NEOTECTONIC FRAMEWORK OF THE NORTH-CENTRAL ALASKA RANGE

FOOTHILLS

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NEOTECTONIC FRAMEWORK OF THE NORTH-CENTRAL ALASKA RANGE
FOOTHILLS

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by

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ABSTRACT

The northern foothills of the Alaska Range form a northward-convex salient at the apex of this orogen and the Denali fault. Despite the proximity of the northern foothills to the Denali fault and several historic large-magnitude earthquakes, the tectonic framework of this region has not been well-studied. A distinct pattern of east-trending folds and faults exists in both the bedrock and the geomorphic features. To assess the active structures of the region, I interpreted previous geologic mapping, developed cross-sections across the foothills belt, analyzed topographic and stream profiles, mapped the sequence of Quaternary fluvial terraces, and performed GPS transects across several terrace treads. A northward topographic slope across the northern foothills corresponding with the pattern of faulting and folding suggests the presence of an orogenic wedge overlying a south-dipping basal detachment. Mapping and GPS transects show evidence for progressive deformation of the terraces. Geomorphic analyses suggest deformation and differential uplift over the entire foothills belt. These results indicate that the northern foothills are an active fold-and-thrust belt and are prograding northward into the Tanana Basin. Tectonic activity of these structures suggests that this region represents a potential seismic hazard for nearby military facilities and important transportation corridors.

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1 INTRODUCTION

1.1 Introduction

Thermochronologic and stratigraphic studies show that the topography of the central Alaska Range formed by rapid uplift over the past ~6 Ma (Wahrhaftig, 1987; Fitzgerald et al., 1995; and Triplehorn et al., 2000). This uplift is best exemplified by the extreme relief of Mount McKinley (Denali), which stands nearly 5600 m higher than the lowlands less than 30 km to the north (Figure 1.1). The recent uplift is also illustrated by the young topography and deformed Neogene sedimentary rocks of the northern foothills of the central Alaska Range (referred to hereafter as the 'northern foothills'). Clyde Wahrhaftig, who did most of the original geologic mapping and interpretations of the northern foothills, suggested that the late Cenozoic orogeny that uplifted this region ended prior to ~2.8 Ma (Wahrhaftig, 1987). However, interior Alaska shows elevated levels of shallow (<30 km) crustal seismicity (Figure 1.2), much of which has not been correlated with any previously recognized structures (Page et al., 1995). Three historic >M7 earthquakes have occurred in this region, as well as numerous M5-6 tremors (Figure 1.2). Previous studies by Wahrhaftig (1958) and Thorson (1979) documented evidence for fault offsets younger than ~70 ka within the northern foothills. Recent seismologic (Ratchkovski and Hansen, 2001) and geodetic studies (Fletcher, 2002) have documented evidence of contractional motion across the central Alaska Range. Therefore, if this seismicity is a consequence of continuing post-2.8 Ma late Cenozoic deformation, that deformation should be reflected in the geology and landforms of the northern foothills.

Figure 1.1 Location map of the northern foothills study area. The shaded-relief digital elevation model of Alaska (from Riehle et al., 1997) shows the northern foothills study area relative to the topography of Alaska. The Alaska Range extends northeast from the “Anchorage” label, curves sharply to the east, then turns southeast toward its end near the Canadian border.

Figure 1.2 Seismicity map of interior Alaska. Earthquake hypocenters are from the Alaska Earthquake Information Center. Earthquakes between January 1987-September 2002 are relocated locations. Earthquakes prior to 1987 are restricted to $M > 4$ to show significant historical tremors. Post-October 2002 earthquakes are restricted to $M > 2$ to avoid clutter from the aftershocks of the 2002 Denali fault earthquake. Note the predominance of shallow earthquakes north of the Alaska Range and the deeper earthquakes associated with the subduction zone beneath the Alaska Range.

1.2 Objectives

This project is a regional-scale geologic study aimed at establishing a tectonic framework for the northern foothills. My approach to addressing this goal includes four components: (1) Identify the late Cenozoic structures and deformation in the northern foothills through analysis of previous geologic mapping, additional field studies, and analysis of topographic patterns. Few young structures have been specifically identified within the northern foothills, despite significant deformation of Late Tertiary sedimentary rocks. (2) Compile the observations and interpretations of (1) as a basis for a series of cross-sectional interpretations of the deep structure below the northern foothills. (3) Compile and assess trends in longitudinal stream profiles of the major north-flowing streams to establish the regional-scale trends of tectonic activity on the structures identified in (1). (4) Develop profiles of the sequence of fluvial terraces preserved along the Nenana River valley to evaluate the progressive evolution of local structures. The results of this study will be directly applicable to regional seismic hazard assessments and will provide a base for further detailed geological and geophysical studies in and adjacent to the northern foothills.

1.3 Hypothesis

The topography and geologic relationships exposed in the northern foothills suggest that this region is an active fold-and-thrust belt. A simple model of this idea was first presented by Geomatrix Consultants (1997) in their site-specific seismic hazard study for Clear Air Force Station. The arcuate topographic salient, northward decrease in relief, orogen-parallel folds, and abrupt mountain front are all typical of a fold-and-thrust

belt that has built outward from an orogen. Such a model implies the existence of a basal detachment that dips toward the interior of the mountain belt, a topographically tapering wedge, and tectonic shortening (Chapple, 1978). Therefore, through this study I will demonstrate the geologic evidence for a basal detachment and shortening within the fold-and-thrust belt, coupled with the topographic slope toward the front of the range. Furthermore, I will present evidence for the young deformation associated with the ongoing development of the fold-and-thrust belt through the documentation and interpretation of young geomorphic landforms, deformed terraces, and anomalous longitudinal stream profiles.

2 LOCATION AND GEOLOGIC BACKGROUND

2.1 *Location*

The Alaska Range is a 1000 km long arcuate mountain belt that extends from the Alaska Peninsula in southwest Alaska to the Canadian border (Figure 1.1). The northern foothills study area forms a north-convex arcuate salient at the apex of the range, and the shape of the foothills belt mimics that of the Alaska Range. This salient lies outboard of the main axis of the range and is bordered on the north by the broad, swampy Tanana Basin (average elevation between ~120-250 m). Significant high topography near the northern foothills includes the Denali massif (6194 m) to the southwest, and the informally named Hayes Range (a complex of high peaks, culminating in Mt. Hayes at 4200 m) to the southeast, with relatively subdued (highest peaks between 2000-2500 m) mountains in between.

Fairbanks is the largest community in the vicinity, and is located ~70 km to the north. The two major transportation corridors between interior and south-central Alaska pass through and adjacent to the northern foothills. The Nenana River forms a natural corridor across the Alaska Range and the northern foothills that the Parks Highway and Alaska Railroad utilize. Beyond the east boundary of the northern foothills, the Delta River forms another corridor that the Richardson Highway and the Trans-Alaska Pipeline follow across the Alaska Range. Each highway also provides access to a major military facility immediately north of the northern foothills, with Clear Air Force Station (Ballistic Missile Early Warning System) adjacent to the Parks Highway and Fort Greely (with the new National Missile Defense site) on the Richardson Highway.

2.2 Geologic setting and background

Geologically, the northern foothills are situated at the apex of the north-convex curve of the Denali fault (Figure 2.1), which follows the Alaska Range for much of its length. The topographic expression of the northern foothills mimics the arcuate trace of the Denali fault. The southern boundary of the northern foothills is the Hines Creek fault, which is an abandoned strand of the Denali fault system (Wahrhaftig et al., 1975; Csejtey et al., 1982). Part of the significance of this fault is that it is the southern boundary of the metamorphic basement that underlies the entire northern foothills. Also, it appears to be the boundary between right-lateral strike-slip motion related to the Denali fault and dominantly contractional motion in the northern foothills (Fletcher, 2002; Ratchkovski and Hansen, 2001). Page et al. (1995) defined three linear, NE-trending, left-lateral seismic zones (Figure 2.2) to the north and west of the foothills. These seismic zones are inferred to represent fault zones that accommodate clockwise rotation of crustal blocks between the Denali and Tintina faults. The westernmost seismic zone, the Minto Flats Seismic Zone, delineates an abrupt topographic and structural boundary between the Kantishna Hills to the west and the northern foothills study area to the east (Figure 2.2). The other two seismic zones appear to end at the northern foothills mountain front.

Clyde Wahrhaftig mapped most of the northern foothills over the course of numerous field seasons between 1944-63. This work originated as studies of the coal deposits near Healy, and subsequently developed into a study of the Pleistocene problems of this area at the request of the Alaska Railroad (Wahrhaftig, 1958). These studies resulted in a series of eight 15-minute quadrangle maps (1:63,360 scale) that cover much

Figure 2.1 Location map of the northern foothills with regional tectonic elements. Shaded relief base from Riehle et al. (1997). Different colors for faults do not indicate fundamental differences, but rather are for better visibility.

Figure 2.2 Recognized tectonic elements of interior Alaska. DEM of interior Alaska (from Riehle et al., 1997) showing the major recognized tectonic elements adjacent to the northern foothills study area. MFSZ = Minto Flats Seismic Zone, FSZ = Fairbanks Seismic Zone, SSZ = Salcha Seismic Zone (from Page et al., 1995). Note how the MFSZ separates the the E-W topographic grain of the northern foothills from the more NE-trending topography of the Kantishna Hills. The white dot in the northern foothills indicates the location of the town of Healy, Alaska.

of the northern foothills (Wahrhaftig, 1970a-h). Wahrhaftig's maps provide great detail on the geologic relations in the region, but also have a few shortcomings. They show no fold axial traces, despite structure contours, outcrop patterns, and bedrock structure that clearly indicate the locations of numerous folds. Furthermore, Wahrhaftig did not interpret a mechanism for deformation and uplift of the northern foothills in any of the associated literature (e.g., Wahrhaftig, 1970a-h, 1958, 1968, 1987; Wahrhaftig et al., 1969).

2.2.1 Description of stratigraphic units

Wahrhaftig also provided the most thorough definitions of the geologic units of this region. These units (as defined in Wahrhaftig, 1958, 1968, and Wahrhaftig et al., 1969) are almost exclusively pre-Cenozoic metamorphic rocks and Tertiary sedimentary rocks. A few small exposures of Cretaceous and Tertiary igneous rocks (Wahrhaftig, 1970a-h) occur generally as small dikes and stocks. The unit descriptions below are summarized from Wahrhaftig (1968, 1987) and Wahrhaftig et al. (1969), with supplemental references where noted.

Birch Creek Schist (bc)

Newberry et al. (1997) used the name 'Healy schist' for this unit, but since this is not a study of the metamorphic rocks, I use "Birch Creek Schist", the name used by the majority of previous workers (e.g., Wahrhaftig, 1968, 1970e-h; Gilbert and Bundtzen, 1978; Gilbert and Redman, 1977), for descriptive purposes. In the northern foothills, this unit is composed of quartz-sericite schist, quartzite, sericite schist, and minor carbonaceous schist and marble. The protolith is interpreted to be Precambrian or

Paleozoic marine sandstone and shale. This unit is highly deformed and is interpreted to have undergone two metamorphic events (Morrison, 1964; Gilbert and Redman, 1977; and Bundtzen and Turner, 1979). The first episode was a pre-Jurassic regional metamorphism (Bundtzen and Turner, 1979) to lower amphibolite facies (Morrison, 1964). A mid-Cretaceous thermal event overprinted the first metamorphic episode (Bundtzen and Turner, 1979), retrograding this unit to lower greenschist facies (Morrison, 1964).

Keevy Peak Formation (kp)

A band of quartz-sericite schist, black carbonaceous schist, gray/green/purple slate, black quartzite, and stretched conglomerate forms this unit. It lies structurally below the Totatlanika Schist and the contact is likely faulted, although it may originally have been an unconformity. The Keevy Peak Formation has lower greenschist metamorphic facies mineral assemblages (Bundtzen and Turner, 1979). Based on fossil and stratigraphic evidence, Gilbert and Bundtzen (1978) assigned a protolith age of Ordovician to Middle Devonian.

Totatlanika Schist (MDt)

Dusel-Bacon et al. (2004) described this unit as bimodal metaigneous and associated carbonaceous and siliceous metasedimentary rocks. The schist is locally divided into submembers based on the presence of additional lithologies, including marble lenses and carbonaceous schists. Fossils from within a marble lens suggest an Upper Mississippian and Lower Devonian protolith age (Wahrhaftig, 1958; Gilbert and Redman, 1977). U-Pb zircon ages and geochemical evidence from Dusel-Bacon et al.

(2004) suggest a period of Late Devonian to Early Mississippian (376-353 Ma) bimodal magmatism as the source for the protolith of Totatlanika Schist. This unit is highly deformed and structurally thickened, with evidence for multiple metamorphic and deformational episodes.

Usibelli Group (Tug)

The Usibelli Group is subdivided into five formations: Healy Creek, Sanctuary, Suntrana, Lignite Creek, and Grubstake (in ascending order). These formations are poorly consolidated terrestrial sediments deposited between Oligocene and Late Miocene time by south- and southwest-flowing streams, prior to development of the present Alaska Range (Ridgway et al., 1999). The Healy Creek, Suntrana, and Lignite Creek Formations are generally pebbly sandstone with interbedded coal and mudstone, and the Sanctuary and Grubstake Formations are dominated by lacustrine mudstones. Wolfe and Tanai (1980) assigned the Healy Creek Formation to Early and Middle Miocene, with another location as old as Late Oligocene. A 6.7 Ma ash layer (Triplehorn et al., 2000) occurs in the Grubstake Formation near the top of this unit.

Nenana Gravel (Tn)

The Nenana Gravel is massive to thick-bedded, poorly consolidated, well-sorted conglomerate. Average clast size ranges from 1 to 8 cm, and coarsens towards the top of the unit. Interstitial material is coarse to very coarse sand, which also occurs as local lenses. The Nenana Gravel is 1200 m thick near its type section east of Healy and thins northward to ~500 m near the mountain front (Thoms, 2000). This unit is interpreted to be the detritus shed northward from the rising Alaska Range, recording its progressive

growth from ~6 to 3 Ma (Triplehorn et al., 2000; Thoms, 2000). This timing is based on the 6.7 Ma age of an ash layer in the uppermost Usibelli Group (Triplehorn et al., 2000) and the intrusion of Jumbo Dome into the Nenana Gravel near 2.8 Ma (Wahrhaftig, 1987)

Quaternary deposits (Qa)

Wahrhaftig (1970a-h, 1958) defined a great variety of Quaternary surficial deposits, including glacial outwash, alluvial fans, glacial erratics, swamp deposits, stream gravels, landslides, and terrace deposits.

2.2.2 Structural framework of the northern foothills

Wahrhaftig's maps (1970a-h) illustrate a clear pattern of east-trending late Cenozoic folding. Structure contours interpreted for the base of the Nenana Gravel define irregular box-shapes for the folds (Wahrhaftig, 1970a-h; 1987). Of the faults identified by Wahrhaftig (1970a-h), most strike either east or northwest. Thorson (1979) identified an additional fault (the Healy fault) and Thorson (1986) speculated about the presence of several others. Two of these faults (the Healy fault and Healy Creek fault) clearly offset fluvial terraces, indicating activity within the past <70 ka (Wahrhaftig, 1958, 1970b,c; Thorson, 1979; Beget and Keskinen 1991). Geomatrix Consultants (1997), Hanson et al. (2002), and Lesh (2002) proposed the interpretation of a fold-and-thrust belt for the northern foothills. Geomatrix Consultants (1997) and Hanson et al. (2002) identified the Northern Foothills thrust fault along the range front of the northern foothills and Hanson et al. (2002) interpreted a simple cross-section based on this fault and the Healy and Healy Creek faults.

2.2.3 Summary of Cenozoic geologic history

The current interpretation of the Cenozoic geologic evolution of the northern foothills is as follows (summarized in Figure 2.3). Provenance analysis and paleocurrent indicators show that the Usibelli Group (beginning in the Oligocene) was deposited by streams that flowed south to southwest across the present location of the Alaska Range (Wahrhaftig et al., 1969; Wahrhaftig, 1987; Ridgway et al., 1999; Lesh, 2002). These sediments were deposited on a basement of Birch Creek Schist, Keevy Peak Formation, and Totatlanika Schist that underlay an erosion surface of moderate relief at the time, as shown by lateral discontinuity and thickness changes in the Healy Creek Formation (Wahrhaftig, 1987). The uppermost unit of the Usibelli Group, the Grubstake Formation, consists of lacustrine deposits with an interbedded ash layer dated at 6.7 Ma (Triplehorn et al., 2000). This formation is interpreted to represent the abrupt paleoflow reversal of the overlying Nenana Gravel due to the first stirrings of uplift of the present Alaska Range. The Nenana Gravel consists of a series of coalescing alluvial fans and braidplain deposits shed northward from the growing Alaska Range (Wahrhaftig, 1958; Thoms, 2000). Wahrhaftig (1958, 1987) interpreted deposition of the Nenana Gravel to have ended at ~2.8 Ma based on deformation of the Nenana Gravel that he interpreted to be caused by the intrusion of Jumbo Dome. The Upper Cenozoic rocks and the geomorphic surface formed by the top of the Nenana Gravel are now deformed into irregular box folds with amplitudes of 600-1800 m (Wahrhaftig, 1987).

A series of glaciations occurred in the central Alaska Range, and Thorson (1986) (supported by Thoms (2000)) suggested that the initial advance contributed the coarse-

Figure 2.3 Timeline for the general geologic evolution of the northern foothills. Note that the figure is not scaled by absolute age.

grained deposits of the uppermost Nenana Gravel in the late Pliocene. The first Pleistocene glacial advance to leave a significant surficial record in the Nenana River valley is what Wahrhaftig (1958) termed the Browne glaciation. The ice lobe from this advance extended just beyond the current mountain front along the Nenana River valley and left an extensive trace of granitic erratics and a few moraines that outline its former extent. After the Browne glaciation, multiple glacial advances left scattered deposits and landforms, although the affinity and timing for some of these deposits are debated in the past literature (Wahrhaftig, 1958; Ten Brink, 1983; Thorson, 1983, 1986; Beget and Keskinen, 1991; and Beget, 2001). The two most recent glacial advances (Healy and Riley Creek) left extensive outwash terraces along the length of the Nenana River valley. The Nenana River valley glacial sequence and inferred ages are summarized in Table 2.1.

Table 2.1 Nenana River valley glacial sequence.

Revised [^] Nenana River valley glacial events	Inferred age
Riley Creek	17-25 ka
Healy glaciation	70 ka [#]
Lignite Creek glaciation*	140 ka [~]
Bear Creek glaciation*	
Browne glaciation	Early to Middle Pleistocene*
Teklanika glaciation*	Late Tertiary or Early Pleistocene*

* Thorson (1986)

[#] Beget and Keskinen (1991)

[~] Beget (2001)

[^] sequence updated from Wahrhaftig (1958) and Ten Brink (1983)

3 TOPOGRAPHIC AND GEOLOGIC EXPRESSION OF LATE CENOZOIC STRUCTURES

3.1 Methods for identifying structures

Several markers are useful for the identification of late Cenozoic deformation in the northern foothills. These markers include the basal unconformity of the Usibelli Group, bedding within the Usibelli Group, the basal unconformity of the Nenana Gravel, the upper surface of the Nenana Gravel, and the fluvial terraces along the Nenana River. Foliations are not reliable markers for identifying recent deformation because of the poly-deformed nature of the basement metamorphic rocks, but are useful where their relation to younger bedding is known. Information on the bedding attitudes, interpreted depth to the Nenana Gravel basal unconformity, and general geologic data are clearly provided in Wahrhaftig's 1:63,360 scale maps (1970a-h) and supplemented with smaller-scale maps of the Fairbanks (Pewe et al., 1966) and Healy quadrangles (Csejtey et al., 1992; Sherwood and Craddock, 1979; Hickman and Craddock, 1976). In addition, I used aerial photographs, digital elevation models (DEMs), and field observations to use topography to constrain the location and shape of the structures.

I first identified many of the folds using the orientation of structural markers, in conjunction with topography. After defining the pattern of folding, I reanalyzed the region to identify the locations of any faults associated with the folding. By combining these observations, I then inferred the location and geometry of several additional faults and folds. The resulting compilation is shown in Figure 3.1.

Map units and symbols

Qs	Quaternary surficial deposits
Tn	Pliocene Nenana Gravel
Tug	Upper Eocene-Miocene Usibelli Group
Tiu	Tertiary undifferentiated intrusive rocks
Tt	Paleocene-Eocene Teklanika Formation (upper Cantwell Formation)
Kcs	Cretaceous lower Cantwell Formation
Kg	Cretaceous granitic rocks
MzPz	undifferentiated Mesozoic and Paleozoic units
MDt	Totatlanika Schist
kp	Keevy Peak Formation
bc	Birch Creek Schist
Thrust fault - solid where known, long dashes where approximate, short dashes where inferred
Fault - with sense of displacement indicated, solid where known, dashed where approximate, dotted where covered
Anticline - solid where known, long dashes where approximate, short dashes where inferred
Syncline - solid where known, long dashes where approximate, short dashes where inferred
Monocline - approximately located
Plunge of fold

Figure 3.1 Revised general geologic map of the northern foothills. Base geology modified from Wahrhaftig (1970a-h), Sherwood and Craddock (1979), Csejtey et al. (1992), Pewe et al. (1966), and Hickman and Craddock (1976). Approximate area of map shown on Figure 1.1.

