpak formation is a thin (few to 10s of meters), deeply weathered stack of fine-grained sandstone to siltstone that is deep red in color and contains numerous gypsum beds (Burgette, 2008). Individual outcrops of the Kokturpak formation have been dated from Cretaceous to early Neogene based on basalt flows and fossils. Believed to be pre-orogenic, it formed in shallow, long wavelength basins on the erosion surface (Burgette, 2008). Outside these patches of sediment the erosion surface is a thick, red, clay-rich, paleosol. It is present on the map in only one small area in the footwall of the South Kochkor Fault (Figure 6).

The Shamsi equivalent (locally the Bjer formation, named for the Bjer River) is approximately 220-830 m thick and represents sedimentation related to the onset of initial Tien Shan uplift around 12-13 Ma (Goode et al. 2011; Abdrakhmatov et al. 2001). It is referred to as an "equivalent" because it is correlated to the Shamsi formation in the well-studied Chu Basin by its color, appearance and stratigraphic setting as the basal unit of the thick orogenic section. Since onset occurred at different times throughout the Tien Shan, it is possible that the age is variable. If the Shamsi Formation and its equivalent formations throughout the range are just what is shed into a basin early in each basin's history, it could be young in younger depocenters like Kochkor. Though estimated to be 12-13 Ma, it is only constrained absolutely to be older than 8 Ma based on paleomagnetic work from the upper Chu equivalent in the Kochkor Basin (Abdrakhmatov et al. 2001). We have found a thin, dateable ash in the lower Shamsi formation, which will provide an absolute date at a later time. At the base of the section, the unit is a well-bedded, pebbly sandstone that grades into a mixture of interbedded terrestrial, fluvial and lacustrine sediments that are less competent (Figure 7). The transition from Shamsi to Chu equivalent is gradational and the location of the contact in the Kochkor region is not well defined and was not mapped in this project.

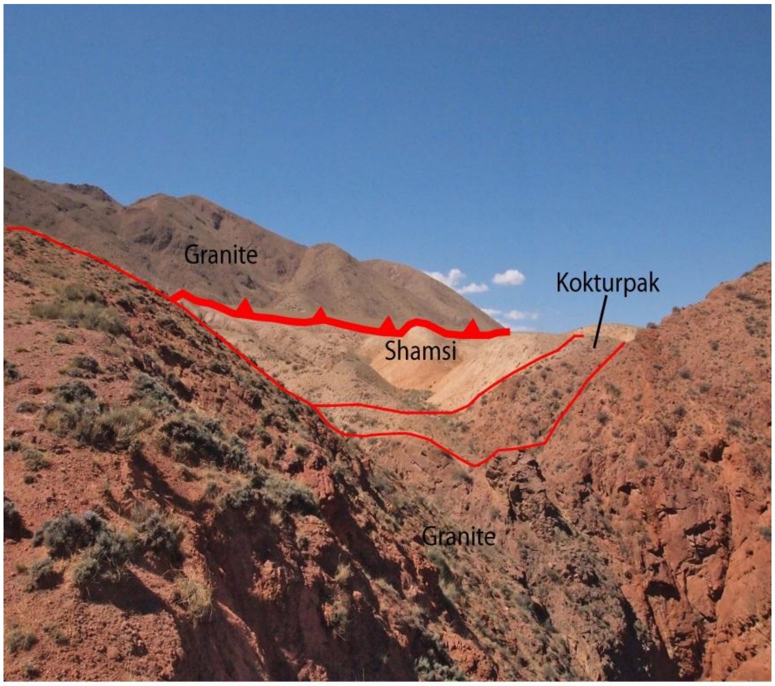

Figure 6- (Top): Annotated photo of the unconformable contact between Paleozoic granite and Neogene sediments. Here the thin, dark red Kokturpak formation that grades into the lighter, coarser Shamsi formation. Also pictured is the South Kochkor Fault, which emplaces the same Paleozoic granite over the younger, Neogene strata. (Bottom): Pieces of gypsum from the Kokturpak formation.

The Chu equivalent or Djuanarik Formation, as it is called locally by some Russian and Kyrgyz scientists, is distinguished from the Shamsi equivalent by texturally-mature fine-grained, well-sorted sand, silt and mudstones of varying color. There are localized channel deposits of medium- to coarse-grained, well-sorted sandstone. The upper Chu equivalent contains more frequent coarse, sandy beds than the lower part of the unit, but transitions back to finer sediments below the contact with the Sharpyldak formation, especially west of the Djuanarik River where the upper Chu equivalent is particularly poorly-indurated (Figure 8). The Chu equivalent is greater than 2.5 km thick in places and comprises the bulk of the Neogene section (Goode et al. 2011).

Figure 7- Coarse, well-bedded sandstones of the lower Bjer Formation or Shamsi equivalent. This portion of the Shamsi is not very thick and mostly appears south of the Bjer River in the study area.

Figure 8- (Bottom): Beds of the fine-grained mud, silts and sandstone of the lower Djuanarik Formation, or Chu equivalent. In the middle, the formation exhibits more frequent sandstone interbeds, but grades finer at the top. (Top): Upper Djuanarik to Sharpyldak contact from afar. The upper Djuanarik is bedded sand and siltstones and the dark capstone is the poorly sorted pebbly conglomerate of the Sharpyldak formation

The uppermost unit is the Late Neogene Sharpyldak formation, estimated to be about 2-3 Ma at the base (Figure 9, Abdrakhmatov et al. 2001). Although the age of its upper boundary is unknown, it is at least is as old as the middle Quaternary (Chediya, 1986). It is a coarse, pebbly conglomerate that is widely associated with climate change at the end of the Neogene (Abdrakhmatov et al. 2001), however, within intermontane basins like Kochkor, Issyk-Kul and Naryn the Sharpyldak formation is not preserved in steep-limbed Neogene folds. As a result, it is unclear if the formation postdates the folds. The Sharpyldak formation is discontinuous and locally unconformable with the upper Chu formation as it is typically preserved in shallow synclines and alluvial plains within the broader Kochkor-Issyk-Kul Basin (Burgette, 2008). In the Kochkor Basin, however, there is no evidence of an angular unconformity between the Chu equivalent and Sharpyldak formation; in fact, there are obvious interbeds between the two formations.

Quaternary units include fluvial terraces, alluvium and colluvium. The terraces are relatively flat platforms that sit above the Djuanarik River on beveled surfaces of Neogene sediments. Alluvium and colluvium are actively deposited throughout the map area. Alluvium is deposited in the active riparian zones as well as the broad, flat valley floor where most farming takes place. Colluvium is gravity- and sheet-wash-deposited material largely eroded from the Neogene section and largely off bedrock to the south. It can be seen covering low hills as well as covering the side of moderately steep slopes. Colluvium and alluvium on the back side of the Aigyrdzal Hills is basin fill that has been uplifted by the Aigyrdzal Hills Fault. Quaternary deposits immediately west of the Djuanarik River are fluvial terraces and Quaternary to the east of the river is young colluvium and alluvium that has collected in the shallow syncline.

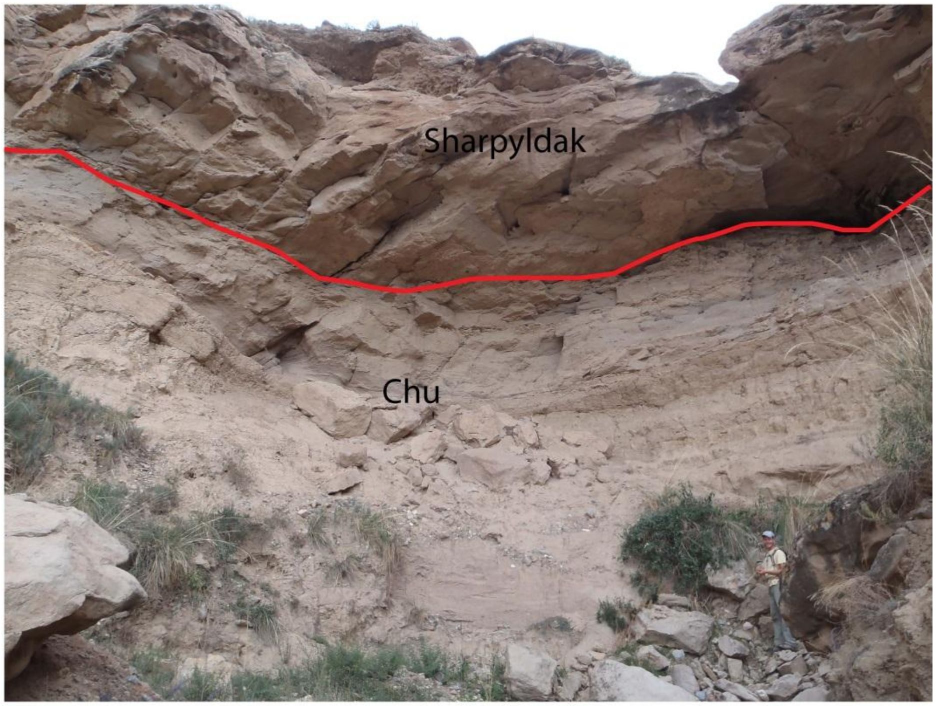

Figure 9- (Top): The contact between upper Chu equivalent and Sharpyldak formations. The course conglomerate of the Sharpyldak formation is more resistant than the poorly consolidated sediments of the Chu formation. In the study area, the Chu and Sharpyldak formation are interbedded, and therefore, conformable (Bottom): Close up of a piece of Sharpyldak formation. The formation consists of poorly sorted, pebbly conglomerate.

Tectonics

Before the active period of Cenozoic deformation began, the ancestral Tien Shan was formed by multiple accretion episodes culminating in the Permian (Lu et al. 2009). The first event joined the Tarim basin with the central Tien Shan and the second joined the northern Tien Shan with the south and the whole block with Eurasia. Any deformation within the Tien Shan that pre-dates the India-Eurasia collision is associated with these two accretion events. At suture zones elsewhere in the range, the Paleozoic basement consists of marine sedimentary rocks like limestone and sandstone in addition to crystalline igneous rocks.

The modern Tien Shan Mountains are a result of the India-Eurasia collision and currently accommodate about half of the total shortening across the plate margin. This shortening amounts to roughly 20 mm/yr. across the entire range (Abdrakhmatov et al. 1996; Holt et al. 2000). The lag between the initial India-Eurasian collision (~55 ma) and the onset of Tien Shan uplift is 30-40 million years (Bullen et al. 2001).

Prior to late Cenozoic shortening, there was a dearth of tectonic activity since at least the early Mesozoic. For most of the Mesozoic and early Cenozoic, the existing land surface was beveled to very low relief (Chediya, 1986). Locally, there are some Jurassic depositional basins and small, Cretaceous to early Cenozoic extensional basins with localized basalt flows, but in the Issyk-Kul/Tersky boundary region, that includes the Kochkor Basin, the unconformity generally extends from Paleozoic to Early Cenozoic (Burgette, 2008). The preserved Paleozoic erosion surface in the study area was formed during this period of quiescence.