3.2 Observations of late Cenozoic folds

The late Cenozoic folds in the northern foothills are characterized by dominantly east-trending fold hinges. Most of these folds show some variation along trend, such as multiple plunge directions, changes in fold geometry, and truncation by transverse structures. The level of certainty in location and correlation of fold hinges is indicated through the symbology used in Figure 3.1. Most of the names used here are introduced informally for this study, unless otherwise noted.

Rex anticline

The Rex anticline forms the topographic mountain front along the entire east-west extent of the northern foothills study area. It is generally an asymmetric anticline with a steeply north-dipping (~30-90 degrees) forelimb and, in general, a gently south-dipping backlimb. However, between Windy and Tatlanika Creeks, this fold has a roughly symmetric box-like shape with a 3-5 km wide crest. Also, east of Tatlanika Creek, this structure changes to a monoclinial geometry, with a steep forelimb and nearly horizontal backlimb.

Bear Creek syncline

This is the next fold south of the Rex anticline. It extends from the topographic break of the Minto Flats Seismic Zone eastward to near Bonnifield Creek, where its end is defined by the flat upper surface of the Nenana Gravel. The shape of the fold varies from gently-curved west of the Nenana River, to box-like east to the Totatlanika River, then gently-curved again east to its end. Limb dips in the west portion are less than 15

degrees, in the central portion between 10 and 30 degrees, and in the east less than 10 degrees.

Ferry syncline

The Ferry syncline begins near the Nenana River and extends east to where it appears to merge with the Bear Creek syncline near Tatlanika Creek. Near its west end, it has an angular hinge, with the north limb dipping ~30 degrees S, and the south limb dipping ~5 degrees N. The geometry of the hinge changes to the east, where the fold is more rounded. Where exposures of the Tertiary rocks end along the fold hinge to the east, the continuation of the syncline is reflected by topography that mimics the structure of the Tertiary rocks located along the strike of the hinge. Here the foliation attitudes also define the location of the syncline. At its east end the structure becomes indistinct, but clearly must end or merge with the Bear Creek syncline.

Boot Hill anticline

This anticline lies between the Bear Creek and Ferry synclines. It begins near the Nenana River and extends east for ~30 km. The shape of this fold is constrained by Tertiary rocks on its limbs, and the topography of the exposed schists along its hinge zone. This control indicates that the fold generally has a box shape, with limbs dipping 10 to 30 degrees.

Jumbo anticline

This structure is named for Jumbo Dome, a 2.79 Ma (Wahrhaftig, 1987) intrusion near its west end, and extends east to near the headwaters of Bonnifield Creek. Its hinge

is offset and deformed near Tatlanika Creek by the Kansas Creek fault (description in next section). The fold is rounded and both limbs dip approximately 20 degrees.

Needle Rock syncline

This west-plunging syncline extends from the Kansas Creek fault west to where it dies out 5-6 miles east of the Nenana River. It has a rounded to angular hinge, and the limbs generally dip 20 to 30 degrees. The hinge is offset dextrally and vertically on the Kansas Creek fault from the Mystic Mountain syncline to the east (described next).

Mystic Mountain syncline

This syncline extends from the Kansas Creek fault in the west, across the Wood River at least to the east edge of the study area. The western portion of this structure is defined by the presence of the Usibelli Group along part of its hinge, and by the topographic relief of the limbs above the hinge. The eastern portion of the fold is delineated clearly by the outcrop pattern of several subunits of the Totatlanika Schist, and by two isolated patches of the Usibelli Group preserved within the hinge of the fold.

Usibelli anticline

This anticline first becomes evident in the Usibelli Group about 15 km east of the Nenana River, from where it plunges west towards the Nenana River. Its eastern extent is uncertain due to a lack of Tertiary rocks. It is tentatively correlated west across the Nenana River for approximately 8 km. The fold is asymmetric, with an angular hinge, a forelimb to the south with dips of 60 to 90 degrees S (locally overturned), and backlimb dips of 8 to 15 degrees N.

Japan Hills anticline

This doubly plunging anticline begins in the west where it gradually rises out of the Quaternary deposits of the Tanana Basin, and ends in the east where it is cut off by the intersection of two thrust faults. It is asymmetric, with a forelimb to the north with a dip of 15 to 25 degrees N, and a gentle backlimb dip illustrated by the wider outcrop extent of the Nenana Gravel on the south side of the anticline.

Stampede anticline

This fold is a doubly plunging anticline with a broad, rounded hinge, that extends from the Nenana River west to the Minto Flats Seismic Zone. The schist at the core of the fold is exposed locally in a drainage near the Nenana River, providing clear definition of its eastern extent. However, two distinct topographic breaks directly south of the fold at this location suggest additional structures. Otherwise, this anticline is well-defined by the outcrop pattern of units, as well as by bedding within the Nenana Gravel. The fold is asymmetric, with the south limb dipping 30 to 45 degrees S, and the north limb dipping more gently around 15 degrees N.

Eight-Mile Lake syncline

This is the next fold south from the Stampede anticline; however, it extends east across the Nenana River, where it parallels the Usibelli anticline. West of the Nenana River, the Eight-Mile Lake syncline is a wide box-shaped fold, with limbs dipping 30 to 45 degrees. East of the Nenana River, it becomes strongly asymmetric, with a steep to vertical north limb, and a south limb that dips 30 to 40 degrees N. Just west of the

Nenana River, the fold appears to be cut by the Healy Creek fault (described in next section).

Mount Healy anticline

Thoms (2000) first identified (and named) this feature as an active anticline. A prominent, elongate, linear ridge in schist is shown to mark an anticline by the presence of Late Tertiary units on both sides, as well as local smooth geomorphic surfaces that form the crest or flanks of the ridge and are the exhumed unconformity between the Birch Creek Schist and the Usibelli Group. Its west end is near the Kantishna Hills (location shown on Figure 2.2), and it extends eastward at least to near the headwaters of Healy Creek. The lack of Tertiary rocks along strike to the east makes it impossible to trace the fold any farther east.

3.3 Observations of late Cenozoic faults

Introduction

Late Cenozoic faults are exposed in very few known locations in the northern foothills. Most of the reverse faults shown on Figure 3.1 and listed below were inferred using a combination of topography, offset geologic units, and abrupt changes in bedding attitudes. Fault scarps are unlikely to be found in much of the field area because many of these faults are interpreted to be either blind or buried thrust faults. Lettis et al. (1997) define blind thrust faults as “. . . those in which the propagating tip of the fault does not reach the Earth’s surface because (1) the fault geometry precludes it, (2) the fault tip has not yet reached the surface, or (3) the rate of sedimentation is higher than the rate of propagation of the fault tip.” They also define buried thrust faults as those whose fault

trace has been covered by subsequent deposition and/or erosion. Furthermore, in compressional environments, thrust earthquakes of $<M7$ may not produce a significant surface rupture (Carver and McCalpin, 1996). For most of these faults without surface exposures, I cannot distinguish between a blind and buried thrust fault. The names for many of these faults are first introduced in this study, unless otherwise noted.

Northern Foothills Thrust

Geomatrix Consultants (1997) first proposed the existence of this thrust fault. The evidence for this fault lies in the abrupt topographic break that constitutes the mountain front across the entire study area. Hanson et al. (2002) identified several possible fault scarps near the Nenana River. Aerial photographs show a topographic lineation along the base of the range front slope east of Tatlanika Creek. A south dip and reverse slip are inferred from the sinuous trace of the range front.

Japan Hills splay

This south-dipping splay of the Northern Foothills Thrust forms the topographic break on the north side of the Japan Hills, and extends westward into the Quaternary sediments. The eastern end curves back toward the Northern Foothills Thrust and appears to merge with it a short distance east of Wood River. It is uncertain if this fault breaches the surface at any point.

Buzzard Creek fault

The trace of this south-dipping thrust fault is inferred to lie along the north side of the Boot Hill anticline, beginning near the Nenana River and extending east to near the Buzzard Creek Maar, a Holocene volcanic feature (Albanese, 1980). The evidence for

this fault is the change in topographic slope between the Boot Hill anticline and Bear Creek syncline and the asymmetry of the Bear Creek syncline. Also, there is an angular unconformity at the base of the Nenana Gravel in Bear Creek syncline between California Creek and the Totatlanika River.

Kansas Creek fault

Wahrhaftig (1970e, f) mapped this as two separate faults, one on either side of Wood River. Beyond Wahrhaftig's (1970e) mapping, I interpreted this fault to extend northwest to where it joins the Mystic Mountain fault (described next) based on the linear topographic trench that continues along strike with the previously mapped portion of the fault. The segment of this fault west of Wood River shows right-lateral offset of the Needle Rock and Mystic Mountain synclines, and also S-side-up slip defined by the vertical offset of the synclinal hinge. The fault plane of this segment has a strike of $\sim 115^\circ$ and a steep dip indicated by its map pattern cutting nearly straight across topography. The east segment has a strike that changes from $\sim 110^\circ$ to $\sim 90^\circ$ with increasing distance east from Wood River. This segment of the fault appears to have a gentler, south dip, based on the more sinuous trace of the fault over irregular topography.

Mystic Mountain fault

Wahrhaftig (1970a, e) mapped the eastern portion of this fault striking about 110° and extending from Wood River northwest to near the headwaters of Bonnifield Creek. At that location, I infer this fault to turn abruptly 20° to a $\sim 90^\circ$ strike and to extend west to near Jumbo Dome, tracing the topographic break and following a trend of steeply north-dipping Tertiary rocks. The eastern portion shows right-lateral, SW-side-up slip on

a steep fault plane of uncertain dip, and the western portion is dominantly reverse-slip on a gentler south-dipping plane. The character of the Usibelli Group and Nenana Gravel contact changes across the projection of the 110° -striking segment of this fault. To the northeast, the contact is apparently conformable, while a distinct angular unconformity exists to the southwest.

Glacier Creek fault

Wahrhaftig (1970e) mapped a short segment of this fault where it juxtaposes Keevy Peak Formation against Totatlanika Schist on the north limb of the Mystic Mountain syncline. It occurs near the base of a steep north-facing topographic slope and shows S-side-up displacement and abrupt changes in foliation attitudes adjacent to the fault. An additional fault of similar geometry may exist ~1 km north of the Glacier Creek fault where vertical and overturned beds of the Usibelli Group are at the base of another north-facing topographic slope (Wahrhaftig, 1970a).

Healy Creek fault

Wahrhaftig (1970g) mapped this north-dipping fault to extend from the Nenana River (near Lignite Creek) eastward into the Healy Creek drainage. Lesh (2002) and Ridgway et al. (2002) first designated this structure as the Healy Creek fault. The fault is clearly defined by the juxtaposition and deformation of the Usibelli Group and Nenana Gravel, and farther east, the Usibelli Group and Birch Creek Schist. Its extent eastward up Healy Creek is uncertain because the fault cuts Birch Creek Schist and no markers are present within this unit to identify offset. Previous mapping (Wahrhaftig, 1958, 1970g) shows that the Healy Creek fault is a reverse fault with a steep north dip ($\sim 65^{\circ}$). The dip

of this fault is similar to the foliation orientation in the adjacent Birch Creek Schist (Wahrhaftig, 1970g). Terrace profiles surveyed using GPS (data presented in Chapter 6) show N-side-up offset along the strike of this fault on the west side of the Nenana River. Further evidence for the westward extension of the Healy Creek fault is visible in aerial photographs that show topographic and drainage anomalies that suggest N-side-up displacement.

Healy fault

Thorson (1979) mapped a short (2 km) fault segment just south of Healy that cuts outwash terraces of Riley Creek age. This fault trace is clearly visible in topography where it forms a distinct north-side-up scarp that has aided beavers in the construction of several ponds. The local drainage is diverted along this fault scarp, forming sharp gullies where the stream crosses terrace risers. Each successively older terrace that is cut by the fault shows slightly greater vertical displacement across the fault. Thorson (1979) observed a shear zone in a small gully where he measured a fault dip of 66° S and a strike of 74° , indicating it to be a normal fault. I was unable to locate the shear zone described by Thorson (1979), probably because it was covered by subsequent railroad construction. Near the west end of the fault, I examined a gully that cuts through the riser of Healy age moraine deposits. Surveys across this gully show displacement in the same sense as the fault scarp in the younger terraces; however, this gully lies south of the projection along strike of the Healy fault. To fit a fault plane to this geometry of scarps requires a north-dipping reverse fault. In addition, the strike of the Healy fault ($250\text{--}260^{\circ}$) is the same as the strike of the underlying north-dipping Usibelli Group ($\sim 255^{\circ}$).

Stampede fault

This north-dipping fault is required by the geometry of the adjacent Stampede anticline, with its unbroken, gently sloping north limb and angular, steeply dipping south limb. The fault appears to trace around the south margin of the Stampede anticline, with an inferred geometry similar to the Healy Creek fault to the east. Also, It is possible that this fault has created local surface ruptures where Wahrhaftig (1970h) has mapped small isolated occurrences of Nenana Gravel within regions of Quaternary deposits.

Little Panguingue fault

This is a short north-dipping reverse fault, evident from the offset surface (either the top of the Nenana Gravel or a younger geomorphic surface) on either side of Little Panguingue Creek. The north dip is indicated by the inferred trace of the fault to the east, where it must curve north of a Healy age outwash terrace that is not offset.

Park Road fault

This fault is a north-dipping thrust that is inferred to extend from the thrust mapped south of Sugarloaf Mountain (Sherwood and Craddock, 1979) to the east and west along the south side of the Mount Healy anticline. It connects with the previously mapped faults that juxtapose Birch Creek Schist against the Nenana Gravel to the south between the Savage and Teklanika Rivers (Hickman and Craddock, 1976; Csejtey et al., 1992). The north dip was defined for a portion of this fault by Sherwood and Craddock (1979), and interpreted to extend the length of the fault.

Hines Creek fault

The Hines Creek fault is generally interpreted to have originated as an older strand of the Denali fault system (e.g., Wahrhaftig et al., 1975; Csejtey, 1982). Significant right-lateral strike-slip displacement ended on this fault before it was cut by a pluton at about 95 Ma (Wahrhaftig et al., 1975), although segments of this fault have likely experienced later episodes of dip-slip faulting (Wahrhaftig et al., 1975; Hickman et al., 1977; Trop and Ridgway, 1997). Specifically, Trop and Ridgway (1997) used basin strata proximal to the Hines Creek fault to recognize that the fault was active (likely as a blind thrust) during the Late Cretaceous (70-80 Ma). In the eastern Alaska Range, Nokleberg et al. (1989, 1992) mapped the Hines Creek fault as a south-dipping Cenozoic thrust fault. The fault juxtaposes two disparate geologic terranes (e.g., Gilbert and Redman, 1977; Csejtey et al., 1992), and is the southern limit of exposures of the Birch Creek Schist (Csejtey et al., 1992). Interestingly, the trace of the fault is interpreted differently on different geologic maps (Hickman and Craddock, 1976; Sherwood and Craddock, 1979; Csejtey et al., 1992).

3.4 Observations of topographic and geomorphic patterns

Numerous topographic and geomorphic features demonstrate active deformation in the northern foothills. The first is the general north to north-northwest trend of major streams that drain the north side of the central Alaska Range. Figure 3.2 shows the streams that have incised steep-sided gorges into the east-trending ridges of schist. A pass occupied by small tributary streams lies to the east or west of many of these streams.

Figure 3.2 DEM of the northern foothills showing major north-flowing streams. All of the streams on this map flow across large east-trending ridges with a pass on either side. The box shows the location of the map in Figure 3.3.

The Japan Hills in the northeast corner of my study area offers a great example of a probable laterally propagating anticline (Figure 3.3). This anticline is the most outboard structure of the northern foothills and, like all other east-trending anticlines in this region, several streams flow through the ridge it forms. Figure 3.3 shows a detailed section of the geologic map for the Japan Hills and illustrates the relationship between the anticlinal ridge and the drainage pattern. South of the highest portion of the ridge where unit MDt is exposed, the north-flowing streams are deflected to the west. Figure 3.3 also shows several wind and water gaps along the crest of the ridge and numerous terraces, glacial outwash deposits, and swamp deposits that indicate recent adjustments to the drainage patterns.

Numerous exposed geomorphic surfaces appear to represent the pre-Usibelli Group erosional surface. These surfaces are shown in Figure 3.4 and are identified by the presence of a smooth topographic surface on the basement schist. These surfaces display the same deformed geometries as adjacent Tertiary strata and the structures that they define.

Characteristically, the average topography of the northern foothills slopes northward; however, regional variations exist in the magnitude of this slope. Figure 3.5 shows the lines for 22 topographic profiles measured across the northern foothills. Figure 3.6 shows the profiles and the best-fit lines used to calculate the average slope. Each profile line is approximately perpendicular to structure and is spaced to best illustrate the east-west variations. Variation in average topographic slope defines 5 zones. The region west of the Nenana River (Zone 1) has an average topographic slope of 0.8° , with

Legend

GW - water gap

Ga - wind gap

Figure 3.3 Geologic map of the Japan Hills, derived from Wahrhaftig (1970a). Area of map shown by box on Figure 3.2. It shows bedrock exposures, major Quaternary units and landforms, drainages, and several wind and water gaps. Compare the features shown with the model of a laterally propagating anticline (a,b,c) from Keller and Pinter (2002), particularly near the wind gap where several drainages have been diverted westward.

(a) initial condition

(b) uplift occurs

1. Ponding of sediment near Gw reduces slope of channel and lowers stream power
2. Stream erodes headward toward gap

(c) diversion and air gap formation

3. point of capture, stream is diverted, Ga is produced

Figure 3.4 Geomorphic surfaces that represent the pre-Usibelli Group unconformity. The black regions are the exhumed and undissected unconformity surface. In several locations, such as Mt. Wright and along the mountain front, this surface defines a distinct fold hinge. In other places, such as the Needle Rock syncline and Stampede anticline, the surface illustrates a more rounded geometry of the fold hinges.

Figure 3.5 Transect lines for the profiles and slope measurements shown on Figure 3.6. Base is a DEM with several major rivers shown for location reference. The heavy black line is the Hines Creek fault, representing the southern boundary of the northern foothills, and in white is the Northern Foothills Thrust, marking the northern boundary. Zones 1-5 delineate regions with similar average slope values.

Figure 3.6 Roughly N-S topographic profiles across the northern foothills. The trace of these profiles is shown on Figure 3.5, with the profiles organized west to east. The thin lines are the best-fit lines illustrating the average slope along the profile. The average slopes calculated from the best-fit lines (in degrees) appear at the end of each profile. Vertical and horizontal scales in meters. Continued next page.

Figure 3.6 continued. Note how remarkably well some of the profiles match the best fit line. WR represents the location of the Wood River valley in these profiles.

measured values ranging from 0.7° to 0.9° . Although the average elevation is higher east of the Nenana River (Zone 2), the slope decreases with an average between 0.5° and 0.6° . Near the Totatlanika River (Zone 3), the average slope doubles to between 1.1° and 1.2° , corresponding to higher elevations on the south end of the profiles and a lower range front. The fourth zone has a consistent slope near 0.9° . The profiles in this region all intersect the wide glacial valley of the Wood River on their south end. The fifth zone borders the east edge of the study area and is distinguished by a high average slope between 1.3° and 1.4° .

3.5 Interpretation of structural pattern

The pattern of east-trending faults and folds that generally verge northward away from the main axis of the Alaska Range suggests a fold-and-thrust belt propagating into the Tanana Basin. This interpretation requires the presence of a south-dipping basal detachment below a wedge with a north-sloping topographic surface (Chapple, 1978). Additional evidence for the presence of an orogenic wedge are the Stampede, Healy Creek, and Park Road faults, which I interpret to be backthrusts from the basal detachment that accommodate thickening within the wedge. Otherwise, the eastern portion of the northern foothills is dominated by forward thrusts (the Mystic Mountain, Glacier Creek, Kansas Creek, Buzzard Creek, Northern Foothills Thrust, and Japan Hills splay faults). Northward propagation of the northern foothills fold-and-thrust belt and in-sequence fault activation is evident from the less-developed and topographically lower structures along the mountain front.

The Japan Hills likely represents the most recent foreland-propagating splay of the basal detachment. Figure 3.3 compares the model of a laterally propagating anticline by Keller and Pinter (2002) to a geologic/geomorphic map of the Japan Hills region to illustrate how the streams that flow across this region display the same properties as the model. Several north-flowing streams were diverted around the largest topographic element of the Japan Hills Anticline when uplift exceeded incision. Further evidence of this is the wind gap labeled near the center of Figure 3.3. The swamp deposits suggest the ponding of water behind the growing anticline, with the stream draining the north side of the largest area of swamp likely representing a future wind gap. The streams on the west still flow unimpeded though the anticline for two reasons. This portion of the Japan Hills anticline has experienced less uplift and these streams have larger drainage basins. Thus, they are likely to maintain greater stream power, allowing incision to keep up with uplift. This is the same process that probably has occurred throughout the development of the northern foothills, allowing all the large streams to maintain their relatively parallel north to north-northeast courses.

The prominent structural changes along strike may be explained by transverse structures and lateral ramps. The Boot Hill anticline, Ferry syncline, and Stampede anticline are not readily traced across the Nenana River. The abrupt termination of these structures likely results from a steeply dipping fault that is parallel to the Nenana River and has accommodated the along-strike variations. Such a structure could explain the linear trace of the Nenana River through the northern foothills, as well as how it cuts all the way through the Alaska Range if this accommodation structure extends farther south.

However, the Healy Creek fault and Mount Healy anticline do not appear to be significantly offset by this structure. The western termination of the Jumbo anticline and the east end of the Boot Hill anticline may mark lateral ramps. A lateral ramp is suggested because the beds dip steeply parallel to the trend of the fold hinges. The Jumbo anticline also shows two smaller-scale (wavelength $\sim 1.5\text{-}2\text{ km}$), west-plunging folds that likely resulted from drag during lateral ramp formation.

Wahrhaftig (1958) interpreted many of the geomorphic surfaces illustrated in Figure 3.4 to represent a preglacial (post-Nenana Gravel), Late Cenozoic erosion surface. The evidence he presented is as follows:

- (1) The surfaces on the tops of ridges commonly form a sharp angle with triangular facets on the flanks of these ridges, indicating two distinct unconformities of different ages.
- (2) The top of the Nenana Gravel is a layer of conglomerate that contains abundant boulders of Birch Creek Schist, suggesting that a proximal source for these boulders had to be available. Thus, Mt. Wright and the adjacent ridge (the Mount Healy anticline) could not have been buried by the Nenana Gravel.
- (3) The drainage pattern of the Sushana, Sanctuary, Savage, and Teklanika Rivers had to form on a north-sloping erosion surface that existed after the formation of the east-trending folds and faults, because these streams would have lacked the stream power to incise through the ridges of schist (although he presented no evidence to support this assertion).

However, the patterns of these erosional surfaces are also consistent with the idea of a relatively planar, north-sloping, upper surface of the Nenana Gravel that formed prior to the development of the east-trending folds and faults in the northern foothills. The change in inclination of the erosion surface in (1) is readily explained by presence of a fold hinge associated with the anticlinal folding at Mt. Wright. In response to (2), Thoms (2000) suggested that uplift of the Mount Healy anticline occurred during the deposition of the Nenana Gravel, and that eventual exposure of the Birch Creek Schist at the core of the anticline contributed the schist fragments found at the top of the Nenana Gravel to the north. This would indicate that the uplift began to prograde northward, forcing the end of deposition of the Nenana Gravel to the south as it began to uplift. The assertion made in (3) is difficult to prove, but it seems likely that these streams would have had sufficient stream power for incision to keep up with uplift of the east-trending anticlines, otherwise the streams would have exploited the lower elevation east-trending synclinal valleys.

3.6 Possible implications of topographic slope variations

A characteristic of fold-and-thrust belts is a wedge-shaped cross-section of deformed rock that tapers toward the leading edge of the mountain belt (Chapple, 1978; Davis et al., 1983). This wedge is defined by the upper topographic surface and a basal detachment. Therefore, changes in the average topographic slope across a fold-and-thrust belt can suggest variations in either the dip of the basal detachment or other physical/mechanical properties of the rock within the wedge (Davis et al., 1983). Other geologic variations that could affect the topographic slope of a fold-and-thrust belt include, but are not limited to, changes in fluid pressure at depth, regions with different

erosion rates within the mountain belt, and variations in basement rock composition, competency, layering, and orientation that would influence the mechanical properties.

The general topographic slope of the northern foothills (0.5° - 1.5°) is low relative to the fold-and-thrust belts of Taiwan (2.9°) and the Himalaya (4°) as presented by Davis et al. (1983). Causes for this overall low slope could be a very weak detachment horizon (e.g., Jaswal et al., 1997 and Pennock et al., 1989), high fluid pressures (Davis et al., 1983), low detachment dip, and recent erosion concentrated in the higher elevations of the northern foothills. Stratigraphy within the highly deformed schistose basement is unknown, so I cannot assume the presence of a particularly weak stratigraphic horizon that served as a detachment. However, the presence of large-scale lithologic layering or faults inherited from the emplacement and/or synmetamorphic deformation (as discussed by Pavlis et al. (1993) in correlative rocks to the north and northeast) of the northern foothills basement could approximate a weak stratigraphic horizon. No data are available to make any interpretations on the state of pore fluid pressures in the northern foothills. A low detachment dip is likely, and will be evaluated in more detail in Chapter 4. Rapid erosional removal of the >1 km thickness of Tertiary sediments on top of the relatively resistant schistose basement along the southern margin of the northern foothills would significantly lower the topographic slope. Thus, the south end of the wedge would have to be rethickened to facilitate further progradation of the wedge. This study cannot decisively differentiate between these possibilities. However, this study can speculate on the causes for variations in the average topographic slope across the northern foothills. Zones 1 and 2 (Figure 3.5) are separated by the Nenana River which, as interpreted

earlier in this chapter, may follow a transverse structure of low displacement. This transverse structure, besides forming the termination of several folds and faults, could also separate different detachment dips. It is unlikely that the mechanical properties of the basement vary significantly across this structure since the rocks on either side are not transported far. The steepening slope from Zone 2 to 3 occurs along the surface expression of an inferred lateral ramp and corresponds with both an increase in elevation on the south end of the profiles and decrease in elevation of the mountain front. This again is likely to result from changes in detachment and ramp geometry and is examined further in Chapter 4. An interesting feature near the Zone 2/3 transition is the presence of two Holocene maars (Wahrhaftig, 1970b; Albanese, 1980). These features resulted from the interaction of basaltic magma with local groundwater and/or permafrost in the subsurface. The magma instantly vaporized the groundwater, creating a small explosion that resulted in two small depressions surrounded by a rim and a small flow of basaltic cinders. The young age (3000 years B.P., Albanese, 1980) of this magmatic activity suggests the likelihood of increased heat flow in this region, which could potentially increase the ductility (or at least decrease friction) of the basement rocks. An additional possibility is that the lateral ramp could have provided a pathway for the magma. Zone 4 is distinguished by four profiles that have similar average slope values that are lower than in Zones 3 and 5. I interpret this difference to be the result of glacial erosion in the upper Wood River valley, which each of the Zone 4 profiles cross. As a result, the wide u-shaped valley of the Wood River is the cause for lower slope values for this narrow zone, and not any change in detachment dip or variation in basement properties.

4 CROSS-SECTION ACROSS THE NORTHERN FOOTHILLS

4.1 Methods of cross-section construction

The development of a cross-section for the northern foothills involved two components. The first was drafting a detailed cross-section (Figure 4.1) along a transect with the most structural data and that shows the known structure at the surface and the preferred and balanced interpretation at depth. The second component was developing a series of schematic cross-sections west and east of the detailed section to provide additional constraint for the detailed section and to illustrate the preferred interpretation of lateral variation in the fold-and-thrust belt geometry. All of the cross-sections extend only to the detachment depth as it is inferred from the surface structure. The lines of section are shown on Figure 4.2.

The geologic data for the detailed cross-section are largely from Wahrhaftig's Fairbanks A-4 and Healy D-4 geologic maps (1970c and g). Data for the southern end near the Hines Creek fault are from Sherwood and Craddock (1979). I incorporated structural measurements made in the Nenana Gravel and Usibelli Group during this study south of the Healy Creek fault and on the south limb of the Boot Hill anticline. Also, observations of a geomorphic surface that represents the unconformity between the Totatlanika Schist and the Usibelli Group/Nenana Gravel helped constrain location of the contact despite the erosion of these Tertiary rocks.

Schematic cross-sections were derived by estimating the height of the upper surface of the Nenana Gravel along approximately N-S transects across the northern foothills. Heights were obtained from a combination of observed schist/Tertiary rock

Figure 4.1. Detailed cross-section across the northern foothills study area. Line of section (Main) shown on Figure 4.2. Cross-section is based on structural data collected for this study and the mapping of Wahrhaftig (1970c, g) and Sherwood and Craddock (1979). Dip tadpoles indicate the distribution of surface data used to interpret the cross section. Sugarloaf Mtn. is the southernmost exposure of Tertiary sedimentary rocks along the line of section. The location of the Keevy Peak Formation near the middle of the section is inferred by projecting the contacts from exposures to the east of the line of section. See text of Chapter 2.2.1 for unit descriptions.

unconformities (e.g., Figure 3.4), the structure contours on geologic maps (Wahrhaftig, 1970a-h), locations where the top of the Nenana Gravel is preserved, and an isopach map from Thoms (2000). This defined a deformed surface on which I tested combinations of faults and folds (using fault-bend fold (Suppe, 1983) and fault-propagation fold (Suppe, 1985) models) until I found a geometry (several have multiple possible geometries) that explains the observed deformation. I then compared the fault/fold geometries of adjacent schematic sections to further constrain possible solutions. Finally, I compared the schematic sections to the detailed cross-section to provide additional constraints for fault geometries at depth.

As a final step, I balanced the detailed cross-section using ArcGIS with the procedures described in Appendix A.

4.2 Geologic constraints and uncertainties

The most useful geologic constraints for developing these cross-sections are the structural attitudes of the Usibelli Group and the Nenana Gravel. Unfortunately, the units combined are only 1800 m at their thickest, and thin overall toward the mountain front. Another problem is that units within the Usibelli Group are locally discontinuous and the Usibelli Group/Nenana Gravel contact locally shows angular unconformities (Wahrhaftig, 1970a-h; Thoms, 2000). Foliation of the schist units provides a useful substitute for bedding where no adjacent bedding attitudes are available. In places such as the Boot Hill anticline, Needle Rock syncline, and several other folds that have well-preserved Tertiary units on their limbs, change in foliation orientations defines a similar degree of folding as is shown by the bedding.

Major uncertainties in the development of the cross-section come from a lack of direct information on the geologic units, pre-existing structures, and fault geometries at significant depth. The basement schist units only have estimated and minimum structural thicknesses. In particular, no data constrain the thickness of the stratigraphically lowest unit, the Birch Creek Schist. The only interpretation of the geology at depth below the northern foothills is from a study by Stanley et al. (1990), who suggest that conductive rocks they interpret to be Upper Jurassic and Cretaceous flysch underlie the southern Yukon-Tanana Terrane (of which the northern foothills is on the southern margin). However, a study of the isotopic compositions of Cretaceous and Tertiary granitic rocks in the Yukon-Tanana Terrane by Aleinikoff et al. (2000) eliminated flysch as a likely source and left the affinity of the conductive layer found by Stanley et al. (1990) unknown. Without knowledge of the stratigraphy below and within the orogenic wedge, I cannot assume an individual unit to act as the basal detachment (Chapple, 1978) and aid in estimation of detachment depth. Finally, no subsurface geophysical data are available to aid in the interpretation of fault geometries.

4.3 Detailed and balanced cross-section across the northern foothills

Figure 4.1 is a balanced cross-section across the northern foothills (the line of section is labeled 'main' on Figure 4.2). The geometry of the southern backthrust (the Park Road Fault, Figure 3.1) is constrained by a small exposure of the Usibelli Group at Sugarloaf Mountain (Wahrhaftig, 1970g; Albanese, 1980), several exhumed unconformity surfaces, and the south limb of the Eight-Mile Lake syncline. The geometry of the Eight-Mile Lake syncline in this section is well-constrained by abundant

exposures of the Usibelli Group and the Nenana Gravel, and I interpreted the south limb of this fold to represent a flat-to-ramp bend at depth. An outcrop of the Usibelli Group at Sugarloaf Mountain and gently north-dipping unconformity surfaces define the inflection point between the Eight-Mile Lake syncline and the Mount Healy anticline. The slight bend in the Park Road fault is required by the dip of the ramp below the Eight-Mile Lake syncline and the location of the exposed Park Road fault. The Healy Creek fault and Usibelli anticline are well-defined by abundant exposures within the drainage of Lignite Creek. The dip of the Healy Creek fault is from Wahrhaftig (1970g) and the curved part of the ramp is required by the shape of the Usibelli anticline. Also, the angular bend in the Healy Creek fault is suggested by an abrupt $\sim 8^\circ$ change in bedding attitudes in the Nenana Gravel. The shape of the fold limb shared by the Ferry syncline and Boot Hill anticline clearly defines a flat-to-ramp geometry beneath the Boot Hill anticline. Thus, the dip of the Buzzard Creek fault is constrained by the shape of this fold and the inferred location of the surface intersection of the fault. Exposures of the Usibelli Group and Nenana Gravel are rare along the line of section between the Boot Hill anticline and the mountain front; however, exposures adjacent to the line of section and several exhumed unconformities clearly define the presence and shape of the Rex anticline and Bear Creek syncline. I used the dip of bedding in exposures of the Usibelli Group along strike and similar foliation dips near the line of section to define the geometry of the south limb of the Rex anticline. This fold limb is interpreted to represent a flat-to-ramp bend of the Northern Foothills Thrust. The dip of this fault is constrained by the geometry of the Rex anticline and the inferred trace of the fault at the range front. I constrained the

detachment dip and depth by projecting fold bisectors and faults to depth and fitting a linear fault that allowed the interpreted and observed fold and fault geometries to remain consistent. This resulted in a small range of possible detachment dips and depths, so I constrained the final result, illustrated in Figure 4.1, by attempting to area-balance several cross-sections with different detachment geometries from this range.

I tested numerous combinations of fault geometries before eliminating them in favor of Figure 4.1. An early model attempted to explain the observed folding by changes in detachment dip between the Healy Creek fault and the Northern Foothills Thrust. I eliminated this model (and several variations of it) by identifying the presence of the Buzzard Creek fault. The identification of this fault also eliminated several models that used a flat-to-ramp geometry but required a significantly deeper detachment. Another model did not account for the significance of the Park Road fault in the development of the Mount Healy anticline and instead used a S-dipping fault, but I could not resolve this configuration with the surface geology and the observed deformation.

Geologic units interpreted down to the detachment and below are notably absent from this cross-section. This emphasizes the fact that the geology truly is unknown at greater than a few kilometers depth for the northern foothills and that this cross-section does not provide any additional information about the rocks at depth.

Only one unit, the Nenana Gravel, is continuous across the entire cross-section, so I used an area balance constrained by the line lengths of the upper and lower contacts of the Nenana Gravel. Figure 4.3 is the restored cross-section, treating the undeformed Tanana Basin as fixed and the plane of the Hines Creek fault as a displaced vertical

Figure 4.3 Restoration of the cross-section in Figure 4.1. I treated the undeformed Tanana Basin as fixed and the plane of the Hines Creek fault as a displaced vertical marker. Unit Tn, the Nenana Gravel, is both line length and area balanced. The remaining rock units are combined into polygons for this restoration and are area balanced. Bold lines are faults.

marker at the south end of the section. This restored cross-section demonstrates that ~8.8 km of shortening has occurred across this portion of the northern foothills.

4.4 Schematic cross-sections across the northern foothills

The development of schematic cross-sections allows me to fully characterize an interpretation of the structural framework of the northern foothills, while staying within the confines of limited geologic subsurface data. These sections are shown in Figure 4.4, and illustrate significant changes along strike in detachment and ramp geometries. Being schematic, these cross-sections do not explain all of the minor structural changes, but they do account for the major structural features and patterns.

The southern portions of section A (Figure 4.4) and the main cross-section (Figure 4.1) are both dominated by north-dipping backthrusts. For section A, these backthrusts appear to be the only ramps above the detachment. The north half of section A is defined clearly by the uplifted but nearly undeformed upper surface of the Nenana Gravel that can be explained only by a gently dipping, planar basal detachment. Immediately east of the Nenana River, the structure is more complicated and is illustrated by the main cross-section (Figure 4.1). Section B is similar to the main cross-section except that a shorter fold wavelength in the middle of the section requires a shallower detachment than is inferred from the fold geometry at the north end. I found the presence of two detachments to be the easiest explanation for the different fold wavelengths, and this fault geometry also worked well for the southern ends of the rest of the sections (C-E, Figure 4.4). Sections C-E are all similar in their requirement for a relatively planar, S-dipping lower detachment based on the presence of the relatively undeformed upper

Figure 4.4 Series of N-S schematic cross-sections across the northern foothills. Lines of section shown on Figure 4.2. Heavy lines are faults, and thinner lines are the estimated surface of the Nenana Gravel. These are dashed under regions with no Tertiary sedimentary rocks or obvious exhumed unconformity surfaces. The thin, gray dashed lines are approximated fold bisectors.

surface of the Nenana Gravel across the north half of these sections. The shape of the Japan Hills anticline suggests a fault-propagation fold geometry because of the longer, gently dipping backlimb and steep forelimb. However, a fault-bend fold geometry is also possible.

4.5 Interpretation of the development of structures

Wahrhaftig (1958) identified and Thoms (2000) confirmed the presence of Birch Creek Schist boulders within the uppermost beds of the Nenana Gravel, indicating that the schist of the Mount Healy anticline was exposed just prior to the cessation of Nenana Gravel deposition. This is required given the northerly paleoflow direction for the Nenana Gravel (Thoms, 2000; Ridgway et al., 1999; Wahrhaftig, 1987) and because since no Birch Creek Schist is exposed anywhere south of the Hines Creek fault, making the Mount Healy anticline the southernmost occurrence. My cross-section model illustrates that because the Mount Healy anticline is the structure farthest from the active mountain front, it likely was the first structure to be active in the fold-and-thrust belt.

5 LONGITUDINAL STREAM PROFILES

5.1 Introduction

The longitudinal profile (abbreviated to long profile) of a stream is simply the along-stream distance from source plotted against elevation. This plot illustrates the result of the competition between stream incision, rock uplift, and lithologic resistance to erosion for a particular stream (Sklar and Dietrich, 1998). An ideal, graded stream will have a long profile that approximates a negative logarithmic function (Hack, 1973) (Figure 5.1a) as a result of increasing discharge with downstream distance (Bagnold, 1977). Therefore, perturbations to the ideal shape of the long profile can represent uplift/subsidence (base level change), lithologic change, or both (Goldrick and Bishop, 1995). These perturbations typically appear as convexities in the general concave shape of the profile, such as in the example shown in Figure 5.1b.

I chose to apply this method to this study of the northern foothills for several reasons. 1) It is a simple, inexpensive method to examine regional-scale trends of tectonic activity. 2) I believe that Lesh (2002), whose work is summarized below, may have missed some details due to the procedures that he used to process his long profiles. 3) The long profiles need to be re-examined in light of the recognition of the numerous structures identified in the northern foothills by this study (Chapter 3). 4) This method is potentially useful elsewhere in Alaska, where tectonic activity is suspected but independent evidence does not exist (or is not yet identified). Therefore, through the examination of long profiles of streams that cross the northern foothills, I intend to

Figure 5.1 Examples of idealized long profiles. (A) shows an idealized form of an equilibrium long profile. (B) shows a single perturbation (shown as a convexity) to the idealized form. Base figure modified from Goldrick and Bishop (1995).

illustrate the trends of profile perturbations and demonstrate that these are due to tectonic activity and are not a result of lithologic change or other variables.

5.2 Previous Work

Lesh (2002) studied long profiles of 25 of the main transverse drainages across the central Alaska Range and northern foothills. His purpose was to examine the geomorphic expression of active tectonics on the regional drainage network. He found that the long profiles helped to “define areas of active transpressional deformation and basin subsidence” (Lesh, 2002). Furthermore, Lesh (2002) determined that no significant difference exists in the lithologic resistance to erosion between the major geologic units found in the northern foothills. However, Wilbur (1995) measured the peak sediment discharge from basins floored by different lithologies in the Lignite Creek drainage to calculate an “erosion rate” for each basin. The result was rates indicating that Nenana Gravel basins are eroding 260 times faster than schistose basins and ten times faster than Usibelli Group basins. This suggests a significant difference in the lithologic resistance of the three major units in the northern foothills. However, the influence of the differences in lithologic resistance on the long profile may be minimal based on the work of Sklar and Dietrich (1998,) who showed that incision rates reach a maximum with intermediate levels of sediment supply and transport capacity. Therefore, since the less-resistant units commonly are preserved in synclines and have alluviated channels (Wahrhaftig, 1970a-h; this study, Chapter 3), these channels would experience less incision since the bedrock is guarded by the veneer of alluvium. Conversely, since the anticlines are commonly cored by more-resistant schists, these should experience a higher

rate of incision due to a lack of alluvial cover, leaving exposed bedrock on the channel floor.