Uplift in the Kyrgyz Range of the Tien Shan began around 13-12 Ma and is marked by syntectonic deposition of Neogene sediments. This age may represent a large part of the northern and central Tien Shan in addition to the Kyrgyz Range (Bullen et al. 2001). Some studies have argued that initial uplift in the southern Tien Shan began as early as 24 Ma (Sobel, et al. 1997). Very few absolute dates are available to better constrain this timeline and inferences regarding similar age of the Shamsi equivalents between different basins based on stratigraphic similarity may be inaccurate. Exhumation rates increased at 11-10 Ma with as much as 1.5 km of uplift in the Kyrgyz Range during this time (Bullen et al. 2001.) Shortening is accommodated by basement-cored uplifts that create a topographic pattern of alternating ranges and intermontane basins. Based on evidence from a study of the Suusamyr earthquake, we know that thick-skinned faults reach to mid-crustal depths and typically dip 40-50 degrees (Ghose et al. 1997). Over time, these faults have propagated into the basins along shallowly-dipping detachments in a thin-skinned manner (Burchfiel, 1999). Figure 2 shows major Cenozoic faults and their relationship to the alternating ranges and intermontane basins in the Tien Shan.

Methods

In order to collect structural data I spent one month in the Kochkor Basin mapping on foot. Along with my field assistants, I took bedding attitudes in the primary map area from the South Kochkor Fault to the Akchop Hills Fault mostly west of the Djuanarik River (Figure 10). Some attitudes, denoted in red on the map (supplemental file) are data compiled from a Russian map by Sadybakasov (1990), a map from S.A.

Tarasov (Tarasov, 1970) and a few attitudes from Thompson et al. (2002). The additional data points were used in locations where my personal data were sparse. To extend coverage beyond where I could travel on foot, I mapped certain faults and units using air photos, viewed in stereo, and satellite imagery.

Since there is ambiguity regarding the Shamsi-Chu contact I chose not to map them as distinct units in the field. Some (including Tarasov, 1970) have mapped these contacts. Focus was placed on structure rather than lithology. The lithologic units in this area are highly friable and moderately consolidated, so they do not yield exceptional bedding planes for measuring attitudes. As a result of internal deformation such as bedding-parallel shear, the beds are discontinuous and contain frequent parasitic folds of varying scales. Raw data (attitudes),

Figure 10- Field assistants Azat and Nyle measure attitudes in the upper Shamsi equivalent.

as seen on the final map (supplementary material) are variable in areas. In the process of making cross sections, representative dips were used to filter out the “noise.” Similarly, only large-scale structures are included on the map. Minor structures like intraformational folds and faults that could not be mapped significant distances were left out. Folds that appear to be part of the overall, fault-controlled structure are considered significant and the hinges are included on the map.

The cross sections were originally drafted using representative dips for each discrete dip panel and balanced by hand through regular iterations and retro deformation to ensure consistent geometry and unit volume. The final figures have been digitized, maintaining original geometry, using Adobe Illustrator. “Bedding” planes indicated on the sections are arbitrary, in order to show structural patterns more clearly. The top bedding plane that I have included represents the top of the Neogene strata.

CHAPTER II

RESULTS

Map Data

Mapping the southern margin of the Kochkor Basin revealed three major fault zones from south to north that bound Paleozoic basement, Neogene sedimentary rocks and the modern alluvial surface (Figure 3). The South Kochkor Fault is a steep (~50 degrees), basement-bounding fault that emplaces Paleozoic granite over the Shamsi equivalent to the west and the Sharpyldak formation to the east of the Djuanarik River. The Akchop Hills Fault and related splays emplace Neogene sediments over the modern alluvial plain and are estimated to dip ~45 degrees at the range front based on the dip of the beds that are inferred to be ramping up the fault plane and creating a dip slope. Farther north into the basin, on the west side of the Djuanarik River, there is a third zone called the Aigyrdzal Hills Fault Zone. This zone is a cluster of fault splays that uplift Sharpyldak-capped Neogene sediments over Quaternary alluvium. The south sides of these hills are clearly dip slopes, allowing an estimate of around 30 degrees dip for the outer faults (supplemental file). I have inferred that the sediments are riding up a fault ramp because the beds flatten abruptly south of the fault trace.

At the Bjer River, the South Kochkor Fault does not break the surface for a few kilometers, and reappears along the range front to the northwest where all three fault zones converge (Figure 3). In the gap, the Neogene sediments are deposited on basement to the south and form a 2 kilometer panel of vertical to overturned beds north of a line that is approximately in-line with the South Kochkor Fault (Figure 11).

To the east, the degree of folding decreases as slip on the South Kochkor Fault increases (discussed further in structural results). East of the Djuanarik River there is only a broad syncline in the footwall of the South Kochkor Fault with shallow dips and a narrow, ~1 km wide moderately dipping section riding up the Akchop Hills Fault ramp (Figure 12).

There are pervasive fold hinges throughout the map area (Figure 3). East of the Djuanarik River, they trend WNW, sub parallel to South Kochkor and Akchop Hills Faults. West of the river, the folds make a broad, south-facing bend that is recognizable in the Neogene outcrop as well as the Aigyrdzal Hills fault zone (Figure 3).

Figure 11- (Top): Tight, nearly isoclinal parasitic folds in upper Shamsi equivalent. (Bottom): Sub vertical beds in the Chu equivalent. Long wavelength folds may be evidence of planar shear.

Figure 12- The South Kochkor Fault east of the Djuanarik River (red line). To the left are the upper Chu equivalent and Sharpyldak formation creating a dip slope as they ramp up the Akchop Hills Fault.

Along strike some anastomose from a single fold (syncline or anticline) into multiple tighter syncline-anticline-syncline sets with significant (mapable) structural relief. This style of folding is most clearly seen south of the Akchop Hills Fault, west of the Djuanarik River as well as north of the South Kochkor Fault, east of the river (Figure 13). Many of these medium scale folds have narrow, discrete hinges that can be seen plainly on an outcrop scale (Figure 14). The structural significance of the folds will be discussed later.

In addition to medium-scale, structurally relevant folds there are numerous small-scale parasitic folds that can be seen in outcrops (Figure 14). We interpret these as intraformational folds that are evidence of bedding-parallel shear within the Neogene sedimentary rocks. Folds such as this are typically located in areas where the bedding has undergone significant deformation (i.e. dip >40 degrees). They are also associated with areas where individual beds cannot be traced laterally as far as they can be in less deformed areas. Locally, one can see beds truncated or repeated by shear zones within bedding.

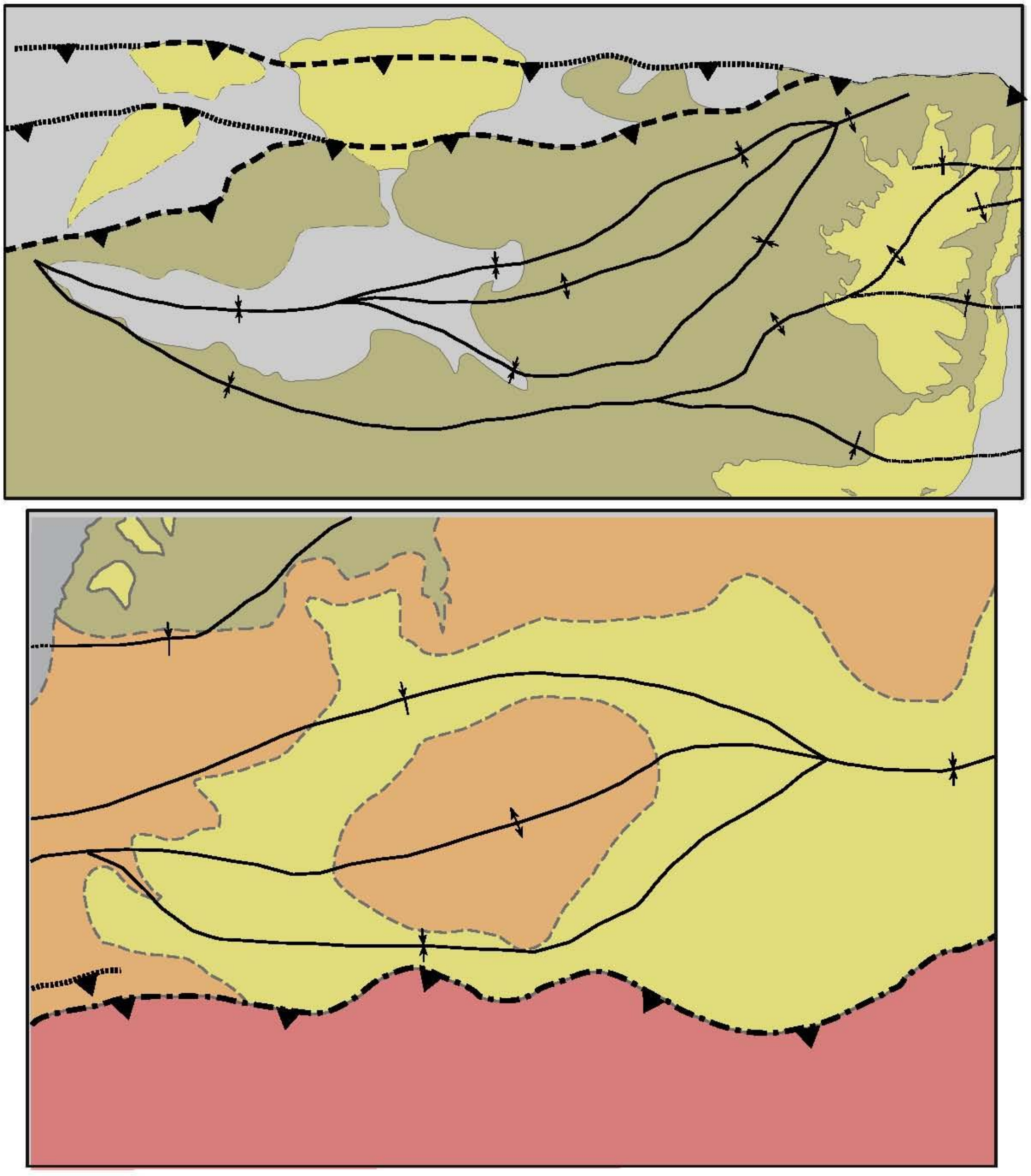

Figure 13- Two map localities of triple fold hinges splaying out from a single fold. (Top) North central area of the map, at the Akchop Hills Fault. (Bottom) South east area, north of South Kochkor Fault.