5.3 Methods

Three basic sources of data were available for obtaining stream profile data. These include topographic maps, digital elevation models (DEMs), and surveying. The most detailed topographic maps available for the northern foothills are the USGS 1:63,360 scale maps that generally have a 100-foot contour interval (50-foot contours in low-relief regions). This scale provides suitable horizontal resolution, but is limited by the vertical resolution. The highest-resolution DEMs currently available for the study are the USGS National Elevation Dataset DEMs with a horizontal resolution of 2 arc-seconds. These products were derived by point-sampling (obtaining x,y,z coordinates) at a regular spacing from the 1:63,360 scale topographic maps and then interpolating a surface from these points. This allows elevation values to be obtained at any point along a stream; however, in regions of high relief (i.e., where a stream has incised through a ridge), the interpolation technique introduces significant error to the elevation values. Lesh (2002) used DEMs for his stream profile data, and then smoothed the data using a 100-point running average. Surveying with a real-time, differential GPS provides the most precise elevation values (as precise as 2 cm, smaller than the variability of the stream surface) for the streams, but is extremely time intensive and logistically difficult for anything besides short (several kilometer) transects. Figure 5.2 shows a comparison of the long profiles resulting from the three different methods of data collection along the Savage River.

Figure 5.2 Comparison of the three methods for long profile data collection. This was tested on the Savage River because of easy access. The thick gray line is the profile from the measurement between contour lines on USGS 1:63360 topographic maps. The thin black line is the profile obtained by extracting evenly spaced points from USGS DEMs. The overlaid plot and thick dashed line shows a section of the same profile surveyed using a Leica RTK differential GPS unit. Note how the three methods describe a similar shape for the prominent convexity near the middle of the profile, but the DEM-derived profile shows numerous bumps that suggest that the stream locally flows uphill. Each distinct saddle in the line is controlled by the presence of a contour line at that location.

I chose to use the 1:63,360 scale topographic maps for several reasons. This approach allowed me to avoid incorporating inaccurate data with accurate data, as would occur with DEM-derived elevations (Figure 5.2). It is virtually free, and involves simple measurement procedures utilizing Geographic Information System (GIS) programs, as opposed to differential GPS surveying, which would require several days to collect data for just one stream. Detailed procedures for profile data collection are provided in Appendix C.

5.4 Observations

All of the long profiles of streams across the northern foothills show departure from an ideal logarithmic shape. The location of the profiled streams is shown on Figure 5.3.

Streams west of the Nenana River

Figure 5.4 shows the long profiles of four streams west of the Nenana River. The most prominent feature of all four profiles is the convexity where they cross the Mount Healy anticline. Furthermore, this convexity appears similar despite significant differences between the streams. The Sushana River crosses the anticline in its headwaters, the Savage River mid-course, and the Sanctuary River just above its confluence with the Teklanika River. The Teklanika is a much larger stream, at greater than 3 times the length of the Sanctuary and Savage Rivers, but the Mount Healy anticline still appears as a distinct convexity. The other identifiable similarity between the Sushana and Teklanika Rivers is the lack of a profile convexity at the Stampede anticline.

Figure 5.3 Map of streams used for long profile analysis. For location of structures, refer to Figure 3.1.

Figure 5.4 Long profiles of north-flowing streams west of the Nenana River. Note the prominent convexity at the Mount Healy anticline in all 4 profiles. Also note the different scales for both horizontal and vertical axes.

Streams between the Nenana River and Tatlanika Creek

Figure 5.5 shows long profiles of the 4 major north-flowing streams in the central northern foothills. Three of these streams (Totatlanika River, Windy-Julius Creek, and Tatlanika Creek) flow across the mountain front into the Tanana Basin and, at this point of each profile, the slope abruptly becomes very gentle and smooth. These same streams also show an elongate convexity that corresponds with the broad hinge of the Rex Anticline. The only anomaly on California Creek is also very prominent on the Totatlanika River and occurs where these streams cross the Boot Hill anticline. The apex of the convexity on both creeks occurs a short distance upstream from the actual hinge of the anticline. The Mystic Mountain fault also occurs near this convexity on the Totatlanika River. No convexity is associated with the Jumbo anticline except possibly on Tatlanika Creek.

Streams east of Tatlanika Creek

Figure 5.6 shows plots of long profiles from Gold King, Bonnifield, and Saint George Creeks, as well as Wood River. All display convexities at several points along their courses through the northern foothills. Saint George, Gold King, and Bonnifield Creeks all show a very similar overall shape, length, and elevation change. All three display a convexity at the Japan Hills anticline, and this is the only anomaly that these streams have in common. However, Gold King Creek shows a prominent convexity near its headwaters where it crosses the Jumbo anticline. Wood River is ~4 times longer than the other creeks in this region. Its long profile does not show significant convexities, but instead the profile is nearly linear across the entire foothills. Downstream of the Japan

Figure 5.5 Long profiles of north-flowing streams from the Nenana River to Tatlanika Creek. The most prominent convexities occur at the Boot Hill and Rex anticlines. There also is a dramatic decrease in gradient north of the Northern Foothills Thrust and associated splays. Note the different vertical and horizontal scales.

Figure 5.6 Long profiles of north-flowing streams east of Tatlanika Creek. All four streams cross the Japan Hills and show some degree of convexity at this point. Wood River has a fairly smooth profile with a very broad convexity through the entire foothills. The smoothness of the profile may be a result of a recent glaciation of the Wood River valley.

Hills splay, the slope changes and the profile tangentially approaches zero slope. Also, breaks in slope in the Wood River long profile at the Hines Creek fault and Japan Hills splay appear to distinguish the northern foothills structural province.

5.5 Interpretation of stream profile anomalies

The perturbations present in the long profiles of streams that cross the northern foothills suggest active deformation throughout the region. The abrupt change in slope at the mountain front and the Northern Foothills Thrust indicates that this is the boundary between uplift in the northern foothills and potential subsidence in the Tanana Basin.

Gold King, Bonnifield, and Saint George Creeks are particularly useful for long profile comparison because their similarity in stream length (~39-47 km), proximity to one another, parallel courses, and lack of lithology changes. However, these streams flow across a region that has experienced a consistent amount of uplift over much of the profile length (Figure 4.4), with the only differential uplift occurring at the mountain front and Japan Hills anticline. The Wood River is difficult to compare with these streams not only because of the drastic size difference, but also because of the recent glaciation of the Wood River valley. Wahrhaftig (1970a,e) mapped moraine deposits of Riley Creek age along much of the length of the Wood River valley. Presumably the ice would be more efficient than streams at smoothing bedrock, thus removing any pre-existing profile anomalies. Also, upon retreating, the glacier would leave behind a veneer of sediments that would allow the Wood River to adjust to uplift through channel modification rather than developing a bedrock knickpoint.

A possible explanation for the lack of an anomaly across the Stampede anticline is that rapid denudation of the Tertiary sedimentary rocks from the crest of the Mount Healy anticline reinvigorated uplift of this structure because of out-of-sequence activity of the Park Road fault, temporarily abandoning uplift of the Stampede anticline. If correct, this would specifically support my interpretation of the northern foothills as an active orogenic wedge since the growth of the Mount Healy anticline would be thickening the rear portion to maintain critical taper. However, the seemingly intact exhumed unconformity across the crest of the Stampede anticline suggests that its exposure is not exceedingly old. Instead, it is possible that the Stampede anticline is experiencing a lower rate of uplift, or the geometry of folding is manifest differently in the long profiles. Another important feature of these profiles is that, if the profile convexities were the result of lithology change, one would expect a convexity on both the Teklanika and Sushana River profiles corresponding with the Stampede anticline, regardless of tectonic activity.

The inconsistent pattern of convexities corresponding with the Jumbo anticline suggests that its tectonic activity changes along strike. No apparent profile anomaly is present where California Creek and the Totatlanika River cross this fold, but an anomaly exists to the east of the Kansas Creek fault, where Tatlanika and Gold King creeks cross the anticline. This relationship suggests that the Kansas Creek fault is still active, and plays a role in partitioning slip and subsequent deformation in the structures on either side of Tatlanika Creek. West of Tatlanika Creek, more recent deformation occurred on the Boot Hill anticline (which does show anomalies) rather than the Jumbo anticline.

East of Tatlanika Creek, this deformation must go into the Jumbo anticline or be transferred to the next structures north, the Northern Foothills Thrust and Rex anticline.

Finally, as interpreted elsewhere by Pazzaglia et al. (1998), the fact that most of these streams (particularly the larger ones) have a strongly concave shape, approximating the equilibrium profile of Figure 5.1a, may be an indication itself that the northern foothills is a tectonically active region. The rock uplift, high percentage of exposed bedrock, landslide-dominated hillslope processes, high drainage density, and generation of excess stream power all contribute to the production of streams that can incise at a rate equal to the rate of uplift (Pazzaglia et al., 1998). In contrast, Pazzaglia et al. (1998) suggest that streams in tectonically inactive regions commonly produce long profiles with a variable shape, including straight to convex. If this interpretation is correct, the individual convexities on the northern foothills long profiles likely represent locations of focused deformation and differential uplift. It remains unknown what influence the extreme seasonality of stream flow and sediment supply in this sub-arctic region have on these results.

6 TERRACE PROFILES

6.1 *Introduction*

A fluvial terrace is a landform that was once the floodplain of a stream which subsequently incised in order to regain equilibrium. This incision occurs because of a disturbance to the stream's equilibrium by base level change, climate change, or tectonic activity (Merritts et al., 1994). Because the resulting fluvial terraces record the long valley profile at a discrete moment in the evolution of a stream, a series of terraces can illustrate progressive deformation over the history of terrace development. Figure 6.1 illustrates several scenarios of tectonic deformation of terraces. In summary, terraces will remain parallel if a landscape experiences uniform uplift (Figure 6.1a), they will converge downstream as a result of tilt (Figure 6.1d), or they will record the progressive growth of structures that are superimposed on the terraces (Figure 6.1b, c).

6.2 *Geology of Nenana River valley terraces*

The Nenana River valley contains an extensive and complex series of fluvial terraces (Wahrhaftig, 1958). These terraces are interpreted to have formed during Pleistocene glacial advances, with the original glacial chronology by Wahrhaftig (1958) and subsequent debates and revisions (Thorson, 1983, 1986; Ten Brink, 1983; Beget and Keskinen (1991); Beget (2001)) shown in Table 2.1. Because of the poor preservation of the older terraces, only terraces correlated with the Healy and Riley Creek glaciations are examined in detail in this study.

Figure 6.1 Four models of tectonic deformation of terraces. Q4 is the oldest terrace and Q1 is the youngest. These models are modified from Keller and Pinter (2002), and represent: (A) uplift and incision without differential deformation, (B) continued surface faulting, (C) terrace warping, and (D) tilting. Note that (B), (C), and (D) all show progressive deformation with time.

6.3 Methods

The collection of terrace profile data included three components. First, I used aerial photography and geologic maps (Wahrhaftig, 1970d,g,h) to compile a map of terrace surfaces and alluvial deposits along the Nenana River valley (Figure 6.2). From this map, I identified the terraces that cross structures and might show subtle deformation detectable only with accurate surveying. The third component was to extract profile data (x,y,z positions) from DEMs. The time-intensive nature of surveying, locally dense vegetation cover, and poor access made surveying terraces along the entire length of the Nenana River valley impractical.

I performed the terrace surveys with a Leica Geosystems SR530 Real-Time, Kinematic (RTK) GPS unit. With a base station positioned on a benchmark (Garner VABM was used for this study; location shown on Figure 6.4), this unit can provide positions within a precision of 2 cm. The actual terrace treads could only be identified to an accuracy of 10-50 cm, making instrument error negligible relative to the variability of the measured surface. I performed the surveys over the course of two weekends in October, 2002, to take advantage of frozen ground conditions and defoliated trees. I chose survey points by pacing ~100 m between positions, with exceptions to this spacing occurring when there was obvious erosion of the terrace surface, or if there was a structural break (i.e., fault scarp).

To obtain profile data for the unsurveyed terraces, I overlaid my terrace map onto DEMs for the Nenana River valley in MapInfo (a GIS program) and sampled x,y,z values

on a transect of each terrace surface with a spacing of approximately 100 m (procedures in Appendix F). All profiles are plotted as distance from Garner VABM.

6.4 Observations from surveys

I selected the terraces near the town of Healy to survey because of their relationship with mapped bedrock structures and ease of access. Figure 6.3 is a map (area of map shown in Figure 6.2) and profile of a Healy-age terrace on the west side of the Nenana River valley. This profile shows an offset of 10-15 m between the two segments of the transect. The location of offset corresponds with a section that could not be surveyed due to the presence of a broad gully and private property. This offset lies along strike with the Healy Creek fault from where it is mapped (Wahrhaftig, 1970g; and Chapter 3 of this study) on the east side of the Nenana River valley. The N-side up sense and magnitude of offset (~10 m) are similar to the relationships mapped (Wahrhaftig, 1958; 1970g) across the Healy Creek fault.

Figure 6.4 is a plot of one long transect along a Riley Creek age terrace tread, and several short transects across the Healy fault on higher levels of Riley Creek terraces and the edge of Healy age moraine deposits (Wahrhaftig, 1970h). The long transect shows slight northward tilting ($\sim 0.6^\circ$) of the planar terrace surface, and N-side up offset on the Healy fault at the south end of the transect. This N-side up offset across the Healy fault is also seen on higher terrace levels and on the edge of the Healy moraine deposits. There is no intact fault scarp on the edge of the Healy moraine deposits due to formation of a gully and alluvium from the terrace riser down onto the lower Riley Creek terrace.

Figure 6.3 Map and profile of surveyed Healy age terraces. Vertical GPS error bars shown on plot. The thick dashed line is the inferred trace to the Healy Creek fault. Note the 8-10 meter, N-side-up offset of the two terrace segments across the projection of the Healy Creek fault. Location of map shown on Figure 6.2.

Figure 6.4 Map and N-S profile of surveyed points on a Riley Creek age terrace. Ovals on the map group survey points taken on separate terrace levels and the letters correspond with the clusters of survey points on the plot. Black lines on the plot mark the location of where the Healy fault crosses each cluster of points. The gray fields on the plot show points surveyed on lower, discontinuous terrace levels. Vertical errors are shown; however, the error is generally below the resolution of this plot.

6.5 Observations from compiled profiles

Large-scale patterns are evident when the surveyed profiles are combined with the DEM-derived profiles (Figure 6.5). The terraces generally converge downstream, to the point where they are nearly indistinguishable beyond the mountain front. Only one terrace, the Healy east, is continuous across the Rex anticline and the NFT, but it clearly is uplifted there and mimics the mapped attitudes of the underlying Nenana Gravel (Wahrhaftig, 1970d). The NFT corresponds exactly with the abrupt hinge point of this terrace. Also, the south dip of the Healy west terrace corresponds with the backlimb of the Rex anticline. Near the middle of the profile, the west terraces clearly converge northward toward the hinge of the Bear Creek syncline. Likewise, a short distance to the south on the east side, these terraces diverge northward toward the hinge of the Boot Hill anticline. Finally, at the south end of the profile, the elevation of the Healy terraces adjacent to the Healy Creek fault differs by approximately 60 m across the Nenana River.

6.6. Interpretation of terrace data

The terrace deformation shown in Figure 6.3 strongly suggests that the Healy Creek fault does extend across the Nenana River. This is supported by map data (Wahrhaftig, 1970h) that shows bedding dips in the Nenana Gravel $>30^\circ$ S (suggesting folding similar to that seen on the south limb of the Usibelli anticline east of the Nenana River) on a bluff on the north side of the westward projection of the Healy Creek fault. The topographic anomaly that forms this bluff continues westward along the hinge of the Eight-Mile Lake syncline. Near the Savage River, this topographic break appears to offset the upper surface of the Nenana Gravel, and causes the drainage from the south

Figure 6.5 Compiled DEM-derived and surveyed terrace profiles, with major structures labeled. The Healy west terrace appears to drop below the Nenana River profile because the preserved terrace angles west from the river and appears to form an outwash plain beyond the range front that slopes away from the river as well as in the downstream direction.

limb of the Eight-Mile Lake syncline to divert abruptly west. However, the Healy Creek fault on the west side of the Nenana River does not show as much overall displacement as to the east (Wahrhaftig, 1970g,h). Thorson (1986) suggested that the aforementioned topographic break could mark a normal fault, but I interpret it as a reverse fault because of the correlation with the Healy Creek fault.

The Riley Creek terrace survey shown in Figure 6. 4 illustrates a couple of interesting features. First of all, the northward tilt of the terrace is greater than the current average gradient of the Nenana River, and corresponds with the northward dip of the underlying Usibelli Group, which lies on the south limb of the Eight-Mile Lake syncline. Therefore, it appears that this terrace has recorded continued growth of the Eight-Mile Lake syncline. Secondly, the survey across the Healy fault scarp and the surveyed offset of the edge of the Healy moraine deposits appear to indicate that the Healy fault is a north-dipping reverse fault, opposite to the original normal fault interpretation by Thorson (1979). Given this fault's strike ($250\text{--}260^\circ$) and the similarity to the orientation of the underlying Usibelli Group ($\sim 250^\circ/45^\circ$ N), I interpret the Healy Fault as a flexural-slip fault that rested from slip on Usibelli Group bedding during folding.

Finally, the northward convergence of terraces (Figure 6.5) agrees with the interpretation in this study that the northern foothills is an active fold-and-thrust belt. The concept of a thickening orogenic wedge, as presented by Chapple (1978), explains the northward tilting of the terraces and northward convergence of different terrace levels since the interior of the mountain belt requires thickening to accommodate progradation of the wedge (Chapple, 1978).

7 DISCUSSION AND CONCLUSIONS

7.1 Discussion

Figures 7.1 through 7.6 are block diagrams of the northern foothills that illustrate the progressive development of the fold-and-thrust belt. Thoms (2000) established a similar chronology for the development of the foreland basin and northward-migrating deformation front in relation to the deposition of the Nenana Gravel. The chronology presented here begins at about the time of Thoms' (2000) Stage 3. A discussion of each step follows.

Step 1 – Deposition of the upper Nenana Gravel

This is the last stage prior to the beginning of widespread uplift within the northern foothills. Thoms (2000) noted that the occurrence at this time of a basin-wide gravelly facies suggests an overfilled basin, and interpreted the cause to be a decrease in subsidence rate and a high sedimentation rate.

Step 2 – End of Nenana Gravel deposition

The beginning of the end for the Nenana Gravel is the appearance of Birch Creek Schist clasts at the top of the unit (Wahrhaftig, 1958; Thoms, 2000). This must indicate the uplift and subsequent erosion of the Mount Healy anticline, since no Birch Creek Schist is exposed south of the Hines Creek fault. It was at this time that the Sushana, Teklanika, Sanctuary, Savage, and Nenana Rivers established their drainages through this uplifting ridge of schist. Also near this time, deformation must have begun on the northwest-striking portions of the Mystic Mountain and Kansas Creek faults. The angular unconformity near Tatlanika Creek (Wahrhaftig 1970b), and possible growth

Figure 7.1 Step 1 - Deposition of the upper Nenana Gravel. The dot-dash lines depict the drainage systems defined by Thoms (2000) during this time. The E-W dashed line is the Hines Creek fault, which has ceased significant right-lateral motion by this time (Wahrhaftig et al., 1975). The labeled streams are the approximate trace of these present-day drainages.

Figure 7.2 Step 2 - End of Nenana Gravel deposition. The Nenana Gravel ends with the deposition of boulders of schist derived from the rising Mount Healy anticline, shown here by the development of this fold related to formation of the Park Road fault. Farther east, the Kansas Creek and Mystic Mountain faults begin development, probably with right-lateral oblique slip. Note the similarity of the drainage systems (from Thoms (2000)) to the present-day drainage.

Figure 7.3 Step 3 - Post-Nenana Gravel. Widespread deformation as structures begin to prograde northward.

Figure 7.4 Step 4 - Focused deformation in the central northern foothills. This central portion between the Nenana River and Tatlanika Creek is interpreted to have become active before areas along strike to the east and west since basement schists are exposed all the way to the range front.

Figure 7.5 Step 5 - Post-Browne glaciation (?). The portion of the range front beyond the central region probably developed after the Browne glaciation since erratics attributed to this event appear near the range front west of the Nenana River at the same elevation as the top of the Nenana Gravel. The central region likely began development earlier as suggested by the higher-elevation ridges and deeper stratigraphic exposure.

Figure 7.6 Current state of the northern foothills.

strata north of Mystic Mountain require that deformation on these faults began before the end of deposition of the Nenana Gravel. Another important possibility to consider is that the upper surface of the Nenana Gravel in this region is significantly younger than the date interpreted from the intrusion of Jumbo Dome farther south. If deformation has prograded northward, then as sections of Nenana Gravel in the south were uplifted and eroded, the resulting sediment may have been deposited just beyond the active deformation front.

Step 3 – Post-Nenana Gravel

At this time, widespread uplift occurred through the southern half of the northern foothills. Deformation began at this time on the Stampede and Healy Creek faults, as well as farther north on the Jumbo anticline.

Step 4 – Focused deformation in the central northern foothills

I suspect that it was during this time that deformation was dominant in the central portion (Zone 4 from Chapter 5) of the northern foothills. This region has experienced the most uplift, and thus likely began development before areas along strike to the east and west. Deformation advanced from the Jumbo anticline basinward to the Boot Hill anticline, and possibly began uplifting the mountain front at about the same time.

Step 5 – Post-Browne Glaciation

I consider this to be a recent stage, since every major structure had developed by this point except for the two splays from the Northern Foothills Thrust. As these splays were developing, rapid erosion of recently uplifted Tertiary sediments locally reduced the topographic slope. The timing for this stage is constrained by the distribution of deposits

and landforms from the Browne Glaciation. Wahrhaftig (1970d) mapped moraine deposits and erratics near the range front that appear to lie on top of the Nenana Gravel, thus these deposits had to exist before significant uplift of the range front occurred at this location.

Step 6 – Today

The current state of the northern foothills fold-and-thrust belt suggests that the entire belt remains active. It is difficult to assess whether recent erosion in the rear portion of the wedge or simply the mechanical properties of the rocks allows the entire wedge to stay active. Based on the low topographic slopes in Zone 4 (Figures 5.3 and 5.4), the continued displacement on the Healy Creek fault, and the deformation of the Mount Healy anticline, I infer that this portion of the wedge is undergoing increased activity because of the erosional denudation of Tertiary sediments.

Several patterns are apparent from the interpreted evolution of the northern foothills fold-and-thrust belt. The successive northward development of thrusts shows that the orogenic wedge has prograded northward from the Hines Creek fault. Backthrusting is a significant component of deformation within the wedge, and deformation continues within the wedge as the deformation front migrates northward. The pattern of backthrusting is likely controlled by the pre-existing foliation within the metamorphic basement, as is suggested by the similarity of the steep north dip of the Healy Creek fault and the $\sim 75^\circ$ N dip of foliation in nearby exposures of Birch Creek Schist (Figure 3.1). However, other possible factors contributing to the development of backthrusts include frontal position in the wedge and the gently dipping basal

detachment. The east-trending topographic grain reflects the dominantly east-trending structures of the orogenic wedge. In turn, the timing of the development of these structures influenced erosion patterns and the progressive changes in the depositional system.

7.2 Conclusions

This study presents a tectonic framework for the northern foothills of the central Alaska Range. I took a four-part approach to addressing this problem by taking geological and geomorphological observations, extending these into structural interpretations in a cross-section, and then supplying the dimension of time with an analysis of stream profiles and fluvial terraces.

- (1) Late Cenozoic deformation of Tertiary bedrock units and several Quaternary geomorphic markers clearly indicates recent tectonism in the northern foothills.
- (2) The patterns of folding, topographic slope, and geographical position all support the interpretation that the northern foothills represents a deforming orogenic wedge overlying a south-dipping basal detachment.
- (3) Longitudinal stream profiles indicate that the northern foothills as a whole are actively uplifting, and delineate specific structures that display relatively greater local tectonic activity.
- (4) Terrace profiles illustrate the progressive deformation of structures and support the interpretation of the northern foothills as an active fold-and-thrust belt

This study provides several contributions to the interpretation of the tectonic framework of interior Alaska. The fundamental conclusion of this study is the identification of

dominantly fold-and-thrust deformation between the Hines Creek fault and the northern range front. The components of this fold-and-thrust belt include a gently south-dipping detachment at a depth of ~6-9 km extending from the range front to the Hines Creek fault. Folding within the northern foothills is related to both north- and south-dipping thrust faults. Furthermore, no evidence exists for left-lateral block rotation south of the range front (Figures 1.2 and 2.2), as is suggested by the model presented by Page et al. (1995). Instead, the Minto Flats seismic zone appears to form the western boundary of the fold-and-thrust belt, and the Fairbanks and Salcha seismic zones appear to end southward at the range front. In addition, no evidence exists for major, orogen-parallel, right-lateral slip north of the Hines Creek fault.

The identification of the active structures within the northern foothills is a significant contribution to the current understanding of seismic hazards of interior Alaska. Earthquakes on the basal detachment and other faults within fold-and-thrust belt could reach magnitudes of >7, as occurred in 1947 (Figure 1.2). The Healy and Healy Creek faults both cut Late Quaternary terraces near the town of Healy (Wahrhaftig, 1958; Thorson, 1979; and this study), and increasing displacement of older terrace levels indicates multiple faulting events (Thorson, 1979) over the past <20,000 years. However, my interpretation of the Healy fault as a flexural-slip fault implies that it is not a seismogenic source (Yeats, 1986). Instead, slip on the Healy fault results from coseismic folding, which results from coseismic displacement on a reverse fault (the Healy Creek or Park Road faults) below or adjacent to the fold (Eight-Mile Lake syncline). Therefore, these fault scarps are a likely target for paleoseismic investigations into the frequency of

surface-rupturing earthquakes in the Healy area. Hanson et al. (2002) described deformed Late Quaternary terraces at the range front near the Nenana River, along the trace of the Northern Foothills Thrust. So, besides these surface ruptures, it is likely that most of the other thrust faults recognized by this study are either blind, or have not ruptured recently enough to leave a recognizable scarp (buried thrust faults). A thrust or reverse fault scarp from even a large earthquake can be difficult to recognize in the field because of rapid degradation of unconsolidated colluvial materials, or only minor tension cracks may break the surface cover despite the creation of a scarp up to several meters high (Carver and McCalpin, 1996).

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APPENDIX A

Cross-section balancing procedures in ArcGIS v.8.3.

This is the method I devised to balance my detailed cross-section. I do not recommend using this procedure because it is cumbersome and very time-consuming.

1. Save a raster image of the cross-section from the drafting program (I used CorelDraw 10), making sure to include the vertical and horizontal scales.
2. Open ArcCatalog and ArcMap. Add the cross-section raster to the ArcMap window.
3. Select a coordinate system (View>Data Frame Properties>Coordinate System).
The coordinate system must be grid-based (equal northing and easting unit values), such as a Universal Transverse Mercator (UTM) projection.
4. Georeference the image by assigning an origin and selecting reference points on the scale on both ends of the cross-section. The units are essentially meaningless since this is not a map and the procedure is trying to make the area of the retrodeformed polygons match that of the deformed ones. However, it is useful to plan a scale when georeferencing so that, for example, 1 km on the cross-section equals 1 km on the screen.
5. In ArcCatalog, create a polygon shapefile for each region of the cross-section that will be retrodeformed and individually area-balanced. Add these shapefiles to the ArcMap window.
6. Open the Editor toolbar and select 'Start Editing'.

7. Trace each region under its respective shapefile. Using the 'Snapping' mode on the Editor toolbar will ensure that nodes of adjacent polygons match.
8. Calculate the area (and perimeter if performing a line-length balance) for each shapefile. Stop Editing, open the attribute table for the shapefile, select Options>Add Field, and name the new field "area". Start editing again, go to the attribute table and right-click on the area field heading. Click 'Calculate Values' and check 'Advanced'. Type the following statement into the first text box (or cut and paste from the ArcGIS help menu):

Dim dblArea as double

Dim pArea as IArea

Set pArea = [shape]

DblArea = pArea.area

Then type dblarea into the text box under the area field name. Click ok.

9. After calculating areas (and perimeters if needed) for all of the polygons, make a copy of each in ArcCatalog. Add them to the ArcMap window. The copies will be retrodeformed.
10. In editing mode, use the cursor to select a polygon, and select 'Modify Feature' from the Task pulldown menu on the Editor toolbar. Then bring up node locations by clicking the 'Sketch Properties' button on the Editor toolbar.
11. For line length balance, open Excel and type the coordinates for each node. Use the spreadsheet to calculate the distance between each node so that these values can be kept constant during retrodeformation.

12. Otherwise, move the nodes back along their deformation paths, recalculating the area for each polygon after retrodeformation.
13. If the section does not balance, return to preferred drafting program, make changes, and return to Step 1.

APPENDIX B

Survey, DEM, and topographic map data for long profile of the Savage River.

Table B-1. Points surveyed along a portion of the Savage River. Projection is WGS 84 UTM Zone 6.

Point Id	Easting	Northing	Ellipsoid Height	Coordinate Quality	survey distance
3pro045	388373.507	7063377.728	870.9162	0.4727	0
3pro044	388350.2659	7063482.247	869.2528	0.037	107.071
3pro043	388448.8233	7063594.873	867.0843	0.0442	256.732
3pro042	388417.1018	7063696.328	865.3417	0.036	363.03
3pro041	388443.0159	7063824.074	863.5891	0.0327	493.378
3pro040	388419.5483	7063930.175	862.2578	0.0357	602.043
3pro039	388390.0842	7064066.285	860.8145	0.0445	741.305
3pro038	388449.5116	7064071.365	859.7252	0.0339	800.95
3pro037	388465.4273	7064172.923	858.0999	0.036	903.747
3pro036	388426.7073	7064244.19	856.837	0.0696	984.853
3pro035	388399.4297	7064351.509	855.4416	0.0531	1095.58
3pro033	388382.9117	7064460.697	854.2897	0.0448	1206.01
3pro032	388416.5444	7064538.809	852.7357	0.0489	1291.06
3pro031	388373.8364	7064678.462	850.6043	0.029	1437.1
3pro030	388316.7657	7064785.311	848.8298	0.0418	1558.23
3pro028	388367.234	7064926.775	846.355	0.0275	1708.43
3pro027	388319.8858	7065028.192	845.0128	0.0337	1820.35
3pro026	388244.9077	7065103.301	843.7018	0.0374	1926.48
3pro025	388189.4237	7065194.785	842.2386	0.0333	2033.48
3pro024	388171.4429	7065297.504	841.1427	0.0286	2137.76
3pro023	388207.3583	7065392.45	839.7442	0.0296	2239.27
3pro022	388268.8579	7065461.639	838.6078	0.024	2331.84
3pro021	388262.3388	7065576.716	836.9694	0.0301	2447.1
3pro020	388248.4624	7065703.145	834.9993	0.0335	2574.29
3pro019	388257.5693	7065817.73	833.3421	0.0332	2689.24
3pro018	388359.2893	7065952.351	831.3516	0.0323	2857.97
3pro017	388377.0905	7066059.702	829.658	0.0296	2966.78
3pro016	388360.0374	7066178.094	828.3477	0.0214	3086.4
3pro015	388325.0634	7066290.154	826.8678	0.023	3203.79
3pro014	388287.6355	7066379.865	825.6941	0.0268	3300.99
3pro013	388267.0674	7066489.616	824.5684	0.016	3412.65
3pro012	388267.1592	7066599.245	823.4103	0.0201	3522.28
3pro011	388231.3864	7066689.585	822.4583	0.0196	3619.45
3pro010	388182.2025	7066776.783	821.5568	0.0204	3719.56
3pro009	388166.7938	7066886.769	820.4922	0.027	3830.62
3pro008	388097.6976	7066949.247	819.8579	0.0262	3923.78
3pro007	387976.5213	7066987.54	818.7008	0.0233	4050.86
3pro006	387888.8916	7067045.131	817.2246	0.0304	4155.72
3pro005	387785.0721	7067100.858	816.4729	0.0224	4273.55
3pro004	387706.207	7067168.848	815.3748	0.0339	4377.68
3pro003	387612.8243	7067219.293	814.5277	0.0398	4483.81
3pro002	387526.8016	7067276.421	813.6569	0.0252	4587.08
3pro001	387414.182	7067339.637	812.789	0.0286	4716.23
prof024	387378.9895	7067498.695	811.8758	0.5689	4879.13
prof023	387288.2697	7067582.055	811.0069	0.0747	5002.33
prof022	387218.7747	7067670.551	809.9122	0.0744	5114.86
prof021	387125.4182	7067757.967	808.8174	0.0708	5242.75

prof020	387038.0826	7067845.292	807.1869	0.038	5366.25
prof019	386992.778	7067951.569	806.3164	0.0427	5481.78
prof018	386967.7948	7068087.36	804.9736	0.0386	5619.85
prof017	387023.0177	7068169.354	804.3381	0.0347	5718.71
prof016	387043.2938	7068307.614	803.3248	0.0513	5858.45
prof014	387072.0135	7068425.464	802.5532	0.1128	5979.75
prof013	386942.012	7068510.924	801.1699	0.0694	6135.32
prof012	386936.7188	7068642.745	800.2939	0.0493	6267.25
prof011	386886.3525	7068768.372	799.1658	0.0394	6402.6
prof010	386890.898	7068902.908	798.1192	0.0416	6537.21
prof009	386885.5244	7069026.61	797.1172	0.0352	6661.03
prof008	386813.4385	7069141.986	796.0971	0.0359	6797.07
prof007	386746.5181	7069298.421	794.8076	0.0343	6967.22
prof006	386733.8228	7069433.857	793.6891	0.0289	7103.25
prof005	386678.3134	7069558.886	792.4686	0.0233	7240.05
prof004	386722.4723	7069663.784	791.714	0.0224	7353.86
prof003	386795.3811	7069741.852	790.8258	0.0192	7460.68
prof002	386815.275	7069841.486	790.0898	0.0235	7562.28
prof001	386789.8818	7069890.803	789.9585	0.6992	7617.75
2pro001	386780.455	7070010.624	788.4463	0.0241	7737.94
2pro002	386854.3943	7070088.144	787.9479	0.0225	7845.07
2pro003	386894.8473	7070170.447	787.5489	0.0231	7936.78
2pro004	386946.579	7070247.415	786.9107	0.0218	8029.52
2pro005	386963.2465	7070340.706	786.4262	0.021	8124.29
2pro006	386939.1101	7070444.67	785.8738	0.0237	8231.01
2pro007	386934.8653	7070547.599	785.2503	0.0222	8334.03
2pro008	386903.8927	7070644.552	784.5574	0.0219	8435.81
2pro009	386903.5523	7070746.036	784.087	0.0188	8537.3
2pro010	386909.6093	7070852.664	782.7001	0.0296	8644.1
2pro011	386945.6815	7070936.172	780.7674	0.0381	8735.06
2pro012	386947.1675	7071032.656	778.5053	0.0291	8831.56
2pro013	386935.6174	7071125.521	777.4163	0.0318	8925.14
2pro014	386931.535	7071224.848	776.181	0.0282	9024.55
2pro015	386941.2193	7071320.745	774.4586	0.0324	9120.93
2pro016	387009.0761	7071381.337	772.0094	0.0367	9211.9
2pro017	387036.9945	7071456.561	768.0813	0.0291	9292.14
2pro018	387010.6325	7071536.994	765.7027	0.0189	9376.78
2pro019	387011.8483	7071624.659	762.5563	0.0244	9464.46
2pro020	387043.0905	7071716.447	759.9557	0.0255	9561.42
2pro021	387064.7163	7071804.423	758.1316	0.0306	9652.01
2pro022	387071.0479	7071896.21	754.841	0.0233	9744.02
2pro023	387060.1569	7071973.791	751.9053	0.0194	9822.36
2pro024	387087.9909	7072058.395	749.2544	0.0266	9911.42
2pro025	387096.2886	7072119.275	744.647	0.0205	9972.87
2pro026	387083.1049	7072208.584	740.066	0.0246	10063.1
2pro027	387033.0242	7072282.364	737.7768	0.0254	10152.3
2pro029	387036.5374	7072419.574	734.3554	0.5427	10289.6
2pro030	387034.2416	7072508.317	729.4564	0.0249	10378.3
2pro031	387004.1354	7072570.994	726.4838	0.0284	10447.9
2pro032	387004.9652	7072651.37	723.8174	0.019	10528.3
2pro033	387014.7035	7072727.527	722.5414	0.0212	10605
2pro034	387007.849	7072815.991	719.4213	0.0156	10693.8
2pro035	387013.2998	7072898.705	715.5184	0.0216	10776.7
2pro036	387008.4818	7072983.323	712.2079	0.019	10861.4
2pro037	386976.892	7073079.095	708.658	0.0196	10962.3
2pro038	386934.2013	7073144.587	706.6395	0.0235	11040.4
2pro039	386924.0413	7073228.917	704.8405	0.0173	11125.4
2pro040	386914.3766	7073304.95	703.4123	0.0206	11202

2pro041	386850.9099	7073363.795	701.0818	0.0143	11288.6
2pro042	386787.7745	7073393.74	699.8735	0.0169	11358.4
2pro043	386734.9627	7073473.971	697.7397	0.0236	11454.5
2pro044	386724.6593	7073546.628	696.2293	0.0212	11527.9
2pro045	386739.455	7073645.093	692.3942	0.0271	11627.5
2pro046	386653.9316	7073647.719	690.5072	0.0242	11713
2pro047	386580.2071	7073704.179	688.9776	0.0262	11805.9
2pro048	386501.2972	7073759.845	688.0579	0.0214	11902.4
2pro049	386434.2861	7073826.253	686.7802	0.0247	11996.8
2pro050	386352.7747	7073901.444	685.6813	0.0997	12107.7
2pro051	386294.1287	7073995.075	684.1455	0.1402	12218.2
2pro052	386323.2844	7074090.142	682.9607	0.0728	12317.6
2pro053	386277.1908	7074188.147	681.4627	0.0865	12425.9
2pro054	386209.2298	7074265.87	680.1987	0.0546	12529.2
2pro055	386193.4818	7074360.803	679.1955	0.0565	12625.4
2pro056	386167.3448	7074452.539	677.0858	0.0409	12720.8
2pro057	386102.1933	7074510.374	676.2013	0.0316	12807.9
2pro058	386049.586	7074579.187	674.3525	0.0282	12894.5
2pro059	385942.315	7074668.408	672.2601	0.0216	13034
2pro060	385860.2703	7074725.369	671.1459	0.0257	13133.9
2pro061	385784.0841	7074781.584	670.1922	0.0156	13228.6
2pro063	385608.2491	7074809.022	667.7597	0.0234	13406.6
2pro062	385699.9644	7074811.806	669.1207	0.0249	13498.3
2pro064	385504.9514	7074833.46	666.3195	0.0299	13694.5
2pro066	385420.8283	7074882.747	665.4117	0.0289	13792
2pro067	385344.0182	7074958.756	664.1518	0.0223	13900.1
2pro068	385326.5553	7074986.762	663.9187	0.0277	13933.1
2pro069	385299.3252	7075091.461	662.6702	0.0266	14041.3
2pro070	385185.719	7075167.719	660.622	0.0248	14178.1
2pro071	385127.702	7075257.26	659.0441	0.0793	14284.8
2pro072	385086.4655	7075358.65	657.6699	0.0338	14394.2
2pro073	385079.7541	7075465.485	655.9449	0.0311	14501.3
2pro074	385047.9016	7075574.545	654.6227	0.0275	14614.9
2pro075	384999.4964	7075666.833	653.5629	0.0282	14719.1
2pro076	384928.3017	7075731.614	652.4416	0.0318	14815.4
2pro077	384854.3536	7075809.753	651.1571	0.0245	14923
2pro078	384802.5454	7075895.123	650.2579	0.034	15022.8
base	387381.3537	7069982.043	1008.1047	0	

Table B-2. Savage River long profile data from topographic maps.

elevation (feet)	distance from source (m)	elevation (meters)	elevation (feet)	distance from source (m)	elevation (meters)
5800	0	1767.8	3300	7545	1005.8
5700	38	1737.3	3200	8751	975.3
5600	72	1706.8	3100	10452	944.8
5500	121	1676.3	3000	12054	914.4
5400	162	1645.8	2900	13987	883.9
5300	230	1615.4	2850	14975	868.6
5200	293	1584.9	2800	16066	853.4
5100	382	1554.4	2700	17834	822.9
5000	458	1523.9	2600	21709	792.4
4900	554	1493.4	2500	24631	762.0
4800	691	1463.0	2400	25521	731.5
4700	829	1432.5	2300	26309	701.0
4600	938	1402.0	2250	27210	685.8
4500	1058	1371.5	2200	28171	670.5
4400	1218	1341.1	2150	29484	655.3
4300	1614	1310.6	2100	30727	640.0
4200	1781	1280.1	2050	32524	624.8
4100	1999	1249.6	2000	34094	609.6
4000	2552	1219.1	1900	36783	579.1
3900	3000	1188.7	1850	39023	563.9
3800	3470	1158.2	1800	40399	548.6
3700	3915	1127.7	1750	41870	533.4
3600	4437	1097.2	1700	44191	518.1
3500	5527	1066.7	1600	46980	487.7
3400	6528	1036.3		48224	