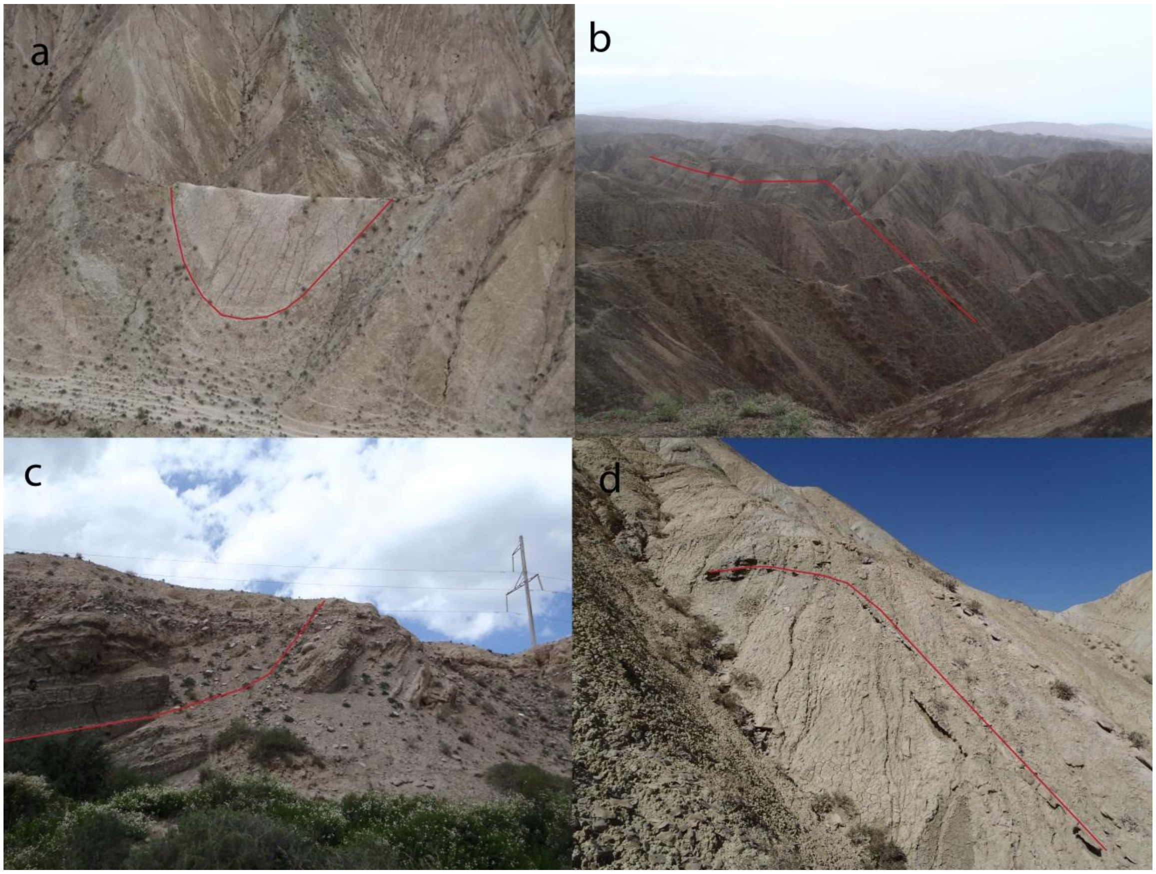

Figure 14- Examples of narrow fold hinges. a) Syncline from just south of the Akchop Hills Fault and west of the Djuanarik River. b) Monocline, same region as photo "a." c) Monocline from along the west bank of the Djuanarik River. d) Small local anticline in the upper Shamsi. These folds represent the typical style of folding within the Neogene sediments as well as show the tendency for small parasitic folds.

Structural Results

I constructed three cross sections within the study area in order to better understand the mechanisms that generate structural relief. A-A' transects the zone of deformation west of the Djuanarik river where the South Kochkor Fault does not break the Neogene rocks, B-B' transects the area just west of the Djuanarik River and C-C' transects east of the Djuanarik River (Figure 15). Overall, I found that the Neogene sedimentary package is 3.5-4 km thick and the structural relief across the basin margin is

4-5 km. The total fault offset across the sections at the surface ranges from 5.5 to nearly 8 km from west to east respectfully, with total slip increasing with decreased folding.

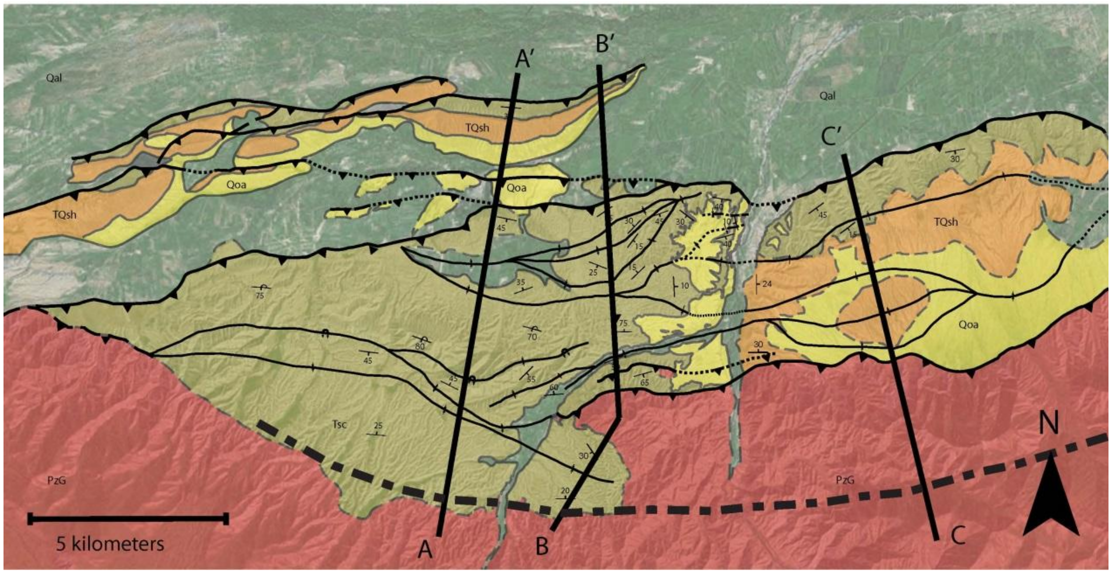

Figure 15- Simplified area map showing locations of the three cross section transects. Also pictured is the approximate location of the fault bend between steep fault and detachment (dash-dot).

Cross section A-A' (Figure 16) shows the area with the greatest degree of folding. At the south end, there is a depositional contact between Paleozoic basement that is dipping shallowly (~5 degrees) north until a hinge which steepens the beds up to 30 degrees. North of the depositional contact and along strike of the South Kochkor Fault the bedding enters a tight syncline-anticline pair. These folds appear to be large enough to be part of the major structures; however, they could potentially be large parasitic folds formed on the margin of the more steeply-dipping panel to the north. After a ~1km, moderately north-dipping panel (60-70 degrees), the beds overturn steeply (70 degrees average). The section of vertical to overturned bedding is about 2 km thick, and the northern margin of the dip panel is a broad synclinal hinge to sub horizontal bedding

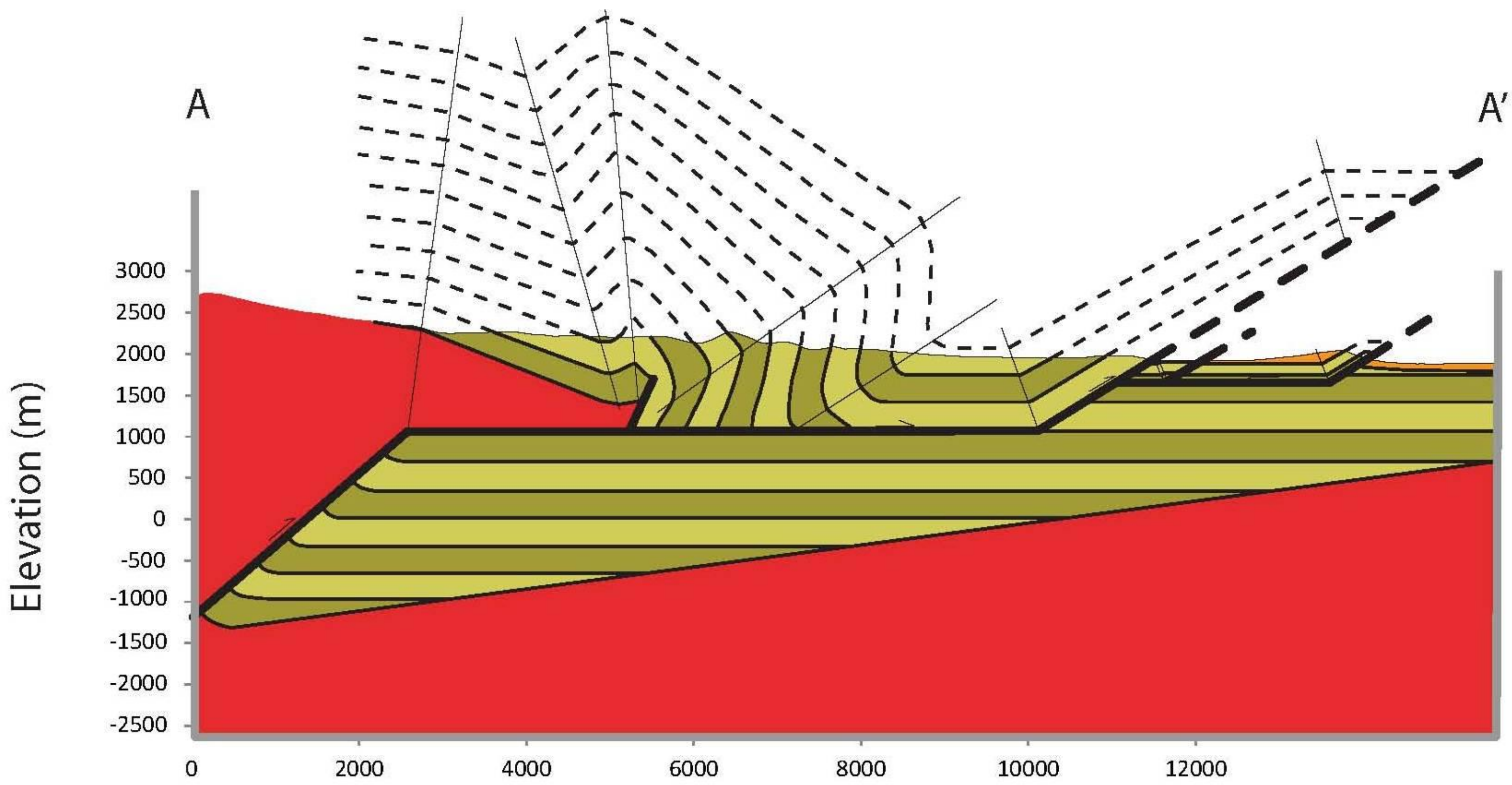

Figure 16- Cross section A-A'. There is a vertical to overturned panel bounded by moderately and shallowly dipping beds. Along this transect there was initially a fault propagation fold with the steep limb dipping 60-70 degrees to the north. As the fault propagated through the fold and into the shallow detachment, the fold in the hanging wall was translated over the fault bend (Fig. 17). This fault bend caused the beds to steepen and overturn. The horizontal bedding that was initially undisturbed by the folding has, in turn, been moved up fault ramps of the Akchop Hills Fault and the Aigyrdzal Hills Fault. A steep (~50 degrees) splay that is the South Kochkor Fault at depth has caused additional folding behind the initial fault propagation fold. All basin faults connect at the range front to a deep, crustal reverse fault that dips ~40-45 degrees. Total fault displacement for A-A' amounts to about 5.5 km with 4 km vertical structural relief and about 5 km total shortening at the surface (33%).

before the beds ramp up to the Akchop Hills Fault. Another 2 km north the beds ramp up again to form the shallow (~30 degrees) dip slope of the Aigyrdzal Hills Fault.

The pattern of a thick section of steeply-dipping beds bounded by shallowly-dipping beds is indicative of a fault propagation fold (Medwedeff and Suppe 1997). This fold geometry could not be generated by a fault-bend fold, the details of which will be addressed in the discussion section. This also accounts for the intermediate panel of moderately dipping beds between shallow and steep, which indicate the original dip of the fold's steep panel was about 60 degrees. The steep limb of the fold was not originally overturned, but rather became so as it passed over a fault bend from ramp to flat that rotated the strata an additional 30 degrees (Figure 17).