Table B-3. Savage River long profile data from USGS digital elevation models.

sample #	easting	northing	elevation	distance from source (m)	sample #	easting	northing	elevation	distance from source (m)
0	393768.0	7053187.5	1347.15	0.00	250	387020.8	7071030.5	805.60	22715.25
1	393703.2	7053251.5	1344.43	91.23	251	387034.2	7071125.5	788.33	23049.27
2	393634.8	7053310.5	1337.75	182.45	252	387054.1	7071218	784.94	23145.04
3	393573.9	7053376	1336.56	273.68	253	387108.3	7071295	785.54	23240.81
4	393558.8	7053465.5	1319.00	364.90	254	387099.6	7071386.5	785.83	23336.58
5	393526.8	7053549.5	1311.72	456.13	255	387114.2	7071481.5	781.96	23432.35
6	393489.7	7053632	1289.57	547.36	256	387135.2	7071575	766.05	23528.12
7	393477.5	7053722.5	1273.55	638.58	257	387157.7	7071668.5	758.55	23623.90
8	393436.2	7053803.5	1258.95	729.81	258	387176.2	7071762.5	760.76	23719.67
9	393383.4	7053878	1250.52	821.03	259	387185.7	7071858	766.28	23815.44
10	393322.2	7053945.5	1247.00	912.26	260	387197.4	7071953.5	768.37	23911.21
11	393271.7	7054021.5	1242.74	1003.48	261	387191.6	7072048.5	763.89	24006.98
12	393242.2	7054108	1241.24	1094.71	262	387137.2	7072123.5	760.77	24102.76
13	393200.8	7054189	1238.73	1185.94	263	387129.2	7072216	751.91	24198.53
14	393147.7	7054262.5	1229.98	1277.16	264	387124.1	7072311.5	735.74	24294.30
15	393078.5	7054322	1221.20	1368.39	265	387115.8	7072407.5	738.11	24390.07
16	392998.5	7054365.5	1217.21	1459.61	266	387100.5	7072501.5	733.21	24485.84
17	392910.1	7054382.5	1212.74	1550.84	267	387096.8	7072597	734.23	24581.62
18	392819.9	7054398.5	1210.77	1642.07	268	387094.8	7072693	735.40	24677.39
19	392731.2	7054420	1194.71	1733.29	269	387094.8	7072789	737.51	24773.16
20	392640.3	7054420	1186.92	1824.52	270	387098.0	7072885	729.26	24868.93
21	392549.0	7054425.5	1183.48	1915.74	271	387063.5	7072973.5	720.72	24964.70
22	392457.5	7054427	1181.65	2006.97	272	387023.4	7073060	711.99	25060.48
23	392369.1	7054448.5	1177.17	2098.20	273	386997.1	7073152	705.36	25156.25
24	392281.8	7054476	1164.48	2189.42	274	386930.1	7073215	704.35	25252.02
25	392197.1	7054510	1157.73	2280.65	275	386875.4	7073288	703.72	25347.79
26	392109.0	7054533.5	1152.14	2371.87	276	386834.1	7073373	702.17	25443.56
27	392018.2	7054542.5	1147.40	2463.10	277	386854.0	7073464.5	701.99	25539.33
28	391926.8	7054547	1139.12	2554.33	278	386788.2	7073505	702.12	25635.11
29	391838.5	7054570	1130.38	2645.55	279	386704.4	7073545	700.58	25730.88
30	391750.6	7054595	1129.10	2736.78	280	386626.5	7073601	700.72	25826.65
31	391679.6	7054652.5	1127.19	2828.00	281	386548.8	7073657.5	692.63	25922.42
32	391597.8	7054684.5	1125.20	2919.23	282	386484.8	7073729	688.87	26018.19
33	391506.4	7054687.5	1122.32	3010.45	283	386439.9	7073814	685.67	26113.97
34	391423.6	7054722	1113.70	3101.68	284	386410.6	7073905	683.91	26209.74
35	391346.3	7054769.5	1100.65	3192.91	285	386380.3	7073996	683.02	26305.51
36	391261.2	7054803	1096.42	3284.13	286	386346.7	7074086	681.69	26401.28
37	391174.0	7054830	1096.12	3375.36	287	386313.5	7074176	678.91	26497.05
38	391087.6	7054859.5	1094.24	3466.58	288	386273.5	7074263	675.14	26592.83
39	391006.5	7054901.5	1093.67	3557.81	289	386225.8	7074346.5	672.00	26688.60
40	390932.1	7054954.5	1091.23	3649.04	290	386150.9	7074406.5	672.48	26784.37
41	390860.5	7055011	1088.60	3740.26	291	386093.3	7074483.5	670.71	26880.14
42	390777.0	7055046	1087.58	3831.49	292	386024.5	7074550	669.99	26975.91
43	390689.6	7055020	1085.76	3922.71	293	385953.1	7074614	669.99	27071.69
44	390602.4	7054992.5	1083.97	4013.94	294	385872.7	7074665.5	669.99	27167.46

45	390512.6	7054984.5	1080.43	4105.17	295	385787.7	7074710	668.82	27263.23
46	390421.2	7054986	1076.71	4196.39	296	385692.8	7074701.5	668.07	27359.00
47	390331.3	7055003.5	1069.89	4287.62	297	385610.7	7074734	668.18	27454.77
48	390245.7	7055033.5	1067.67	4378.84	298	385540.5	7074798.5	666.99	27550.54
49	390161.1	7055068	1065.58	4470.07	299	385489.6	7074880	665.62	27646.32
50	390071.5	7055086.5	1065.05	4561.30	300	385428.2	7074953	664.01	27742.09
51	389982.2	7055106	1060.85	4652.52	301	385360.3	7075021	664.00	27837.86
52	389891.0	7055108.5	1057.47	4743.75	302	385301.3	7075096.5	663.28	27933.63
53	389820.2	7055157.5	1056.02	4834.97	303	385244.3	7075174	662.13	28029.40
54	389756.8	7055223.5	1059.35	4926.20	304	385234.5	7075268.5	658.91	28125.18
55	389688.4	7055284	1056.37	5017.42	305	385212.1	7075362	655.52	28220.95
56	389609.7	7055330.5	1052.90	5108.65	306	385177.9	7075450.5	654.35	28316.72
57	389532.0	7055378.5	1042.98	5199.88	307	385126.6	7075531.5	652.05	28412.49
58	389478.1	7055445	1037.07	5291.10	308	385068.4	7075607.5	649.05	28508.26
59	389453.2	7055533	1034.28	5382.33	309	385004.3	7075679.5	647.45	28604.04
60	389445.8	7055623	1031.56	5473.55	310	384939.3	7075750	647.45	28699.81
61	389450.3	7055714	1028.51	5564.78	311	384873.2	7075819.5	648.59	28795.58
62	389454.8	7055805.5	1025.75	5656.01	312	384804.6	7075886.5	649.04	28891.35
63	389452.4	7055897	1022.82	5747.23	313	384732.6	7075950	649.18	28987.12
64	389456.5	7055988	1019.73	5838.46	314	384663.2	7076016.5	648.53	29082.90
65	389467.9	7056079	1016.61	5929.68	315	384595.3	7076084.5	648.37	29178.67
66	389475.1	7056170	1012.97	6020.91	316	384521.8	7076146	645.73	29274.44
67	389480.7	7056261.5	1009.19	6112.14	317	384447.2	7076206.5	642.63	29370.21
68	389474.7	7056352	1005.96	6203.36	318	384371.8	7076266	639.34	29465.98
69	389459.4	7056442	1003.73	6294.59	319	384311.7	7076340	638.61	29561.76
70	389444.1	7056532.5	1000.66	6385.81	320	384283.1	7076430.5	638.04	29657.53
71	389413.4	7056617.5	998.77	6477.04	321	384282.1	7076525.5	638.00	29753.30
72	389376.2	7056701	997.01	6568.26	322	384265.2	7076618	637.35	29849.07
73	389352.9	7056789.5	995.91	6659.49	323	384218.7	7076700	637.00	29944.84
74	389339.7	7056879	994.37	6750.72	324	384153.0	7076770	636.93	30040.61
75	389352.4	7056968	993.08	6841.94	325	384079.8	7076831.5	635.16	30136.39
76	389395.8	7057048.5	993.47	6933.17	326	384002.9	7076889	633.34	30232.16
77	389433.9	7057131.5	992.60	7024.39	327	383931.1	7076952	633.39	30327.93
78	389479.3	7057210.5	993.01	7115.62	328	383871.8	7077027.5	634.44	30423.70
79	389479.0	7057301.5	989.72	7206.85	329	383826.7	7077112	634.31	30519.47
80	389459.3	7057390	983.75	7298.07	330	383766.9	7077185.5	634.37	30615.25
81	389416.3	7057470.5	979.33	7389.30	331	383696.8	7077251	633.98	30711.02
82	389384.1	7057556	974.94	7480.52	332	383615.1	7077301	633.46	30806.79
83	389364.3	7057645.5	972.09	7571.75	333	383527.1	7077338.5	634.31	30902.56
84	389303.6	7057712.5	971.50	7662.98	334	383439.4	7077375.5	636.38	30998.33
85	389242.8	7057780.5	970.23	7754.20	335	383378.7	7077440	635.44	31094.11
86	389197.9	7057858	968.66	7845.43	336	383397.9	7077531.5	627.83	31189.88
87	389176.4	7057947	967.17	7936.65	337	383399.8	7077625	624.41	31285.65
88	389179.4	7058037.5	966.42	8027.88	338	383363.7	7077713.5	623.99	31381.42
89	389197.8	7058127	964.61	8119.11	339	383295.8	7077781.5	623.65	31477.19
90	389230.7	7058211.5	964.52	8210.33	340	383257.9	7077867	623.02	31572.97
91	389270.1	7058294	965.88	8301.56	341	383224.8	7077956.5	623.03	31668.74
92	389285.3	7058384	966.69	8392.78	342	383181.8	7078042.5	623.00	31764.51
93	389257.3	7058471	963.56	8484.01	343	383114.8	7078110	623.00	31860.28

94	389226.7	7058557.5	960.56	8575.23	344	383061.3	7078188	623.00	31956.05
95	389195.3	7058643	959.23	8666.46	345	383015.3	7078272.5	623.00	32051.82
96	389163.8	7058729	959.48	8757.69	346	382963.0	7078353	623.02	32147.60
97	389214.1	7058796.5	955.80	8848.91	347	382915.1	7078436	622.57	32243.37
98	389294.6	7058839.5	953.44	8940.14	348	382880.9	7078525.5	621.91	32339.14
99	389333.6	7058911	952.66	9031.36	349	382838.7	7078611	620.09	32434.91
100	389323.1	7059002	947.82	9122.59	350	382784.7	7078690.5	617.40	32530.68
101	389300.0	7059088.5	945.37	9213.82	351	382716.8	7078758.5	614.50	32626.46
102	389276.8	7059175.5	944.58	9305.04	352	382652.6	7078828.5	612.97	32722.23
103	389227.2	7059246.5	945.02	9396.27	353	382627.4	7078919.5	610.26	32818.00
104	389175.3	7059314	945.20	9487.49	354	382653.8	7079012	610.02	32913.77
105	389225.3	7059387.5	942.46	9578.72	355	382687.0	7079102	610.01	33009.54
106	389308.5	7059423.5	943.90	9669.95	356	382741.7	7079178	610.01	33105.32
107	389332.3	7059494	942.52	9761.17	357	382811.4	7079244	610.01	33201.09
108	389270.4	7059560.5	940.07	9852.40	358	382869.0	7079320.5	610.01	33296.86
109	389265.4	7059650	937.85	9943.62	359	382877.4	7079414	610.01	33392.63
110	389243.8	7059733	935.87	10034.85	360	382844.0	7079499	610.01	33488.40
111	389205.6	7059807	933.81	10126.07	361	382796.9	7079581	610.08	33584.18
112	389202.2	7059898	931.83	10217.30	362	382776.5	7079674	610.13	33679.95
113	389201.5	7059989.5	929.94	10308.53	363	382772.7	7079770	610.06	33775.72
114	389201.4	7060081	928.02	10399.75	364	382762.6	7079865.5	610.02	33871.49
115	389192.6	7060172	925.66	10490.98	365	382742.5	7079959	608.83	33967.26
116	389197.0	7060262.5	922.83	10582.20	366	382722.4	7080053	606.42	34063.04
117	389201.8	7060352	921.33	10673.43	367	382702.6	7080147	605.22	34158.81
118	389148.4	7060421.5	916.05	10764.66	368	382673.9	7080238.5	604.95	34254.58
119	389129.0	7060511	914.25	10855.88	369	382623.8	7080313	603.28	34350.35
120	389109.0	7060600	912.12	10947.11	370	382562.8	7080372.5	601.83	34446.12
121	389084.9	7060688.5	910.34	11038.33	371	382575.0	7080465	600.41	34541.89
122	389054.9	7060774.5	908.93	11129.56	372	382606.2	7080555.5	601.61	34637.67
123	389020.7	7060859	906.44	11220.79	373	382613.2	7080650.5	600.75	34733.44
124	389015.8	7060948.5	906.03	11312.01	374	382641.2	7080737	598.91	34829.21
125	388987.1	7061035.5	904.46	11403.24	375	382647.6	7080832.5	595.41	34924.98
126	388968.5	7061125	903.40	11494.46	376	382607.7	7080919	591.67	35020.75
127	388944.0	7061212.5	902.24	11585.69	377	382574.2	7081008	588.32	35116.53
128	388914.3	7061299	902.19	11676.92	378	382559.3	7081103	586.01	35212.30
129	388899.7	7061388.5	902.20	11768.14	379	382544.5	7081198	584.03	35308.07
130	388864.6	7061473	901.66	11859.37	380	382526.7	7081292.5	582.18	35403.84
131	388844.9	7061561.5	900.72	11950.59	381	382510.3	7081386.5	578.13	35499.61
132	388774.7	7061562.5	902.74	12041.82	382	382510.3	7081482.5	575.42	35595.39
133	388710.5	7061594	908.54	12133.04	383	382510.3	7081578.5	573.94	35691.16
134	388686.3	7061681.5	908.00	12224.27	384	382509.8	7081674.5	573.62	35786.93
135	388642.1	7061761.5	909.30	12315.50	385	382489.4	7081768.5	573.07	35882.70
136	388629.0	7061849	905.79	12406.72	386	382468.0	7081862	572.44	35978.47
137	388610.9	7061938.5	901.63	12497.95	387	382440.9	7081954.5	572.05	36074.25
138	388625.7	7062028.5	892.92	12589.17	388	382413.8	7082046.5	571.99	36170.02
139	388639.9	7062118.5	887.20	12680.40	389	382383.2	7082137.5	571.99	36265.79
140	388645.5	7062210	882.89	12771.63	390	382345.3	7082225.5	571.99	36361.56
141	388661.9	7062294	880.53	12862.85	391	382307.5	7082314	571.99	36457.33
142	388744.4	7062333.5	879.93	12954.08	392	382281.0	7082406	571.99	36553.10

143	388814.2	7062391.5	880.06	13045.30	393	382255.0	7082498.5	572.37	36648.88
144	388820.9	7062473	879.05	13136.53	394	382221.3	7082588.5	572.90	36744.65
145	388765.8	7062546	876.94	13227.76	395	382170.8	7082669	572.23	36840.42
146	388806.8	7062608.5	876.71	13318.98	396	382113.8	7082746.5	573.22	36936.19
147	388856.9	7062665.5	877.06	13410.21	397	382088.4	7082838	573.43	37031.96
148	388798.3	7062728.5	874.42	13501.43	398	382068.8	7082932	572.53	37127.74
149	388722.7	7062780	871.94	13592.66	399	382059.3	7083027.5	571.64	37223.51
150	388679.9	7062858	869.42	13683.89	400	382051.3	7083123	571.06	37319.28
151	388676.1	7062943.5	867.99	13775.11	401	382051.3	7083219	569.46	37415.05
152	388681.8	7063029	867.21	13866.34	402	382051.3	7083315	568.01	37510.82
153	388696.5	7063117.5	866.61	13957.56	403	382051.3	7083411	566.05	37606.60
154	388714.7	7063205	865.56	14048.79	404	382051.3	7083507.5	564.08	37702.37
155	388643.6	7063261	863.81	14140.01	405	382057.5	7083603	563.07	37798.14
156	388576.9	7063234	864.02	14231.24	406	382067.9	7083698.5	562.33	37893.91
157	388501.5	7063210.5	865.08	14322.47	407	382070.9	7083794	562.00	37989.68
158	388469.3	7063286	864.15	14413.69	408	382062.9	7083889.5	561.87	38085.46
159	388496.6	7063372.5	862.07	14504.92	409	382054.9	7083985.5	561.18	38181.23
160	388552.3	7063445	859.11	14596.14	410	382028.8	7084076.5	561.09	38277.00
161	388557.8	7063535.5	857.07	14687.37	411	381988.0	7084163	561.12	38372.77
162	388528.0	7063617.5	855.01	14778.60	412	381949.7	7084251.5	559.92	38468.54
163	388529.3	7063709	853.40	14869.82	413	381911.2	7084339.5	557.62	38564.31
164	388487.8	7063787.5	853.70	14961.05	414	381868.2	7084425	556.30	38660.09
165	388477.3	7063878	852.59	15052.27	415	381822.8	7084509.5	554.85	38755.86
166	388495.8	7063965.5	850.85	15143.50	416	381774.4	7084592.5	552.61	38851.63
167	388479.7	7064055.5	849.84	15234.73	417	381720.6	7084671	551.44	38947.40
168	388473.6	7064146.5	848.89	15325.95	418	381649.8	7084736	549.26	39043.17
169	388452.6	7064235.5	848.75	15417.18	419	381595.6	7084815	548.22	39138.95
170	388465.7	7064324	846.78	15508.40	420	381542.3	7084895	547.99	39234.72
171	388468.8	7064410.5	845.39	15599.63	421	381489.7	7084975.5	547.47	39330.49
172	388426.8	7064490	844.20	15690.85	422	381444.7	7085060.5	547.16	39426.26
173	388409.7	7064579	842.75	15782.08	423	381415.6	7085150.5	546.88	39522.03
174	388426.1	7064668.5	841.30	15873.31	424	381399.8	7085245	546.02	39617.81
175	388432.2	7064756	838.92	15964.53	425	381382.8	7085339.5	545.32	39713.58
176	388388.8	7064835	837.64	16055.76	426	381365.2	7085434	545.68	39809.35
177	388332.2	7064907	836.06	16146.98	427	381347.3	7085528.5	545.77	39905.12
178	388282.8	7064982.5	834.38	16238.21	428	381314.1	7085618.5	544.12	40000.89
179	388268.1	7065071.5	831.88	16329.44	429	381280.9	7085708.5	541.99	40096.67
180	388292.4	7065158	829.35	16420.66	430	381247.7	7085799	540.48	40192.44
181	388305.8	7065248.5	826.83	16511.89	431	381213.8	7085888.5	538.99	40288.21
182	388330.7	7065336.5	823.74	16603.11	432	381179.8	7085978.5	536.96	40383.98
183	388339.3	7065427	822.52	16694.34	433	381146.0	7086068.5	535.13	40479.75
184	388334.7	7065518.5	821.82	16785.57	434	381112.9	7086158.5	533.29	40575.53
185	388331.8	7065609	820.80	16876.79	435	381079.9	7086248.5	533.00	40671.30
186	388363.5	7065694.5	820.09	16968.02	436	381028.4	7086329	532.05	40767.07
187	388409.3	7065772	820.08	17059.24	437	380971.4	7086406.5	531.76	40862.84
188	388398.4	7065861.5	818.96	17150.47	438	380915.2	7086484	531.37	40958.61
189	388384.9	7065952	818.04	17241.70	439	380859.1	7086562	531.12	41054.38
190	388375.6	7066042.5	817.13	17332.92	440	380808.8	7086643.5	530.91	41150.16
191	388372.8	7066134	816.70	17424.15	441	380765.8	7086729.5	530.41	41245.93