The depth of the detachment was determined by projecting the broad synclinal hinge located just south of the Akchop Hills Fault to where it intersects a ramp that is inferred to be a dip slope of the hanging wall of the Akchop Hills Fault. The synclinal hinge should be analogous to the bend from flat to ramp in the fault because the fault breakout seems to have followed existing bedding planes. For the same reasons, I have inferred that the detachment is sub-horizontal. North of the Akchop Hills, the detachment shallows again (dictated by the position of the synclinal hinge south of the Aigyrdzal Hills Fault dip slope) slightly before ramping up as the Aigyrdzal Hills Fault. Given the proximity of the exposed South Kochkor Fault both east and west of the A-A' transect, we infer that the fault tip must not be too far below the surface. It appears to lie somewhere under the tight syncline and anticline hinges just north of the broad

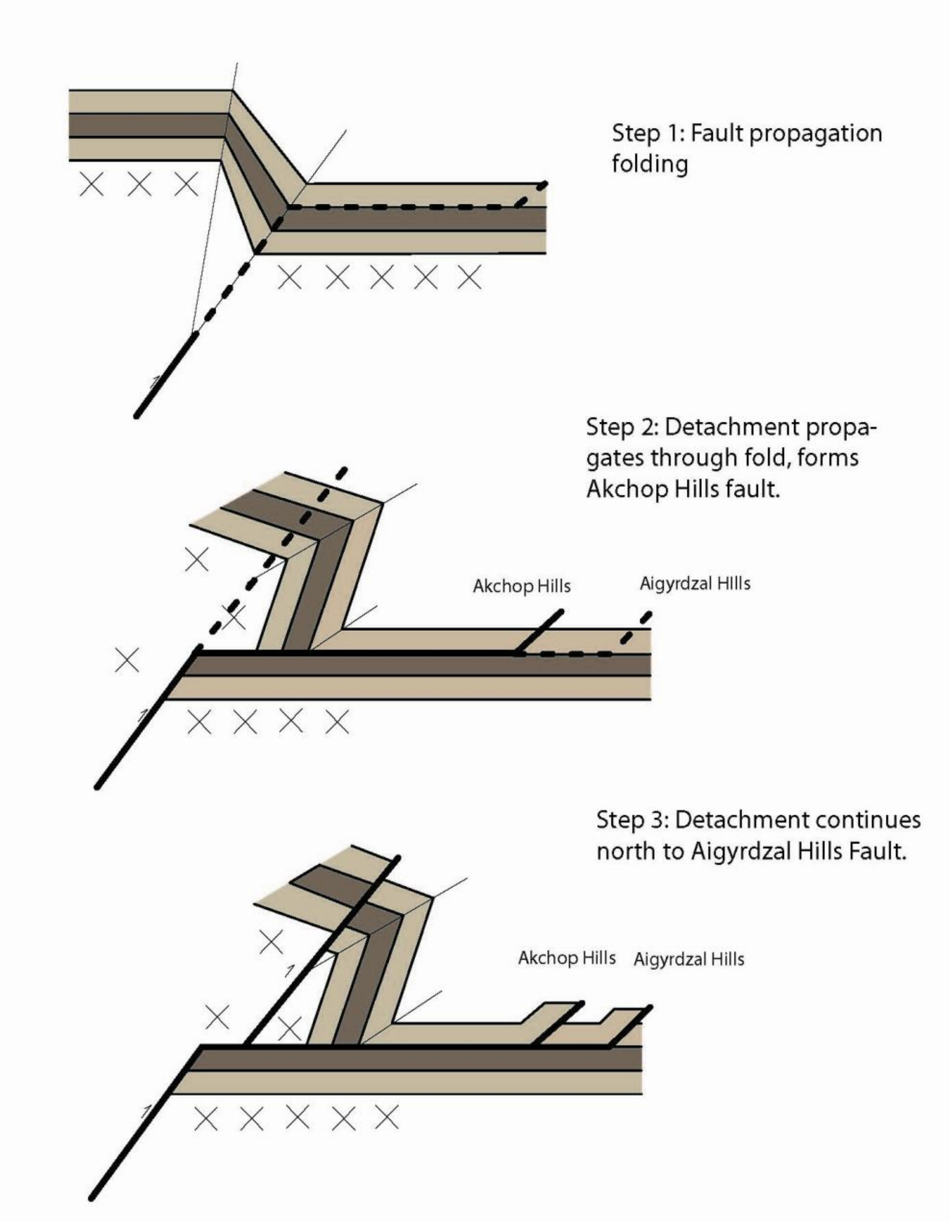

Figure 17- Schematic illustration of the temporal relationships between major structures. Step 1: Fault propagation folding occurs to different degrees, locally generating kilometers of structural relief. (Dashed lines indicate next step of faulting.) Step 2: Steep ramp shallows into a sub horizontal detachment, probably taking advantage of bedding planes where possible. Steep limb of the fold moves over the fault bend in the hanging wall, causing the beds to steepen. Akchop Hills Fault breaks to surface Step 3: Aigyrdzal and South Kochkor Faults break to surface, creating additional fault bend folds. Small splays break off detachment, creating localized anticlines at surface (not pictured).

monocline and south of the main propagation fold. Therefore I have interpreted that the fault generates the tight folds south of the vertical panel.

Cross section B-B' (Figure 18) transects an area with more complex faulting and a lesser degree of folding as the steep panel only dips 60-70 degrees north (Figure 3). Here, there is a clear hanging wall syncline with a depositional contact between Neogene and Paleozoic as well as an anticline within the Paleozoic granite. The hanging wall anticline sits over the ramp of the South Kochkor Fault, which has two splays in this transect. Northward from the South Kochkor Fault there is a narrow anticline right across the Bjer River. Beds continue to dip steeply northward for about 2 kilometers (average 75 degrees) before encountering a synclinal hinge. After the syncline, there is a series of tight fold hinges leading up to the Akchop Hills Fault. There are two splays in this fault zone, but the northern one has very little offset (<50m) based on local relief compared to the other northern fault splays. Just as A-A', the shallow detachment continues out to the Aigyrdzal Hills Fault Zone.

The main fold in this section is the same fault propagation fold as in A-A'; however, the steep limb was only dipping 35-45 degrees originally. After fault-bend folding, the steep panel dips 60-70 degrees. South of the Akchop Hills Fault there is a series of changing ramp angles- from ~30 degrees to 10-15 degrees to ~45 degrees- further complicated by an additional fault tip projected below the smaller anticline hinge (from 8-10 km on B-B'). These were inferred from the bedding dips within and around the small anticline, as this area of the Neogene would have been sub-horizontal before faulting. The development of additional faults in this region account for about 0.75 km more slip than A-A'. The syncline hinge in the footwall of the South Kochkor Fault is a

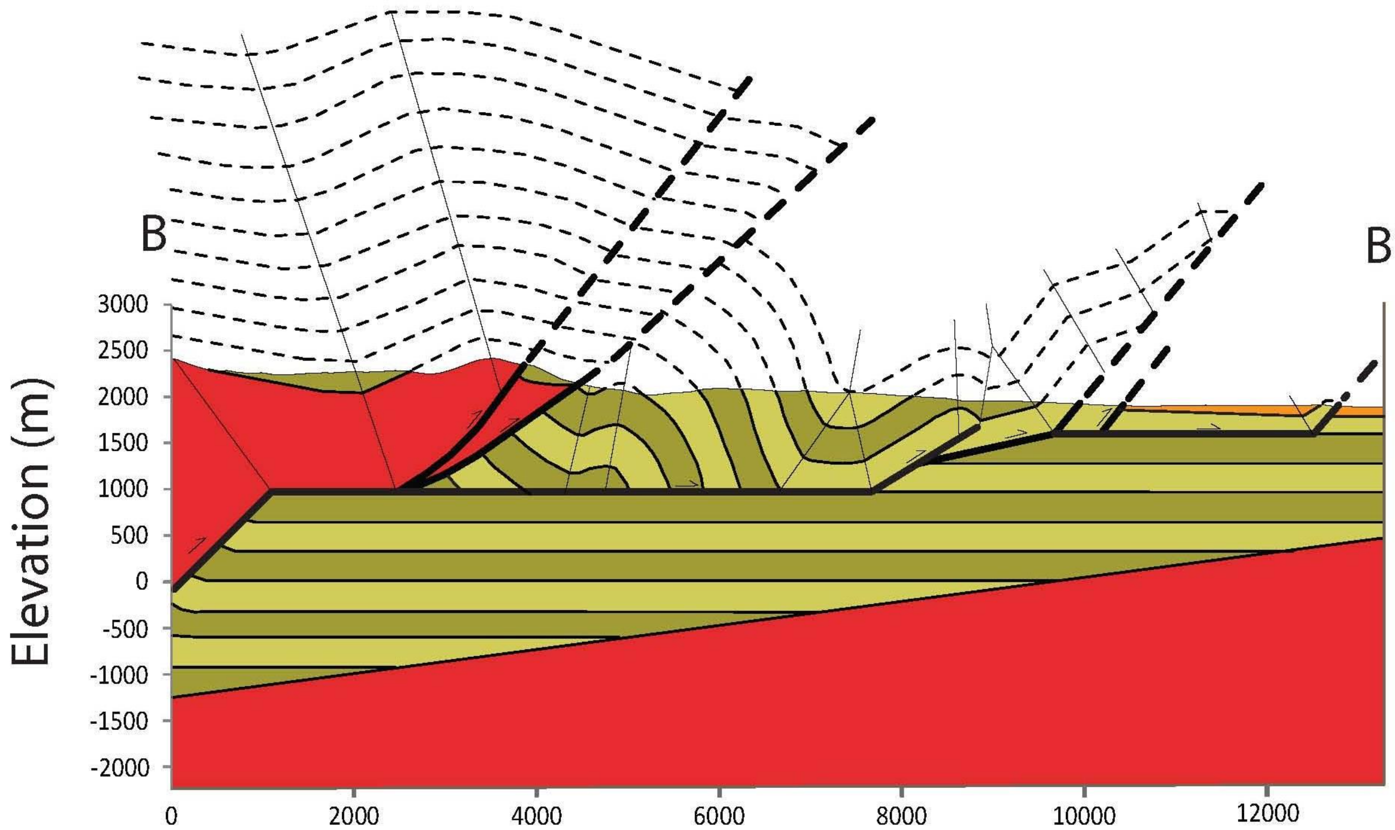

Figure 18- Cross section B-B'. Here we have the same fault propagation fold as in Figure 16. The steep limb has again moved over a fault bend, so we can see an over-steepened dip of about 60-70 degrees rotated from an initial 35-45 degrees. The southern shallow limb in the footwall of the South Kochkor Fault exhibits a tight pair of folds that may be caused by the compression experienced from basement in the hanging wall moving along the fault. Complex ramps along the Akchop Hills zone have created a newer propagation fold from a blind thrust fault splay. The South Kochkor Fault has more offset here and has multiple splays. The ramp to detachment bend is located such that it causes basement to fold as it is translated over the bend. Total fault offset is around 7.9 km with 4 km of structural relief and 5.9 km of shortening (33%).

result of fault bend folding and compression from basement moving up the South Kochkor Fault (step 2, Figure 17). The larger syncline in the hanging wall has formed from basement moving up the ramp of the South Kochkor Fault.

Cross section C-C' displays structural relief generated almost exclusively by fault slip; here the total fault slip is nearly 8 km (Figure 19). In the hanging wall of the South Kochkor Fault there is evidence of basement folding as it moves over fault bends. The topography implies an anticline-syncline pair from propagation of the detachment and the ramp of the South Kochkor Fault. The granite near the South Kochkor Fault is pervasively deformed and brecciated, with visible foliation (Figure 5), much more so than the granite south of the folded area. North of the fault is a broad, folded geomorphic surface underlain by colluvium and alluvial material that caps the slope and forms a footwall syncline with the ramp of the Akchop Hills Fault. Within the syncline, there is a round, uplifted region that has been deeply incised compared to the rest of the surface. Air photo interpretation suggests that incision is exposing Sharpyldak in what appears to be a small anticline popping up within the larger syncline. We have interpreted this to be a fold propagated from a steep splay off of the detachment. As can be seen in Figure 18, the detachment underlies a broad syncline between the Akchop Hills and South Kochkor Faults; therefore, a fault splay produces a spatially limited anticline (Figure 13).

The presence of north-dipping Neogene strata, inferred by a significant slope in topography north of the South Kochkor Fault, suggests fault-bend folding and helps to constrain the amount of slip along the detachment. The smaller anticline in the footwall indicates propagation of a small fault splay from the detachment. Neogene rocks on the

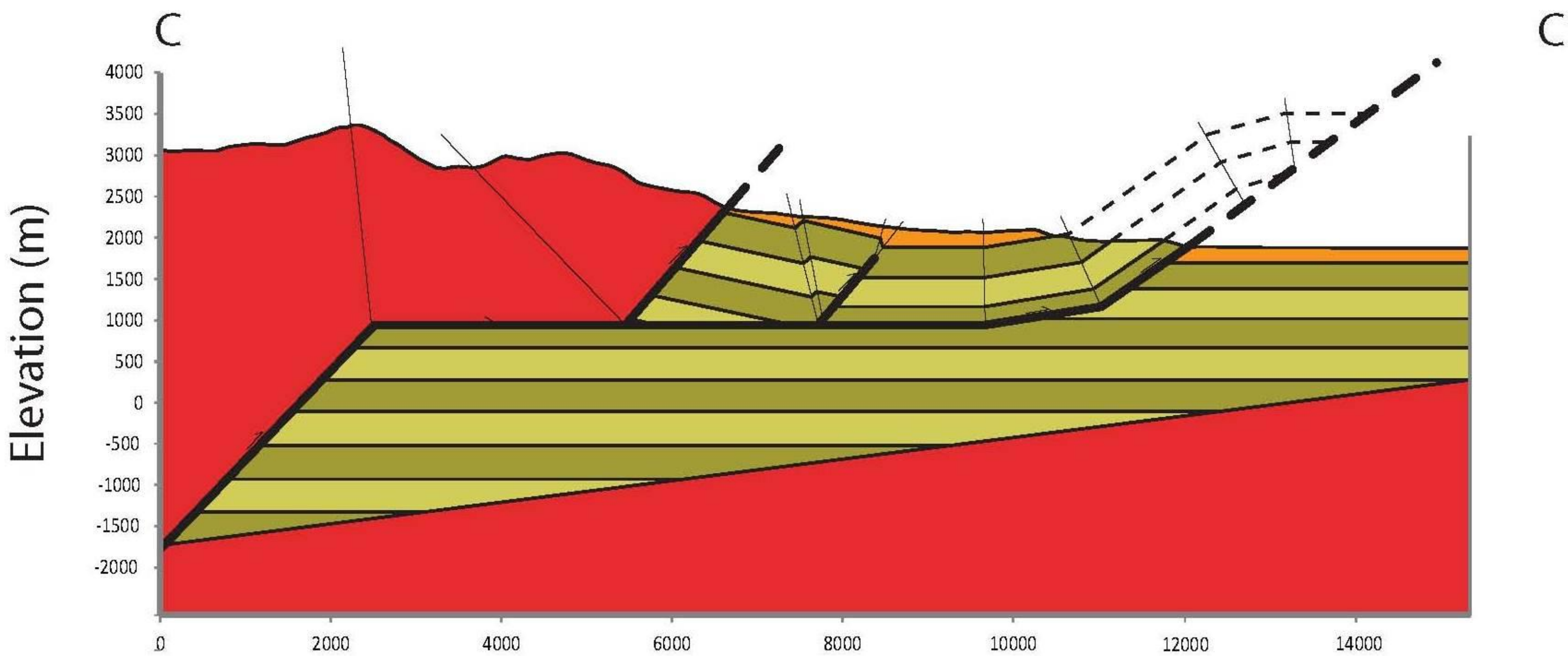

Figure 19- Cross section C-C'. In this region there was no apparent initial folding. Just north of the South Kochkor Fault there is about 2 km of north dipping beds (~30 degrees). These beds were tilted by fault-bend folding. The detachment in this transect ramps up in two, increasingly steeper ramps (~10, 45 degrees) creating a dip slope with the uplifted Chu equivalent and Sharpyldak formation. A small fault splay creates an anticline bump in the gently sloping, terrace-topped surface where increased incision has exposed Sharpyldak formation. The South Kochkor Fault has substantial offset on it here (at least 2 km) and there is a large portion of Paleozoic basement topping Neogene sediments, and folding as it encounters fault bends. The total fault slip here is about 7.8 km generating at least 5 km of vertical structural relief and 6.2 km shortening (35%).

Akchop Hills Fault ramp have two distinct dips of 10-15 degrees and 40-50 degrees, indicating a two-part fault ramp that steepens upward.

Across the basin margin, there has been ~33% shortening. I calculated this by comparing undeformed length of the Neogene with the deformed length so it includes shortening attributed to both folding and faulting. In order to measure the cumulative surface fault slip I measured all apparent fault offsets in each cross section. This method doesn't include the amount of deep fault slip that was needed to create the initial fault propagation fold that generated about half of the total structural relief across the margin.

Through the Tien Shan multiple generations of basement-cored uplifts have bisected established basins, creating two basins separated by a young range, as in the Naryn Province. This chronology applies at the South Kochkor margin where the young Tersky Range has been uplifted. Here, it is important to note that the sediments are not syntectonic with the local uplift, but were already deposited at the time of fault propagation folding and thrusting. This is evident because there is a lack of unconformities or growth strata along the range front. The parallel-bedded initial sedimentary package implies that the fault zone must post-date the Neogene strata.

CHAPTER III

DISCUSSION

Structural Implications

Along strike there is significant variability of structures that accommodate shortening across the margin. West of the field area there is only a bedrock fault lifting Paleozoic granite above the basin and the beginning of the Aigyrdzal Hills Fault. Along strike, this bedrock fault splits into the South Kochkor Fault and the Akchop Hills Fault. In this same western area, we see more splays of the Aigyrdzal Hills Fault north into the basin. From the initial split to the Djuanarik River there are three fault zones with multiple splays and large folds that have shared relief generation and shortening between them. Across the Djuanarik to the east, there are only two distinct fault zones, the Akchop Hills and South Kochkor, and no large folding. Farther east, past the study area, the Akchop Hills Fault tapers out and the single South Kochkor Fault remains.

Through field mapping and multiple cross section models I have constructed a hypothesis for the structural evolution of the southern margin of the Kochkor Basin. These cross sections (Figures 16, 18, 19) illustrate the subsurface variability as well and give us an idea of how shortening is partitioned between deep faulting, shallow detachment faulting and large-scale fault propagation folding. The area west of the Djuanarik River is characterized by multiple faults and heavy folding. It is apparent that about half of the 4 km of structural relief in this area is generated by the initial fault propagation folding. Firstly, propagation of the shallow detachment or related faults could not have generated the fold geometry that we see in the folded Neogene rocks. The 2 km vertical panel is too steep and thick to have been deformed by fault-bend folding alone. It would require a vertical fault bending 90 degrees to deform horizontal bedding to that degree (Medwedeff and Suppe 1997). Therefore, the folding must have been the result of a deep-propagating fault tip (Figures 16, 18), the depth of which is constrained by the position of the fold's synclinal and anticlinal hinges. While fault propagation folding could have completely turned a vertical limb, I propose a two-stage process because the initial propagation folding was only moderate. Half of the relief must have been generated by faulting. The fold must have existed before any detachment propagation because it has been secondarily deformed by a fault bend. In addition, the faults in the valley must connect to the range front fault, meaning the propagation fold must be in the hanging wall of a detachment. The South Kochkor Fault alone does not have enough displacement to generate 4 km of relief. West of the river the fault has only tens to hundreds of meters of slip; not enough to create a 2 km wide panel of vertical beds. The other half of the relief must have been generated by material moving up the deep ramp and onto the detachment. In the vicinity of A-A', we see the South Kochkor Fault terminate adjacent to a depositional contact between Neogene and Paleozoic. This constrains the fault offset along the west side of the map to significantly less than the 4 km of relief in the area.

Cross section C-C' (Figure 19) suggests that east of the river, fault breakout occurred before a large propagation fold could develop. As a result, this region is only minimally folded and has the most cumulative fault slip near the surface within the study area. There are two possible scenarios to explain the difference in structure from A-A’ to C-C’. One, folding occurred simultaneously, but fault breakout happened earlier to the east and subsequently moved westward, or two, folding initiated to the west and developed to the east over time, then fault breakout occurred simultaneously. The first option is more likely, folding occurred all at once, and the initial fault breakout propagated from east to west as this is typical fault growth behavior observed in the Tien Shan (Naryn Basin, Burbank et al. 1999). The fault breakout would have initiated at an early stage of folding east of the Djuanarik River and subsequently propagated westward into increasingly more folded strata.

Given the proximity of the three cross sections, there is significant along-strike variability between them. Aside from the similar basic structure of the basin margin, there are three features that evolve along strike: the ramp geometry just south of the Akchop Hills breakout, the horizontal location of the fault bend that connects the steep crustal fault with the shallow detachment and the presence of the Aigyrdzal Hills Fault. The ramps of the three cross sections must be modeled differently to satisfy the surface geology; A-A’ has a very basic flat to ramp fault bend (Figure 16), C-C’ has a steepening, two stage ramp (Figure 19) and B-B’ lies somewhere in the middle with an additional splay off of a ramp (Figure 18). Additionally, in all three sections the detachment is 1-1.5 km deep. This is an important consistency between the sections because the detachment is the major structure. From section to section the differences in the Akchop Hills Fault bend evolve with a logical progression. Given the great variety in observable surface structure (such as fault traces and large folds) from one area to the next, it would not be unreasonable for faults to also behave differently at depth on that same scale.

The south edge of the detachment, where it connects to the deep crustal reverse fault, varies in location from east to west. In A-A' the bend is just south of the South Kochkor Fault under the shallow monocline in the hanging wall (Figure 16). Eastward, it progresses to >2km south of the South Kochkor Fault at the C-C' transect (Figure 3). A possible explanation for this might be that the deep crustal fault is not striking parallel to the other exposed fault traces along the margin. If the fault has a northwesterly strike, similar to other large structures south of the Tersky Ala-Too range (Figure 2), this may account for the apparent trend of the location of the fault bend from west to east.