192	388353.9	7066223.5	815.98	17515.37	442	380723.8	7086816	530.00	41341.70
193	388340.8	7066314	814.99	17606.60	443	380682.4	7086902.5	529.16	41437.47
194	388333.3	7066405	815.01	17697.82	444	380666.9	7086995	528.99	41533.24
195	388327.4	7066496.5	816.11	17789.05	445	380666.9	7087091	528.05	41629.02
196	388324.5	7066588	817.25	17880.28	446	380685.3	7087184.5	528.00	41724.79
197	388259.2	7066651	817.28	17971.50	447	380713.5	7087276	527.59	41820.56
198	388195.9	7066717	818.50	18062.73	448	380746.6	7087366	526.67	41916.33
199	388132.5	7066783	818.45	18153.95	449	380763.3	7087460.5	525.61	42012.10
200	388065.8	7066845	818.75	18245.18	450	380719.3	7087540.5	523.84	42107.88
201	387987.2	7066891.5	817.94	18336.41	451	380641.8	7087591	522.53	42203.65
202	387908.6	7066938.5	816.59	18427.63	452	380554.1	7087630	522.00	42299.42
203	387829.9	7066985	814.12	18518.86	453	380468.2	7087673	522.07	42395.19
204	387758.1	7067041	814.00	18610.08	454	380393.2	7087731.5	522.03	42490.96
205	387689.4	7067101.5	814.00	18701.31	455	380323.8	7087798	521.80	42586.74
206	387620.7	7067162	814.00	18792.54	456	380250.4	7087859	520.71	42682.51
207	387552.0	7067222.5	814.12	18883.76	457	380193.8	7087927	520.31	42778.28
208	387489.0	7067288.5	815.00	18974.99	458	380190.9	7088022	518.38	42874.05
209	387427.2	7067356	815.36	19066.21	459	380225.4	7088111	516.68	42969.82
210	387365.4	7067423.5	816.00	19157.44	460	380257.8	7088201	516.20	43065.59
211	387308.0	7067494.5	815.03	19248.66	461	380264.4	7088295.5	514.61	43161.37
212	387250.9	7067566	814.98	19339.89	462	380258.2	7088391.5	512.29	43257.14
213	387203.3	7067644	813.90	19431.12	463	380255.8	7088487	509.68	43352.91
214	387159.8	7067724.5	812.09	19522.34	464	380267.7	7088582.5	507.27	43448.68
215	387122.5	7067807	810.46	19613.57	465	380297.3	7088673.5	504.48	43544.45
216	387099.5	7067896	808.01	19704.79	466	380307.4	7088767.5	504.00	43640.23
217	387077.5	7067984.5	805.46	19796.02	467	380318.1	7088863	504.99	43736.00
218	387085.5	7068075.5	804.07	19887.25	468	380309.8	7088957.5	507.20	43831.77
219	387093.5	7068166.5	801.50	19978.47	469	380285.0	7089050	507.80	43927.54
220	387090.7	7068257.5	799.34	20069.70	470	380253.3	7089140.5	504.10	44023.31
221	387077.7	7068348	797.06	20160.92	471	380204.8	7089223	505.08	44119.09
222	387055.3	7068436.5	795.22	20252.15	472	380120.4	7089266.5	515.04	44214.86
223	387027.4	7068523.5	793.82	20343.38	473	380033.2	7089306.5	514.65	44310.63
224	386986.5	7068605.5	793.96	20434.60	474	379944.3	7089342.5	506.91	44406.40
225	386948.1	7068688	792.41	20525.83	475	379853.9	7089375	504.00	44502.17
226	386916.3	7068774	790.75	20617.05	476	379761.6	7089401	504.00	44597.95
227	386906.9	7068865	788.93	20708.28	477	379667.6	7089420.5	504.12	44693.72
228	386889.5	7068954.5	787.34	20799.51	478	379576.3	7089450	504.00	44789.49
229	386868.9	7069043.5	786.89	20890.73	479	379485.0	7089479	504.00	44885.26
230	386831.8	7069127	786.79	20981.96	480	379399.6	7089522	505.46	44981.03
231	386801.2	7069213	785.89	21073.18	481	379308.8	7089548.5	513.11	45076.81
232	386783.2	7069302.5	785.83	21164.41	482	379214.0	7089535.5	515.08	45172.58
233	386781.6	7069393	786.53	21255.63	483	379119.1	7089543	514.81	45268.35
234	386801.4	7069482	786.85	21346.86	484	379026.1	7089567	503.86	45364.12
235	386826.5	7069570	785.54	21438.09	485	378934.9	7089593	500.58	45459.89
236	386853.3	7069657	785.51	21529.31	486	378852.5	7089642	493.94	45555.66
237	386881.2	7069743	786.23	21620.54	487	378764.3	7089680	491.92	45651.44
238	386892.1	7069833	785.92	21711.76	488	378679.9	7089725.5	489.05	45747.21
239	386933.6	7069912.5	786.04	21802.99	489	378593.3	7089766.5	491.14	45842.98
240	386981.1	7069990	788.15	21894.22	490	378499.4	7089787	490.37	45938.75

241	387022.8	7070071.5	788.20	21985.44	491	378403.7	7089794.5	489.01	46034.52
242	387035.9	7070160.5	786.38	22076.67	492	378308.3	7089786	489.02	46130.30
243	387020.9	7070250.5	783.64	22167.89	493	378216.8	7089799	489.02	46226.07
244	387010.5	7070341	784.30	22259.12	494	378129.5	7089839.5	489.06	46321.84
245	387004.3	7070432.5	787.19	22350.35	495	378041.0	7089876.5	489.38	46417.61
246	386997.9	7070523.5	789.14	22441.57	496	377950.9	7089909.5	491.24	46513.38
247	386993.2	7070615	791.05	22532.80	497	377859.4	7089938.5	490.39	46609.16
248	387005.7	7070705.5	797.36	22624.02	498	377765.6	7089959	486.01	46704.93
249	387031.6	7070792.5	809.64	22715.25	499	377671.4	7089977.5	479.61	46800.70

APPENDIX C

Procedures for collecting long profile data from USGS topographic maps.

1. Digitize streams as polylines in ArcMap.
2. Import the rasterized, georeferenced USGS topographic maps for the length of the stream into ArcMap
3. Open an Excel worksheet to record the downstream distance at each topographic contour.
4. Using the measurement tool in ArcMap, start at the drainage divide and trace the stream downstream, stopping at each topographic contour and recording the distance in the Excel worksheet.
5. Plot as elevation vs. downstream distance in your favorite graphing program (I used Grapher v. 4).

APPENDIX D

Long profile data for streams across the northern foothills.

Table D-1. Long profile data for Bonnifield Creek.

elevation (feet)	distance from source (m)	elevation (meters)
4000	0	1219.1
3900	342	1188.7
3800	603	1158.2
3700	878	1127.7
3600	1263	1097.2
3500	1702	1066.7
3400	2361	1036.3
3300	3264	1005.8
3200	3940	975.3
3100	4710	944.8
3000	5414	914.4
2900	6102	883.9
2800	7029	853.4
2700	8184	822.9
2600	9136	792.4
2500	9942	762.0
2400	11119	731.5
2300	12126	701.0
2200	13410	670.5
2100	14297	640.0
2000	15909	609.6
1900	16710	579.1
1800	17819	548.6
1700	18904	518.1
1650	19704	502.9
1600	20430	487.7
1500	22141	457.2
1400	23631	426.7
1300	25357	396.2
1200	26813	365.7
1100	28855	335.3
1000	30764	304.8
950	32024	289.5
900	33237	274.3
850	35192	259.1
800	37046	243.8
750	39329	228.6
700	42493	213.3
650	47489	198.1

Table D-2. Long profile data for California Creek.

elevation (feet)	distance from source (m)	elevation (meters)
3100	145	944.8
3000	470	914.4
2900	771	883.9
2800	1294	853.4
2700	2116	822.9
2600	3415	792.4
2500	5241	762.0
2400	6680	731.5
2300	8350	701.0
2200	9985	670.5
2100	11556	640.0
2000	13703	609.6
1900	15915	579.1
1850	18873	563.9
1800	21620	548.6
1700	23856	518.1
1600	26040	487.7
1500	29820	457.2
1450	31271	441.9
1400	35373	426.7

Table D-3. Long profile data for Gold King Creek.

elevation (feet)	distance from source (m)	elevation (meters)
4200	314	1280.5
4100	921	1250.0
4000	1333	1219.5
3900	1914	1189.0
3800	2148	1158.5
3700	2399	1128.0
3600	2815	1097.6
3500	3448	1067.1
3400	5197	1036.6
3300	6001	1006.1
3200	6496	975.6
3100	7335	945.1
3000	7944	914.6
2900	8973	884.1
2800	10348	853.7
2700	11392	823.2
2600	12784	792.7
2500	14097	762.2
2400	16122	731.7
2300	17147	701.2
2200	18626	670.7
2100	20057	640.2
2000	22230	609.8
1900	23784	579.3
1800	25343	548.8
1700	26626	518.3
1600	28018	487.8
1500	29741	472.6
1400	31480	457.3
1300	32784	426.8
1200	34290	396.3
1100	35635	365.9
1000	37342	335.4
950	38278	304.9
900	39496	289.6
850	40870	274.4
800	42534	259.1
750	44299	243.9
700	46603	228.7
	51319	

Table D-4. Long profile data for Saint George Creek.

elevation (feet)	distance from source (m)	elevation (meters)
3800	0	1158.5
3700	361	1128.0
3600	616	1097.6
3500	831	1067.1
3400	1159	1036.6
3300	1442	1006.1
3200	1728	975.6
3100	2122	945.1
3000	2585	914.6
2900	3026	884.1
2800	3362	853.7
2700	3843	823.2
2600	4383	792.7
2500	5019	762.2
2400	5727	731.7
2300	6318	701.2
2200	7400	670.7
2100	8218	640.2
2000	9280	609.8
1900	10423	579.3
1800	11497	548.8
1700	13293	518.3
1600	15037	487.8
1550	16093	472.6
1500	16550	457.3
1400	18351	426.8
1300	19365	396.3
1200	20268	365.9
1100	22062	335.4
1000	23398	304.9
950	24215	289.6
900	25472	274.4
850	26670	259.1
800	29057	243.9
750	31490	228.7
700	33990	213.4
650	39511	198.2
	43457	

Table D-5. Long profile data for the Sanctuary River.

elevation (feet)	distance from source (m)	elevation (meters)	elevation (feet)	distance from source (m)	elevation (meters)
6700	0	2042.1	4200	2630	1280.1
6600	38	2011.6	4100	2731	1249.6
6500	80	1981.1	4000	2872	1219.1
6400	132	1950.6	3900	2983	1188.7
6300	170	1920.1	3800	3054	1158.2
6200	247	1889.7	3700	3134	1127.7
6100	322	1859.2	3600	3696	1097.2
6000	420	1828.7	3500	4537	1066.7
5900	503	1798.2	3400	6053	1036.3
5800	606	1767.8	3300	7391	1005.8
5700	673	1737.3	3200	8858	975.3
5600	726	1706.8	3100	10196	944.8
5500	775	1676.3	3000	13443	914.4
5400	896	1645.8	2900	16578	883.9
5300	1051	1615.4	2800	23403	853.4
5200	1252	1584.9	2700	28215	822.9
5100	1422	1554.4	2600	30916	792.4
5000	1548	1523.9	2500	33381	762.0
4900	1615	1493.4	2400	38572	731.5
4800	1713	1463.0	2300	40102	701.0
4700	1810	1432.5	2200	41013	670.5
4600	1902	1402.0	2100	42002	640.0
4500	2016	1371.5	2000	43871	609.6
4400	2313	1341.1	1900	47630	579.1
4300	2494	1310.6			

Table D-6. Long profile data for the Sushana River.

elevation (feet)	distance from source (m)	elevation (meters)
4000	84	1219.1
3900	202	1188.7
3800	368	1158.2
3700	611	1127.7
3600	874	1097.2
3500	1228	1066.7
3400	1666	1036.3
3300	2147	1005.8
3200	3095	975.3
3100	4206	944.8
3000	5741	914.4
2900	7175	883.9
2800	8438	853.4
2700	9015	822.9
2600	9316	792.4
2500	10033	762.0
2400	11326	731.5
2300	12906	701.0
2200	15210	670.5
2100	18011	640.0
2000	20766	609.6
1900	23890	579.1
1800	26831	548.6
1700	29674	518.1
1600	33173	487.7
1500	36439	457.2
1400	40066	426.7
1300	44051	396.2
1200	49039	365.7
1100	54820	335.3
1050	58100	320.0
1000	61430	304.8
950	65143	289.5
900	68238	274.3
850	71658	259.1
800	74831	243.8
750	79716	228.6
	82552	

Table D-7. Long profile data for Tatlanika Creek.

elevation (feet)	distance from source (m)	elevation (meters)	elevation (feet)	distance from source (m)	elevation (meters)
6300	27	1920.1	2900	12049	883.9
6200	78	1889.7	2800	12911	853.4
6100	121	1859.2	2700	14126	822.9
6000	220	1828.7	2600	15178	792.4
5900	332	1798.2	2500	15894	762.0
5800	450	1767.8	2400	17108	731.5
5700	564	1737.3	2300	18442	701.0
5600	660	1706.8	2200	19187	670.5
5500	749	1676.3	2100	20981	640.0
5400	832	1645.8	2000	23737	609.6
5300	894	1615.4	1900	25690	579.1
5200	952	1584.9	1800	28141	548.6
5100	1051	1554.4	1700	30274	518.1
5000	1132	1523.9	1600	32860	487.7
4900	1233	1493.4	1500	36846	457.2
4800	1484	1463.0	1400	39046	426.7
4700	1759	1432.5	1300	40857	396.2
4600	2010	1402.0	1200	42094	365.7
4500	2321	1371.5	1150	43473	350.5
4400	2612	1341.1	1100	44812	335.3
4300	2993	1310.6	1050	46658	320.0
4200	3357	1280.1	1000	47877	304.8
4100	3776	1249.6	950	49183	289.5
4000	4154	1219.1	900	50297	274.3
3900	4723	1188.7	850	51778	259.1
3800	5258	1158.2	800	53436	243.8
3700	5863	1127.7	750	56128	228.6
3600	6511	1097.2	700	58651	213.3
3500	7290	1066.7	650	62022	198.1
3400	7854	1036.3	600	66007	182.9
3300	8651	1005.8	550	76280	167.6
3200	9656	975.3	500	84651	152.4
3100	10554	944.8	400	97601	121.9
3000	11347	914.4		109362	

Table D-8. Long profiles data for the Teklanika River.

elevation (feet)	distance from source (m)	elevation (meters)	elevation (feet)	distance from source (m)	elevation (meters)
6800	0	2072.5	3100	15000	944.8
6700	48	2042.1	3000	16975	914.4
6600	101	2011.6	2900	21402	883.9
6500	136	1981.1	2800	25073	853.4
6400	176	1950.6	2700	27809	822.9
6300	214	1920.1	2600	30249	792.4
6200	266	1889.7	2500	32613	762.0
6100	318	1859.2	2400	35132	731.5
6000	382	1828.7	2300	38809	701.0
5900	415	1798.2	2200	42091	670.5
5800	513	1767.8	2100	43204	640.0
5700	691	1737.3	2000	45715	609.6
5600	935	1706.8	1900	49827	579.1
5500	1022	1676.3	1800	53335	548.6
5400	1157	1645.8	1700	56689	518.1
5300	1257	1615.4	1600	60541	487.7
5200	1498	1584.9	1500	66222	457.2
5100	1653	1554.4	1400	71212	426.7
5000	1899	1523.9	1300	74965	396.2
4900	2090	1493.4	1250	78364	381.0
4800	2352	1463.0	1200	80702	365.7
4700	2600	1432.5	1150	83019	350.5
4600	2845	1402.0	1100	85392	335.3
4500	3025	1371.5	1050	87788	320.0
4400	3248	1341.1	1000	90208	304.8
4300	3453	1310.6	950	92564	289.5
4200	3611	1280.1	900	95026	274.3
4100	3830	1249.6	850	97602	259.1
4000	4132	1219.1	800	100229	243.8
3900	4729	1188.7	750	102831	228.6
3800	4857	1158.2	700	105488	213.3
3700	5178	1127.7	650	108346	198.1
3600	5690	1097.2	600	113081	182.9
3500	7332	1066.7	550	121276	167.6
3400	8790	1036.3	500	144916	152.4
3300	10945	1005.8	450	162638	137.2
3200	13539	975.3	401	181908	122.2

Table D-9. Long profile data for the Totatlanika River.

elevation (feet)	distance from source (m)	elevation (meters)	elevation (feet)	distance from source (m)	elevation (meters)
6000	0	1828.7	2600	11758	792.4
5900	52	1798.2	2500	13902	762.0
5800	90	1767.8	2400	15717	731.5
5700	159	1737.3	2300	18493	701.0
5600	231	1706.8	2200	22258	670.5
5500	290	1676.3	2100	23945	640.0
5400	388	1645.8	2000	24921	609.6
5300	492	1615.4	1900	26676	579.1
5200	629	1584.9	1800	30376	548.6
5100	731	1554.4	1700	32658	518.1
5000	839	1523.9	1650	33889	502.9
4900	942	1493.4	1600	35623	487.7
4800	1008	1463.0	1550	37527	472.4
4700	1083	1432.5	1500	39701	457.2
4600	1160	1402.0	1400	43873	426.7
4500	1261	1371.5	1300	47217	396.2
4400	1399	1341.1	1200	49739	365.7
4300	1610	1310.6	1100	51806	335.3
4200	1741	1280.1	1000	55549	304.8
4100	1906	1249.6	950	56809	289.5
4000	2099	1219.1	900	58387	274.3
3900	2306	1188.7	850	59619	259.1
3800	2621	1158.2	800	62540	243.8
3700	2877	1127.7	775	63730	236.2
3600	3198	1097.2	750	64237	228.6
3500	3588	1066.7	700	65790	213.3
3400	3966	1036.3	650	68446	198.1
3300	4400	1005.8	600	71307	182.9
3200	4900	975.3	550	79243	167.6
3100	5539	944.8	500	86932	152.4
3000	6261	914.4	450	94743	137.2
2900	7284	883.9	400	106808	121.9
2800	8306	853.4		116262	
2700	9802	822.9			

Table D-10. Long profile data for Windy-Julius Creek.

elevation (feet)	distance from source (m)	elevation (meters)
3600	28	1097.2
3500	94	1066.7
3400	156	1036.3
3300	255	1005.8
3200	353	975.3
3100	437	944.8
3000	590	914.4
2900	815	883.9
2800	1004	853.4
2700	1169	822.9
2600	1428	792.4
2500	1687	762.0
2400	1976	731.5
2300	2344	701.0
2200	2769	670.5
2100	3195	640.0
2000	3904	609.6
1900	4608	579.1
1800	6106	548.6
1700	7095	518.1
1600	8873	487.7
1500	10454	457.2
1400	11820	426.7
1300	12633	396.2
1200	13316	365.7
1100	14062	335.3
1000	16226	304.8
900	17488	274.3
800	19327	243.8
700	21215	213.3
650	22714	198.1
600	26181	182.9
550	29093	167.6
500	36246	152.4
450	42420	137.2
400	53452	121.9
	54682	

Table D-11. Long profile data for the Wood River.

elevation (feet)	distance from source (m)	elevation (meters)	elevation (feet)	distance from source (m)	elevation (meters)
7600	0	2316.4	3200	20883	975.3
7500	32	2285.9	3100	23392	944.8
7400	65	2255.4	3000	26141	914.4
7300	88	2224.9	2900	29030	883.9
7200	151	2194.5	2800	33313	853.4
7100	371	2164.0	2700	35526	822.9
7000	470	2133.5	2600	40141	792.4
6900	562	2103.0	2500	43602	762.0
6800	635	2072.5	2400	47781	731.5
6700	700	2042.1	2300	51699	701.0
6600	784	2011.6	2200	55446	670.5
6500	828	1981.1	2100	58470	640.0
6400	994	1950.6	2000	63017	609.6
6300	1098	1920.1	1900	66881	579.1
6200	1211	1889.7	1800	70363	548.6
6100	1339	1859.2	1700	75696	518.1
6000	1563	1828.7	1600	79026	487.7
5900	1822	1798.2	1550	80768	472.4
5800	2079	1767.8	1500	82067	457.2
5700	2359	1737.3	1450	83738	441.9
5600	2631	1706.8	1400	86032	426.7
5500	2926	1676.3	1350	87515	411.5
5400	3380	1645.8	1300	89347	396.2
5300	3728	1615.4	1250	90925	381.0
5200	4057	1584.9	1200	92574	365.7
5100	4288	1554.4	1150	94040	350.5
5000	4563	1523.9	1100	95787	335.3
4900	4792	1493.4	1050	97229	320.0
4800	5037	1463.0	1000	99084	304.8
4700	5239	1432.5	950	102105	289.5
4600	5423	1402.0	900	104828	274.3
4500	5570	1371.5	850	106877	259.1
4400	5768	1341.1	800	108772	243.8
4300	6188	1310.6	750	111088	228.6
4200	6951	1280.1	700	115075	213.3
4100	7619	1249.6	650	120715	198.1
4000	8300	1219.1	600	127832	182.9
3900	9204	1188.7	550	139738	167.6
3800	10250	1158.2	500	152302	152.4
3700	11679	1127.7	475	164818	144.8
3600	12927	1097.2	450	169205	137.2
3500	14421	1066.7	425	177219	129.5
3400	15777	1036.3	400	191429	121.9
3300	17495	1005.8		205596	

APPENDIX E

Survey and DEM data for terrace profiles along the Nenana River valley.