The Aigyrdzal Hills Fault zone consists of young, active faults at the north end of the deformation zone. This zone is only west of the Djuanarik River and extends about 20-25 km westward before meeting up with the South Kochkor Fault. It is this region, west of the Djuanarik River; the Akchop Hills Fault does not appear to be active anymore. Instead, the Aigyrdzal Hills are accommodating all of the modern shortening, except the .2 mm/yr. along the South Kochkor Fault (Thompson et al. 2002). This western segment of the Akchop Hills Fault has no clear scarp or dip slope and the hills near its trace are low relief and heavily eroded suggesting that it is no longer active. The Aigyrdzal Hills, on the other hand, have a clear scarp and barely eroded dip slope in the hanging wall. East of the river, where only the South Kochkor and Akchop Hills Faults exist, the Akchop Hills breakout exhibits a clear dip slope and scarp trace. In only 25 km east to west, shortening along the south Kochkor margin is transferred between two completely different fault zones.

We can infer some temporal relationships between the major structures in the study area. Figure 17 is a three-panel schematic illustrating the main steps in generating the structures we see today. First, a broad fault propagation fold began to form. Given the dips of the limbs and proximity of the hinges, the fault tip must have been quite deep at the time of fold generation. When the deep crustal fault propagated to the point that it encountered the Neogene sediments, it formed a sub-horizontal detachment fault that propagated north into the valley, most likely utilizing bedding planes where possible and breaking out into the Akchop Hills Fault. Lastly, the detachment propagated northward and Aigyrdzal Hills Fault broke to the surface and secondary splays formed, creating small propagation fold anticlines. Since these smaller splays have not yet reached the surface and break off of the existing detachment, they are probably younger than the Akchop Hills and Aigyrdzal Hills Faults.

Timing of the breakout of the South Kochkor Fault west of the river remains somewhat in question. Given the position of the fault relative to the overall fold, it is unlikely that the original breakout would occur behind the anticline hinge of the fault propagation fold. It is more likely that the detachment formed first and the South Kochkor Fault is just another splay off the detachment. This timing differs east of the river, where there is at least 2 km of displacement on the South Kochkor Fault and, given the lack of folding, there had to be fault activity for a longer amount of time. The well-developed South Kochkor Fault must have broken out east of the river (Figure 19) before it broke out to the west (Figures 16, 18). It most likely broke out before the detachment, while fault propagation folding was still taking place to the west and has subsequently been offset to the north along the detachment.

In the larger regional geography, Kochkor Basin and the Tersky Ala-Too range sit between the older Kyrgyz and At-Bashi ranges to the north and south respectfully. North of At-Bashi is the Naryn Basin, which contains similar Neogene strata to Kochkor as well as markedly similar structural evolution which will be further discussed in the next section (Burbank et al. 1999). Between the Tulek Basin south of Kochkor and the Naryn Basin the Paleozoic erosion surface is exposed. I hypothesize that Kochkor was once part of a larger basin whose sediment deposition was controlled by exhumation of a more distal range (like the Kyrgyz range) and spanned from the erosion surface north of Naryn to the Kyrgyz Range. Subsequently, a structure propagated from the mid-crust and thus initiated uplift of the modern day Tersky Ala-Too range and divided the large basin into smaller ones: The Tulek Basin (south) and the Kochkor Basin. There is strong evidence to support the idea that structures at the south Kochkor margin post-date deposition of the Neogene rocks. We observed no growth strata or indicative angular unconformities throughout the formations. Similarly, there are no inter-fingering coarse gravels near the range front that might indicate syntectonic deposition. This supports the hypothesis that the structures seen in the Kochkor Basin are markedly younger than the age of the Neogene strata.

Comparison to Other Work

Before the increase of western work in the Tien Shan, there were many studies done by Russian scientists. Tarasov (1970) worked specifically in the Kochkor region and his cross section is pictured below (Figure 20). He interpreted the vertical panel of Neogene rocks as a drag fold caused by the uplift of Paleozoic basement along a vertical reverse fault. These vertical faults shallow toward the surface in order to reflect the dips we see in the outcrop. This style of vertical tectonics is typical of past Russian work.

Others, such as Dmitrieva and Nesmeianov (1982) also interpret basin-bounding faults as vertical, with an abrupt bend to shallow at the surface. The issue with this interpretation is that vertical faults do not allow for horizontal shortening, yet the basins in Russian cross sections still exhibit shortening-related folding. In order to create a model that accomplishes horizontal shortening, we need to operate under the theory of horizontal tectonics, just as Western scientists have applied to their research (Thompson et al. 2002, Abdrakhmatov et al. 2001, Bullen et al. 2002, Park et al. 2003, Burbank et al. 1999). Where Russian scientists interpret a drag fold as the cause for vertical bedding, we have interpreted it as a classic example of fault propagation folding which is far more capable of generating the forces and geometry necessary to create a 2 km thick panel of vertical-dipping beds (Medwedeff and Suppe, 1997). Tarasov (1970), in his cross section of Kochkor, did not recognize the Akchop Hills or Aigyrdzal Faults. Instead, the deformed and exposed areas of Neogene rocks are interpreted as small folds that bump above the valley floor. Once again, with vertical faults, there is no source of compression or shortening that could create such folds. One similarity between my interpretation and Tarasov's (1970) interpretation is the shallow southward dip of the basement under the basin. His cross section depicts northward thinning in the Neogene leading up to a contact where the Neogene laps onto the Paleozoic basement (Figure 20a).

Studies specific to the south Kochkor margin have all resulted in similar fault geometries to one another and large-scale structural relationships. They agree that there is some degree of fault propagation folding followed by a steep crustal fault breakout and a shallow detachment (Park et al. 2003; Abdrakhmatov et al. 2001; Thompson et al. (2002). The detachment (Akchop Hills) and the South Kochkor Fault must meet up

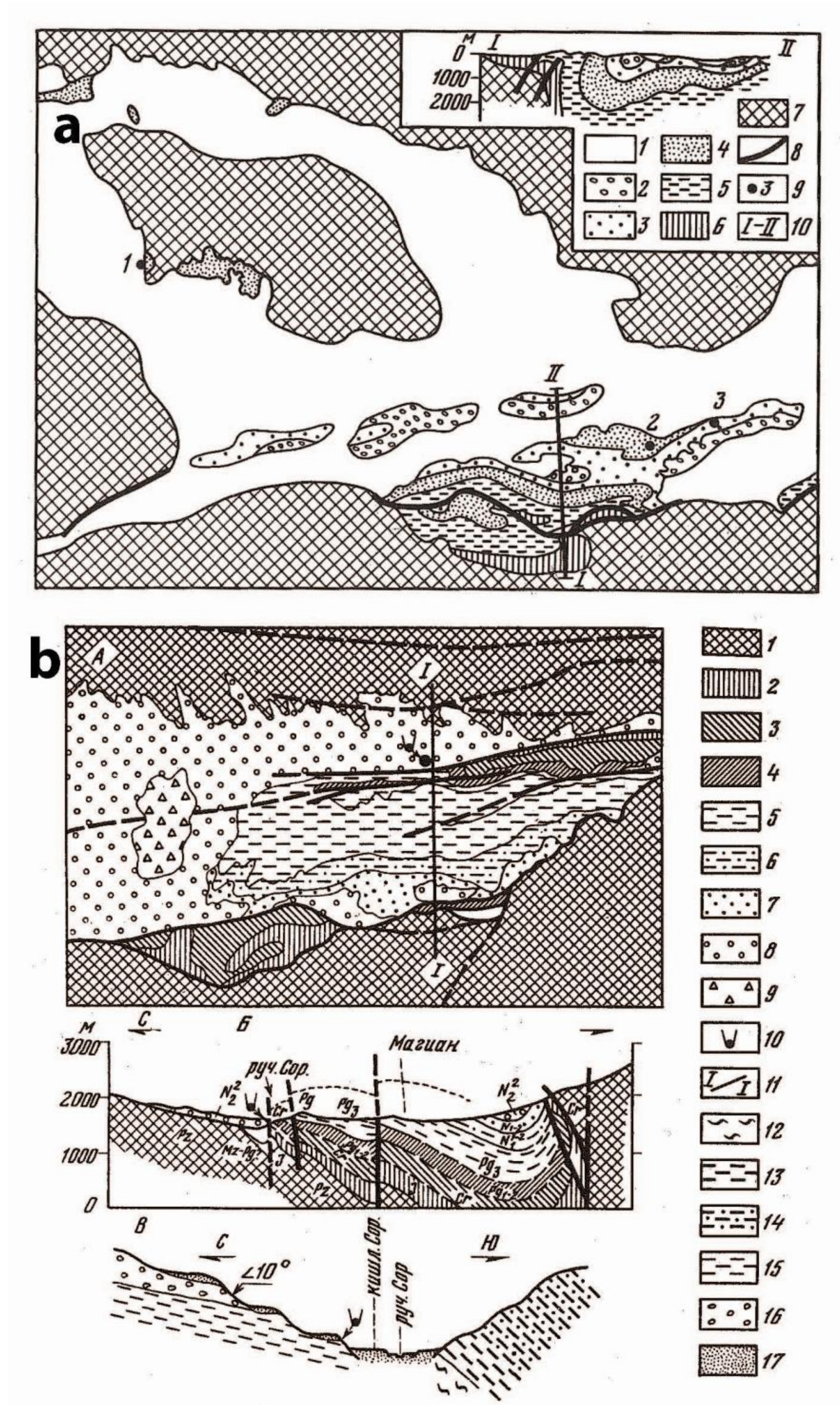

Figure 20-Russian maps and cross sections of Tien Shan basins. Note the vertical faults bounding basement. They shallow at the surface to reflect dips observed in outcrop. Within the sedimentary basins, Neogene rocks are folded in a drag fold. From Dmitrieva and Nesmeianov (1982). Image a) is the Kochkor Basin, adapted from Tarasov (1970). Image b) is from the Fergana valley, by Dmitrieva and Nesmeianov (1982).

and they do so less than a few kilometers below the surface (Park et al. 2003). Park et al. (2003) and Thompson et al. (2002) agree that the fault bend that transitions from the deep crustal fault and the detachment must be at least 2 km into the Tersky Ala-Too Range (Figure 15). This supports my hypothesis that the deep fault could be striking more NW than the local basin faults and, therefore, become farther away from the basin to the east.

As for more specific structure, there are limited cross sections from Abdrakhmatov et al. (2001) and Thompson et al. (2002), created primarily from terrace deformation data and attitudes taken only along the Djuanarik River (Figure 21). Near the breakout of the Akchop Hills Fault, the section includes a fault splay creating the tight-hinged anticline that we also see in the hanging wall syncline of the Akchop Hills Fault. Both sections have a ~10 degree fault ramp off which the steeper (~45 degrees) fault splays from (Abdrakhmatov et al. 2001; Thompson et al. 2002). Similarly, my B-B' section has a two part ramp with similar dips that propagates out from the sub-horizontal detachment. There is a noteworthy difference between my work and others with regard to this shallow ramp; both Abdrakhmatov et al. (2001) and Thompson et al. (2002) have extended this ~10 degree ramp as the basal detachment without it shallowing further. This disagreement could be a result of the basic assumptions I made in constructing the cross sections: I assumed all unfolded strata was within a few degrees of horizontal. The other studies assume a subtle but constant dip that spans the width of the basin and reflects a tilt in the basement erosional surface (Figure 4). The Neogene on the north side of the Kochkor Basin is visibly lapping onto the south-dipping Paleozoic basement and appears to be sub horizontal. Additionally, south of the Akchop Hills Fault in section A-

A’, there is a flat alluvial plain that suggests the Neogene rocks are sub horizontal beneath it.

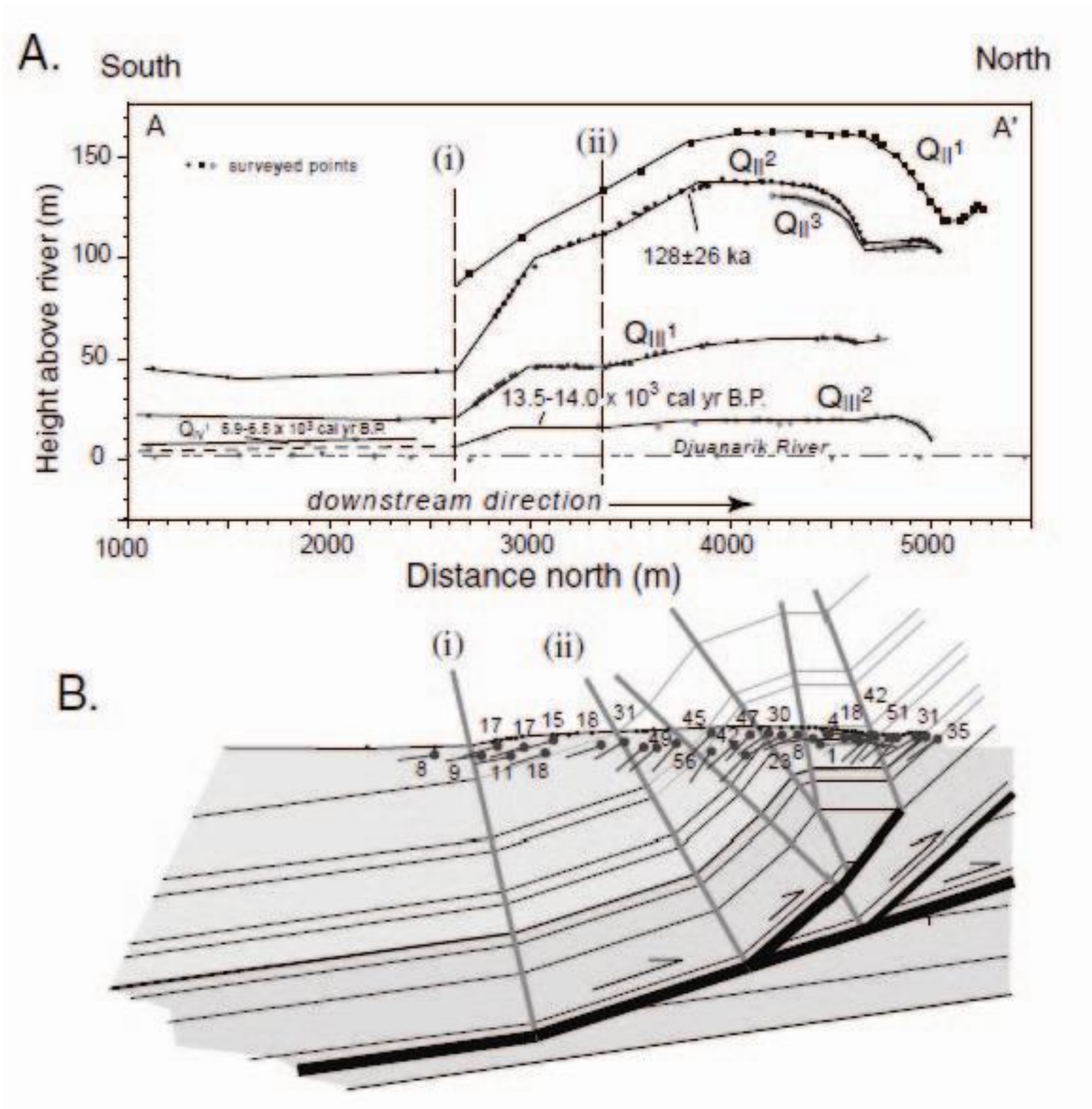

Figure 21- A) Terrace profiles along the west side of the Djuanarik River from Abdrakhmatov et al. (2001, Figure 4) study. Data indicates that hinge (i) is currently active and hinge (ii) is inactive. B) Structural cross section of the same area. Strikes and dips are indicated at the surface and hinges are marked with grey lines. The sections show a gently dipping detachment breaking along beds of the same dip. The ramp progressively steepens to break at the surface and create additional splays. Aside from the non-horizontal detachment, this is the same structural pattern that I determined for B-B’ at 8-10 km (Figure 18).

This is a fair assumption because we observe outcrop of the Neogene everywhere that it is dipping more than a few degrees. So for the purposes of my cross sections, I assumed horizontal strata deposited on an 8 degree (Abdrakhmatov, et al. 2001), south-dipping basement (Figures 17, 18, 19).

Park et al.'s (2003) magnetotelluric study resulted in a cross section constructed from the imaging. It indicates a shallow detachment, much like mine, and a substantial package of sediments over thrust by Paleozoic basement. In Park et al.'s study area, the tip of the deep crustal fault is located farther south than the C-C' cross section and the two faults are connected by a flat detachment. This follows the pattern of growing distance between the breakout of the South Kochkor Fault and the deep crustal fault. Overall, Park et al. (2003), Abdrakhmatov et al. (2001) and Thompson et al.'s (2002) studies, conducted with two different methods have resulted in similar results to mine as far as fault geometry is concerned. Temporal relationships, aside from the acknowledgement of initial fault propagation folding, are not addressed except to say that the timing between South Kochkor and Akchop Hills could not be determined (Park et al. 2003).

There are some marked similarities between structural studies done in other basins within the Tien Shan such as the Chu Basin to the north (Bullen et al. 2001 and 2003), the Naryn Basin to the south (Burbank et al. 1999) and Issyk-Kul Basin to the east (Burgette, 2008). The Chu Basin, north of the Kyrgyz range, is a sedimentary basin much like Kochkor. The Neogene strata are nearly 4 km thick here and, because more research has been done on the stratigraphy, are defined in more detail. The deformation in the Chu Basin is thought to be about 10 million years old, which constrains deformation in the Kochkor region to at least that young (Bullen at al. 2001). Bullen et al. (2001) describes a steep basement fault that connects to young inter-basin faults by way of a shallow detachment. There is also a well-developed backthrust that incorporates basement. This is a similar structural framework to the Kochkor Basin with some variations. Unlike Kochkor, the Chu Basin Neogene rocks have not undergone as much folding. Fault bend folds are present in the hanging wall of the Issyk-Ata Fault which has propagated into the basin (analogous to the Akchop Hills Fault) but there is no evidence of fault propagation folding. The lack of folding could be due to the growth strata and prograded gravels that are in the Neogene rocks (Bullen et al. 2001). These types of sediments could make it more difficult to fold since they did not have consistent bedding planes for shearing. In summary, both Kochkor and Chu Basins share a similar basic fault structure of a steep bedrock fault that propagates into a basin along a shallow detachment. In terms of folding, however, the Chu Basin has almost no shortening or relief generation from folds. In the Kochkor Basin shortening and relief generation are partitioned differently between fault and fold structures.

In the Naryn Basin, there is substantial evidence for basement-involved folding (Burbank et al. 1999). Large fault propagation folds have had the Neogene rocks stripped away, leaving the more resistant Paleozoic basement exposed within the fold limbs. This supports our model of the basement in the hinterland of the South Kochkor Fault folding as it is translated over multiple fault bends. Unlike in the Kochkor Basin, Burbank et al. (1999) found very laterally consistent fault geometry, indicated by widespread uniform dip panels. This could be due to the uniformity between the types of structures partitioning strain along the south Naryn margin. *En echelon* fault propagation folds seamlessly distribute shortening along strike without much partitioning shared between faults and folds (Burbank et al. 1999). In the Kochkor Basin, on the other hand, what begins as two simple fault zones to the west (South Kochkor and a single splay of Aigyrdzal Hills) transitions into three intricate fault zones bounding high relief fault propagation folds along strike to the east. Here, there is clear partitioning along the basin margin, but it is more complex by accommodating shortening between multiple overlapping fault zones and significant folds. With regard to the temporal relationships between fault breakouts, Burbank et al. states that there is no uniform sequencing northward into the basin. This is not entirely true in the Kochkor Basin, because the Akchop Hills Fault is no longer active west of the Djuanarik River and the Aigyrdzal Hills Fault has taken over most of the shortening; however, the South Kochkor Fault is still active (.2 mm/yr, Thompson et al. 2002). Similarly, faults on the east side of the river have exhibited a sequential progression as the South Kochkor Fault in this region is inactive and the Akchop Hills Fault accommodates all active shortening.

East of Kochkor is the large Issyk-Kul Basin, bounded on the south by the same Terskey Ala-Too Range as Kochkor. Here, Reed Burgette conducted research for his dissertation using deformed terraces to model the structural geometry in the area. Just like in Kochkor, the southern margin of Issyk-Kul has large structural relief with only minimal fault offset on the bedrock fault. Neogene rocks in the Issyk-Kul Basin are not syntectonic with the local range (Terskey), just as in Kochkor. In this region the Shamsi, Chu and Sharpyldak formations can all be found deposited directly on the Paleozoic erosion surface. This depositional relationship supports my assertion that the Neogene strata laps onto the gently dipping basement in my area as well. In addition to the steep bedrock fault, there are a series of backthrusts that also incorporate bedrock and may be accommodating tri-shear from a deep fault propagation fold (Burgette, 2008, Figure 22). The degree of fault propagation folding in Issyk-Kul is less extreme than in Kochkor, the strata dip moderately north, no more than about 50 degrees and the dip panel extends for around 10 km. Despite the similarities of fault propagation folding between the two areas, faulting at the southern margin of Issyk-Kul does not propagate northward along a detachment; rather, the steep fault tip continues to propagate, generating a narrower panel of steepening beds as it nears the surface. The mechanisms that initiated uplift in the Issyk-Kul Basin are very much the same as those along the south Kochkor margin; however, as the structures matured, they continued to accommodate shortening and relief generation in very different ways. A shallow detachment in the Kochkor Basin is shortening the southern margin and translating an old fault propagation fold northward while the Issyk-Kul Basin continued fault propagation folding which, in turn, caused a series of bedrock-involved backthrusts that accommodate tri-shearing.

Aside from a few small variations in structural mechanisms and relationships, active basin margins throughout the central Tien Shan accommodate shortening in the same way. Steep basement faults initiate varying degrees of propagation folding, and as they develop, tend to incorporate basement into large fold structures. As these steep faults encounter Neogene strata, they tend to propagate away from the hinterland along shallow detachment faults that eventually break the surface by means of steeper ramps (30-45 degrees).

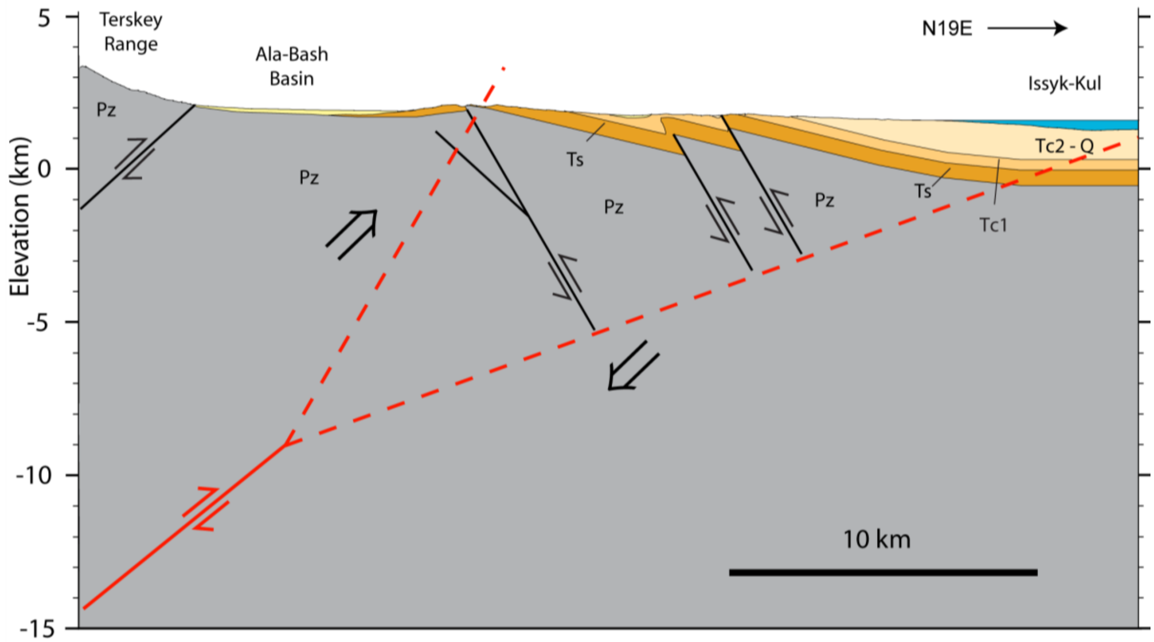

Figure 22- A cross section from the southern margin on the Issyk-Kul Basin. There is a large panel of Neogene sediments incorporated in a deep fault propagation fold. Backthrusts accommodate tri-shear in the thick section of basement involved in the folding. Neogene strata dip moderately to the north, never dipping more than ~50 degrees. Figure 26 from Burgette, 2008.

Conclusion

The primary mechanisms for relief generation along the southern margin of the Kochkor Basin are a combination of fault propagation folding and steep (~45 degree) reverse faults. A steep fault, propagating from the mid crust, caused fault propagation folding at the surface. As the fault encountered Neogene sediments, it shallowed and the fold has been subsequently translated along this detachment structure in the hanging wall. The detachment broke out into the Akchop Hills Fault and Aigyrdzal Hills Fault. Further structural relief has been generated by breakout and slip along the South Kochkor

Fault- this relief is on the order of tens of meters to the west, and grows to over two kilometers to the east.

There is a trade-off between folding and faulting in a consistent trend within the study area. Cumulative fault slip in the western region of greatest folding is ~5.5 km; in comparison, slip to the east amounts to nearly 8 km where there is no sign of any fault propagation folding. Similarly, the location of the fault bends that transition from steeply dipping, crustal fault to shallow detachment changes from west to east. As we move east, this fault bend is farther south under the Tersky Ala-Too range, resulting in an increasing amount of basement that is thrust over Neogene sediments.

The structural patterns and relationships between faulting and folding across the Kochkor Basin's southern margin are similar to what other scientists have found in nearby basins in the central Tien Shan. Uplift is initiated by a steep, bedrock fault that may cause fault propagation folding at the surface. Eventually, this deep fault tip either propagates to the surface, as in the east area of my study area; or propagates along a detachment further into the valley, as in the west. As rock continues to move along the faults, younger episodes of fault-bend folding occur. These fault-bend folds often incorporate crystalline basement. Throughout the deformation zone, shortening is partitioned between different structures along strike.

REFERENCES CITED

Abdrakhmatov, K. Ye., S. A. Aldazhanov, B. H. Hager, M. W. Hamburger, T. A. Herring, K. B. Kalabaev, V. I. Makarov, P. Molnar, S. V. Panasyuk, M. T. Prilepin, R. E. Reilinger, I. S. Sadybakasov, B. J. Souter, Yu. A. Trapeznikov, V. Ye. Tsurkov, and A. V. Zubovich. "Relatively Recent Construction of the Tien Shan Inferred from GPS Measurements of Present-day Crustal Deformation Rates." *Nature* 384.6608 (1996): 450-53.

Abdrakhmatov, Kanatbek, Ray Weldon, Stephen Thompson, Douglas Burbank, Charles Rubin, Meghan Miller, and Peter Molnar. "Onset, Style and Current Rate of Shortening in the Central Tien Shan, Kyrgyz Republic." *Russian Geology and Geophysics* 42.10 (2001): 1585-609.

Avouac, J. P., Tapponnier, P., Bai, M., You, H., and Wang, G. "Active thrusting and folding along the northern Tien Shan and late Cenozoic rotation of the Tarim relative to Dzungaria and Kazakhstan." *Journal of Geophysical Research*, v. 98, (1993) p. 6755-6804.

Bullen, M. E., D. W. Burbank, and J. I. Garver. "Building the Northern Tien Shan: Integrated Thermal, Structural, and Topographic Constraints." *The Journal of Geology* 111.2 (2003): 149-65.

Bullen, M. E., D. W. Burbank, J. I. Garver, and K. Ye Abdrakhmatov. "Late Cenozoic Tectonic Evolution of the Northwestern Tien Shan: New Age Estimates for the Initiation of Mountain Building." *Geological Society of America Bulletin* 113.12 (2001): 1544-559.

Burbank, D. W., J. K. McLean, M. Bullen, K. Y. Abdrakhmatov, and M. G. Miller. "Partitioning of Intermontane Basins by Thrust-related Folding, Tien Shan, Kyrgyzstan." *Basin Research* 11 (1999): 75-92.

Burchfiel, B. C., Brown, E. T., Qidong, D., Xianyue, F., Jun, L., Molnar, P., Jianbang, S., Zhangming, W., and Huichuan, Y., 1999, "Crustal shortening on the margins of the Tien Shan, Xinjiang, China." *International Geology Review*, v. 41, p. 665-700.

Burgette, Reed J. "Uplift in Response to Tectonic Convergence: The Kyrgyz Tien Shan and Cascadia Subduction Zone." Diss. University of Oregon, 2008.

Chediya, O. K. Morphology and neotectonics of the Tien Shan (in Russian): Frunze (Bishkek), Ilim, (1986). 313 p.

Chen, Jie, D. W. Burbank, K. M. Sharer, E. Sobel, Jinhui Yin, C. Rubin, and Ruibin Zhao. "Magnetochronology of the Upper Cenozoic Strata in the Southwestern Tian Shan: Rates of Pleistocene Folding and Thrusting." *Earth and Planetary Science Letters* 195 (2002): 113-130.

Dmitrieva, E. L., S. A. Nesmeianov. “Mammals and stratigraphy of continental Cenozoic deposits of South-East part of Central Asia.” Academy of Science SSSR, Paleontological Institute, V. 193, Nauka Publishing House, Moscow, 1982.

Ghose, S., Hamburger, M. W., and Ammon, C. “Source parameters of moderate-size earthquakes in the Tien Shan, Central Asia from regional movement tensor inversion.” *Geophysical ResearchLetters*, v. 25, no. 16, (1998) p. 3181-3184.

Ghose, S., Mellors, R. J., Korjenkov, A. M., Hamburger, M. W., Pavlis, T. L., Pavlis, G. L., Omuraliev, M., Mamyrov, E., and Muraliev, A. R. “The M (sub s) = 7.3 1992 Suusamyr, Kyrgyzstan, earthquake in the Tien Shan; 2, Aftershock focal mechanisms and surface deformation.” Bulletin of the Seismological Society of America, v. 87, no. 1, (1997). p. 23-38.

Goode, Joseph K., Douglas W. Burbank, and Bodo Bookhagen. "Basin Width Control of Faulting in the Naryn Basin, South Central Kyrgyzstan." *Tectonics* 30 (2011).

Holt, W. E., N. Chamot-Rooke, X. Le Pichon, A. J. Haines, B. Shen-Tu, and J. Ren. "Velocity Field in Asia Inferred from Quaternary Fault Slip Rates and Global Positioning System Observations." *Journal of Geophysical Research* 105.B8 (2000): 19185-9209.

Makarov, V. I. “New tectonic structures of the Central Tien Shan (in Russian).” Moscow, Order of the Red Banner Geology Institute, Akad. Sci., (1977). 171 p.

Medwedeff, Donald, and John Suppe. "Multibend Fault-bend Folding." *Journal of Structural Geology* 19.3-4 (1997): 279-92.

Mellors, R. J., Vernon, F. L., Pavlis, G. L., Abers, G. A., Hamburger, M. W., Ghose, S., and Iliasov, B. “The M (sub s) = 7.3 1992 Suusamyr, Kyrgyzstan, earthquake: 1. Constraints on fault geometry and source parameters based on aftershocks and body-wave modeling.” *Bulletin of the Seismological Society of America*, v. 87, no. 1, (1997). p. 11-22.

Molnar, P., Brown, E. T., Burchfiel, B. C., Deng, Q., Feng, X., Li, J., Raisbeck, G. M., Shi, J., Wu, Z., Yiou, F., and You, H. “Quaternary climate change and the formation of river terraces across growing anticlines on the north flank of the Tien Shan, China.” *Journal of Geology*, v. 102, no. 5, (1994). p. 583-602.

Oskin, MiIchael E., and Douglas Burbank. "Transient Landscape Evolution of Basement-cored Uplifts: Example of the Kyrgyz Range, Tian Shan." *Journal of Geophysical Research* 112 (2007).

Park, Stephen K., Stephen C. Thompson, Anatoly Rybin, Vladimir Batalev, and Robert Bielinski. "Structural Constraints in Neotectonic Studies of Thrust Faults from the Magnetotelluric Method, Kochkor Basin, Kyrgyz Republic." *Tectonics* 22.2 (2003).

Sun, Jimin, and Zhenqing Zhang. "Syntectonic Growth Strata and Implications for Late Cenozoic Tectonic Uplift in the Norther Tian Shan, China." *Tectonophysics* 463 (2009): 60-68.

Sadybakasov, I. "Neotectonics of the central Tien Shan (in Russian)." Frunze (Bishkek), Ilim, (1972). 117 p.

Sadybakasov, I. "Neotectonics of High Asia (in Russian)." Moscow, Nauka, (1990). 176 p.

Sobel, E. R., and Arnaud, N. "Cretaceous--Paleogene basaltic rocks of the Tuyon basin, NW China and the Kyrgyz Tian Shan: the trace of a small plume." Lithos, v. 50, no. 1-3, (2000). p. 191-215.

Sobel, E. R., and Dumitru, T. A. "Thrusting and exhumation around the margins of the western Tarim Basin during the India-Asia collision." *Journal of Geophysical Research*, v. 102, (1997). p. 5043-5063.

Tarasov, S. A. 1970. Cenozoic geology and neotectonics of the Tien Shan (in Russian): Frunze (Bishkek), Ilim, 211. p.

Thompson, Stephen C., Ray J. Weldon, Charles M. Rubin, Kanatbek Abdrakhmatov, Peter Molnar, and Glenn W. Berger. "Late Quaternary Slip Rates across the Central Tien Shan, Kyrgyzstan, Central Asia." *Journal of Geophysical Research* 107.B9 (2002).