Table E-1. GPS data from the survey of a Healy-aged terrace north of the town of Healy. Survey points are listed in order of increasing distance from Garner VABM. The adjusted elevation column is the surveyed ellipsoid elevations adjusted to match the elevation of the Garner benchmark. All measurements are in meters. Survey performed October 19, 2002.

station id	easting	northing	elevation	error	adjusted elevation	distance from Garner
TOPO0001	399829.413	7085404.82	482.2729	0.0481	469.2787	6318.1
TOPO0002	399860.204	7085498.11	479.3679	0.5281	466.3737	6384.6
TOPO0003	399830.737	7085622.2	479.8918	0.0628	466.8976	6507.7
TOPO0004	399799.606	7085739.21	479.8294	0.0985	466.8352	6625.5
TOPO0005	399755.513	7085843.52	476.9877	0.0421	463.9935	6738.2
TOPO0006	399731.82	7085946.53	473.7786	0.0607	460.7844	6840.3
TOPO0007	399664.64	7086097.51	475.9286	0.0295	462.9344	7005.2
TOPO0008	399637.782	7086195.27	471.7877	0.5382	458.7935	7104.2
TOPO0009	399581.048	7086283.16	470.135	0.0356	457.1408	7208.4
TOPO0010	399492.629	7086272.38	470.0628	0.0292	457.0686	7240.4
TOPO0011	399408.722	7086267.01	470.8016	0.0432	457.8074	7276.0
TOPO0025	399456.288	7086337.18	468.8502	0.4648	455.856	7314.7
TOPO0012	399264.181	7086259.69	472.3848	0.0257	459.3906	7340.7
TOPO0013	399267.588	7086319.3	471.6541	0.0463	458.6599	7390.7
TOPO0024	399420.401	7086445.71	469.7756	0.5584	456.7814	7427.3
TOPO0014	399238.375	7086376.86	471.4319	0.0253	458.4377	7455.2
TOPO0023	399441.999	7086496.26	468.5246	0.5584	455.5304	7461.7
TOPO0015	399255.713	7086432.19	471.5364	0.5782	458.5422	7494.8
TOPO0016	399241.33	7086501.98	470.3424	0.6806	457.3482	7562.7
TOPO0017	399316.617	7086587.62	469.2761	0.5645	456.2819	7601.4
TOPO0022	399347.705	7086631.68	469.825	0.533	456.8308	7625.6
TOPO0018	399307.34	7086623.81	469.2457	0.4775	456.2515	7637.7
TOPO0019	399331.356	7086667.67	470.2119	0.5417	457.2177	7665.0
TOPO0021	399351.399	7086678.78	469.5853	0.5859	456.5911	7665.4
TOPO0020	399320.402	7086766.42	471.4868	0.5388	458.4926	7757.4
TOPO0066	398653.73	7087519.8	478.8621	0.0196	465.8679	8737.8
TOPO0064	398703.614	7087560.71	478.7394	0.4533	465.7452	8749.3
TOPO0065	398660.504	7087551.09	478.897	0.0171	465.9028	8761.8
TOPO0067	398600.36	7087522.89	478.7446	0.0185	465.7504	8766.8
TOPO0063	398706.136	7087609.02	478.6143	0.0347	465.6201	8790.4
TOPO0068	398607.189	7087569.87	479.4273	0.1524	466.4331	8804.3
TOPO0062	398655.29	7087641.92	478.494	0.0198	465.4998	8843.8
TOPO0069	398604.524	7087632.33	479.2717	0.1237	466.2775	8860.1
TOPO0070	398604.412	7087632.8	478.5547	0.0235	465.5605	8860.5
TOPO0061	398624.384	7087673.44	478.3941	0.0566	465.3999	8886.3
TOPO0071	398565.061	7087683.61	478.5312	0.4926	465.537	8924.1
TOPO0060	398609.276	7087720.69	478.2605	0.0505	465.2663	8935.0
TOPO0059	398558.319	7087749.76	478.0028	0.0314	465.0086	8985.1
TOPO0072	398464.614	7087791.29	478.2957	0.55	465.3015	9067.2
TOPO0058	398520.325	7087831.6	478.2156	0.0295	465.2214	9075.1

TOPO0057	398487.448	7087882.56	477.7934	0.0252	464.7992	9135.6
TOPO0056	398429.334	7087975.75	478.0316	0.4421	465.0374	9245.3
TOPO0055	398401.167	7088018.37	477.5423	0.0282	464.5481	9296.2
TOPO0054	398347.949	7088056.59	477.1338	0.4946	464.1396	9355.6
TOPO0053	398328.951	7088132.29	476.5478	0.5767	463.5536	9430.9
TOPO0052	398310.137	7088161.16	476.7383	0.596	463.7441	9465.3
TOPO0051	398262.966	7088196.54	476.5019	0.0295	463.5077	9519.2
TOPO0050	398231.982	7088258.48	476.5324	0.0271	463.5382	9588.4
TOPO0049	398188.968	7088304.93	476.6119	0.0258	463.6177	9650.0
TOPO0048	398182.874	7088367.35	476.3387	0.0275	463.3445	9707.4

Table E-2. GPS data from a survey across the Healy fault on a Riley Creek aged terrace. The adjusted elevation reflects the difference between the survey height (ellipsoid height) and the height of the Garner benchmark. All measurements in meters. Surveyed October 12, 2002.

station id	easting	northing	elevation	error	adjusted elevation
Garner base	402932	7079901	601.8091	0	590
TOPO0001	402028.2806	7081201.844	543.6439	0.0226	531.8348
TOPO0002	402026.8596	7081225.922	545.0688	0.0212	533.2597
TOPO0003	402012.1243	7081257.416	546.3369	0.0153	534.5278
TOPO0004	402006.5672	7081283.291	546.4676	0.0212	534.6585
TOPO0005	402019.5373	7081309.523	546.5478	0.0215	534.7387
TOPO0006	402039.0772	7081289.873	544.9534	0.0137	533.1443
TOPO0007	402074.7061	7081280.807	542.8254	0.0169	531.0163
TOPO0008	402086.5012	7081283.043	542.0216	0.02	530.2125
TOPO0009	402102.1682	7081270.854	535.2226	0.0315	523.4135
TOPO0010	402126.7762	7081270.805	530.0051	1.0423	518.196
TOPO0011	402102.3775	7081122.356	538.101	0.0174	526.2919
TOPO0012	402103.6616	7081101.544	540.3993	0.0255	528.5902
TOPO0013	402105.0431	7081087.455	541.0684	0.0175	529.2593
TOPO0014	402108.8345	7081048.99	539.8825	0.0164	528.0734
TOPO0015	402091.1227	7081031.555	541.2247	0.0169	529.4156
TOPO0016	402074.3655	7081013.66	541.4649	0.0165	529.6558
TOPO0017	402125.1207	7081037.938	539.738	0.0153	527.9289
TOPO0018	402148.2913	7081055.279	539.9025	0.0193	528.0934
TOPO0019	402169.5641	7081057.071	538.9302	0.0152	527.1211
TOPO0020	402184.5568	7081075.624	540.7342	0.0153	528.9251
TOPO0021	402202.7466	7081069.027	540.6523	0.0209	528.8432
TOPO0022	402231.2174	7081060.767	540.0709	0.0183	528.2618
TOPO0023	402240.5208	7081061.37	536.4138	0.0224	524.6047
TOPO0024	402251.8067	7081073.04	534.9708	0.0198	523.1617
TOPO0025	402242.9406	7081103.756	533.5291	0.0173	521.72
TOPO0026	402225.7281	7081105.029	535.1919	0.022	523.3828
TOPO0027	402213.0443	7081101.049	540.3151	0.0176	528.506
TOPO0028	402199.6772	7081102.03	540.75	0.0151	528.9409
TOPO0029	402193.2571	7081116.533	540.0583	0.0141	528.2492
TOPO0030	402204.842	7081125.107	539.1713	0.0137	527.3622
TOPO0031	402186.3514	7081140.705	538.7188	0.0135	526.9097
TOPO0032	402063.553	7081207.671	542.3053	0.0164	530.4962
TOPO0033	402045.9689	7081221.38	544.0959	0.0171	532.2868
TOPO0034	402044.0002	7081244.892	544.9451	0.015	533.136
TOPO0035	402059.8266	7081239.588	544.2746	0.0176	532.4655
TOPO0036	402035.7664	7081267.054	545.0274	0.0158	533.2183
TOPO0037	402042.4596	7081292.499	544.8537	0.0155	533.0446
TOPO0038	402001.2584	7081344.514	543.9961	0.0206	532.187
TOPO0039	401989.6257	7081358.576	545.418	0.0161	533.6089
TOPO0040	401967.0975	7081355.307	549.8101	0.0166	538.001
TOPO0041	401949.8102	7081361.272	550.6644	0.0163	538.8553
TOPO0042	401946.7415	7081382.763	551.8294	0.0186	540.0203
TOPO0043	401965.0796	7081388.419	549.9405	0.0197	538.1314
TOPO0044	401979.0653	7081395.615	547.3284	0.0157	535.5193
TOPO0045	401944.0035	7081389.539	551.6645	0.0188	539.8554
TOPO0046	401934.3249	7081363.562	550.5182	0.0177	538.7091

TOPO0047	401925.7252	7081352.052	547.2694	0.0308	535.4603
TOPO0048	401924.9789	7081329.576	547.211	0.0218	535.4019
TOPO0049	401942.6188	7081294.247	547.4531	0.0171	535.644
TOPO0050	401968.1716	7081266.727	547.5068	0.0159	535.6977
TOPO0051	402013.9958	7081221.282	544.8447	0.0275	533.0356
TOPO0052	402064.0094	7081189.249	540.0198	0.0197	528.2107
TOPO0053	402566.8863	7081699.39	478.8843	0.0176	467.0752
TOPO0054	402527.4609	7081661.613	479.2114	0.0188	467.4023
TOPO0055	402495.0944	7081623.312	478.0763	0.0265	466.2672
TOPO0056	402516.4954	7081576.807	479.1703	0.0169	467.3612
TOPO0057	402550.994	7081461.641	476.1768	0.022	464.3677
TOPO0058	402575.6492	7081427.571	475.1204	0.0174	463.3113
TOPO0059	402610.4223	7081411.395	474.2097	0.0169	462.4006
TOPO0060	402649.0518	7081443.411	475.254	0.014	463.4449
TOPO0061	402523.8089	7081431.119	476.5107	0.0237	464.7016
TOPO0062	402522.51	7081412.587	477.4257	0.0193	465.6166
TOPO0063	402520.8369	7081403.392	475.6966	0.0134	463.8875
TOPO0064	402518.8913	7081372.042	475.401	0.0128	463.5919
TOPO0065	402499.7326	7081345.569	475.6208	0.0122	463.8117
TOPO0066	402502.3406	7081313.71	475.7891	0.0151	463.98
TOPO0067	402477.4886	7081343.828	475.6984	0.028	463.8893
TOPO0068	402459.5702	7081376.377	475.8964	0.012	464.0873
TOPO0069	402454.8022	7081387.225	476.4914	0.019	464.6823
TOPO0070	402449.2592	7081399.829	478.7891	0.0232	466.98
TOPO0071	402442.6405	7081422.82	478.8204	0.0249	467.0113
TOPO0072	402380.2681	7081397.475	481.5453	0.0222	469.7362
TOPO0073	402358.2524	7081450.55	481.4823	0.0216	469.6732
TOPO0074	402386.8852	7081513.453	478.7422	0.0233	466.9331
TOPO0075	402451.2325	7081572.216	478.9433	0.014	467.1342
TOPO0076	402478.9436	7081604.542	478.5877	0.0133	466.7786
TOPO0077	402625.9057	7081709.191	477.8708	0.0123	466.0617
TOPO0078	402719.8836	7081750.472	468.3279	0.0134	456.5188
TOPO0079	402799.3062	7081786.616	470.3856	0.0153	458.5765
TOPO0080	402889.8893	7081800.664	471.1632	0.0141	459.3541
TOPO0081	402971.465	7081816.735	470.7315	0.0193	458.9224
TOPO0082	403019.442	7081828.16	470.9571	0.0132	459.148
TOPO0083	403225.8601	7081593.054	467.8108	0.0145	456.0017
TOPO0084	403226.5484	7081581.529	467.4681	0.0128	455.659
TOPO0085	403226.8133	7081565.488	465.4426	0.0177	453.6335
TOPO0086	403227.3006	7081555.168	464.7055	0.0177	452.8964
TOPO0087	403243.3824	7081592.805	467.8508	0.0133	456.0417
TOPO0088	403241.4848	7081577.493	467.1085	0.0128	455.2994
TOPO0089	403259.0071	7081552.848	464.3706	0.0166	452.5615
TOPO0090	403286.735	7081519.396	464.7005	0.013	452.8914
TOPO0091	403294.2684	7081488.153	465.3055	0.0135	453.4964
TOPO0092	403249.4033	7081619.246	468.2081	0.0138	456.399
TOPO0093	403186.4565	7081679.039	469.6446	0.0275	457.8355
TOPO0094	403075.1761	7081788.281	469.4212	0.0151	457.6121
TOPO0095	403264.1797	7081930.999	454.986	0.0153	443.1769
TOPO0096	403227.3699	7082033.691	454.7404	0.0135	442.9313
TOPO0097	403188.6942	7082155.875	453.5714	0.013	441.7623
TOPO0098	403143.4746	7082277.234	452.9156	0.0156	441.1065
TOPO0099	403152.1566	7082310.675	456.0988	0.0155	444.2897
TOPO0100	403163.4805	7082305.583	452.4299	0.0203	440.6208

TOPO0101	403105.0584	7082392.496	454.4146	0.0184	442.6055
TOPO0102	403075.2315	7082488.223	453.3309	0.0153	441.5218
TOPO0103	403043.6529	7082573.023	452.1576	0.0167	440.3485
TOPO0104	403014.9055	7082672.393	450.1935	0.0163	438.3844
TOPO0105	402987.6641	7082790.763	446.6769	0.0137	434.8678
TOPO0106	402954.8284	7082855.995	444.7543	0.0183	432.9452
TOPO0107	402936.4129	7082907.451	444.1601	0.0155	432.351
TOPO0108	402919.645	7082959.334	445.569	0.0206	433.7599
TOPO0109	402878.4928	7083077.195	444.1705	0.0211	432.3614
TOPO0110	402831.8011	7083221.86	442.6498	0.0229	430.8407
TOPO0111	402792.5713	7083345.827	441.9735	0.0204	430.1644
TOPO0112	402744.4429	7083483.352	441.092	0.0202	429.2829
TOPO0113	402790.1326	7083488.963	441.3162	0.0286	429.5071
TOPO0114	402820.4204	7083485.883	441.1662	0.021	429.3571
TOPO0115	402907.6818	7083478.684	441.713	0.0191	429.9039
TOPO0116	402704.402	7083600.373	440.1977	0.0191	428.3886
TOPO0117	402690.424	7083658.419	439.7764	0.0227	427.9673
TOPO0118	402663.8205	7083776.736	438.5321	0.0283	426.723
TOPO0119	402628.7964	7083881.795	437.971	0.0208	426.1619
TOPO0120	402423.7109	7084129.017	437.4577	0.02	425.6486
TOPO0121	402429.4361	7084179.121	435.7595	0.0181	423.9504
TOPO0122	402446.9005	7084196.212	435.5348	0.0239	423.7257
TOPO0123	402488.1829	7084228.098	435.8174	0.02	424.0083
TOPO0124	402513.0839	7084275.596	436.2069	0.0172	424.3978
TOPO0125	402495.6473	7084363.641	435.4658	0.0243	423.6567
TOPO0126	402431.122	7084393.329	434.836	0.0192	423.0269
TOPO0127	402370.8964	7084355.851	434.8254	0.0181	423.0163
TOPO0128	403091.7141	7082401.532	454.0433	0.0124	442.2342
TOPO0129	403084.1214	7082327.431	454.8673	0.013	443.0582
TOPO0130	403067.1535	7082294.073	454.9591	0.0134	443.15
TOPO0131	403055.7972	7082192.448	456.081	0.0143	444.2719
TOPO0132	403061.2859	7082106.24	456.9733	0.0181	445.1642
TOPO0133	403068.7695	7081945.559	459.108	0.0168	447.2989
TOPO0134	403137.2	7081858.932	460.1441	0.0155	448.335
TOPO0135	403181.0736	7081861.642	456.5764	0.0154	444.7673
TOPO0136	403286.3821	7081852.536	454.3733	0.0171	442.5642
TOPO0137	403306.0835	7081791.34	455.0301	0.0212	443.221
TOPO0138	403344.2329	7081683.756	455.7263	0.0194	443.9172
TOPO0139	403339.5762	7081892.745	456.2486	0.0231	444.4395
TOPO0140	403461.7226	7081700.269	456.3729	0.0271	444.5638
TOPO0141	403458.1852	7081636.652	456.1865	0.0315	444.3774
TOPO0142	403461.2757	7081627.982	453.8531	0.0353	442.044
TOPO0143	403445.0315	7081946.467	456.066	0.0297	444.2569
TOPO0144	403489.2491	7082063.032	443.0245	0.0208	431.2154
TOPO0145	403516.5262	7082046.635	443.525	0.0168	431.7159
TOPO0146	403495.8163	7082010.719	445.1966	1.3931	433.3875

Table E-3. Terrace profile data for Healy age terraces west of the Nenana River. All data is derived from USGS digital elevation models. All measurements are in meters. Each individual terrace segment begins with sample # 0.

sample #	easting	northing	elevation	distance from Garner
Garner VABM	402957.2	7079888.9		0.0
0	393426.1	7104380.5	344.5	26280.9
1	393327.4	7104530.5	344.4	26456.5
2	393228.7	7104681.0	344.0	26632.6
3	393130.0	7104831.0	344.0	26808.3
4	393031.4	7104981.0	341.6	26984.0
5	392932.7	7105131.0	335.5	27159.9
6	392834.0	7105281.0	333.0	27335.7
7	392735.4	7105431.0	332.1	27511.6
8	392636.7	7105581.0	331.2	27687.5
9	392538.0	7105731.0	331.0	27863.5
10	392439.3	7105881.0	330.8	28039.6
11	392341.6	7106031.5	330.0	28215.8
12	392282.1	7106201.0	329.0	28395.2
13	392222.5	7106370.5	327.1	28574.7
14	392162.9	7106539.5	325.2	28753.7
15	392103.4	7106709.0	323.7	28933.1
16	392043.8	7106878.5	322.0	29112.6
17	391984.3	7107048.0	320.0	29292.1
18	391924.8	7107217.5	318.4	29471.5
19	391865.2	7107387.0	317.7	29651.0
20	391805.7	7107556.0	316.6	29830.0
21	391746.1	7107725.5	315.0	30009.5
22	391686.6	7107895.0	313.6	30188.9
23	391627.0	7108064.5	312.1	30368.4
24	391567.5	7108234.0	310.1	30547.9
25	391507.9	7108403.0	308.6	30726.9
26	391436.6	7108567.5	307.3	30906.1
27	391356.5	7108728.5	307.8	31085.4
28	391276.4	7108889.0	307.6	31264.2
29	391196.3	7109050.0	306.0	31443.5
30	391116.2	7109210.5	305.2	31622.3
31	391036.1	7109371.0	304.1	31801.1
32	390956.0	7109532.0	303.8	31980.4
33	390875.9	7109692.5	303.0	32159.2
34	390795.8	7109853.5	302.6	32338.5
35	390715.8	7110014.0	301.0	32517.4
36	390635.7	7110175.0	301.4	32696.7
37	390555.6	7110335.5	300.9	32875.5
38	390475.5	7110496.5	300.9	33054.8
39	390395.4	7110657.0	301.9	33233.7
40	390356.5	7110830.0	301.8	33408.6
41	390337.1	7111008.5	300.4	33581.3
42	390317.6	7111187.0	299.1	33754.0
43	390298.2	7111365.5	297.3	33926.8
44	390278.7	7111544.0	296.1	34099.8
45	390259.3	7111722.5	294.6	34272.7
46	390239.8	7111901.0	293.7	34445.7

47	390220.4	7112079.5	292.8	34618.9
48	390200.9	7112258.0	292.2	34792.0
49	390181.5	7112436.5	291.9	34965.2
50	390162.0	7112615.0	290.0	35138.6
0	390176.9	7113089.5	279.3	35575.6
1	390176.1	7113100.5	279.1	35586.1
2	390175.4	7113111.5	278.9	35596.6
3	390174.7	7113122.0	278.7	35606.7
4	390173.9	7113133.0	278.6	35617.2
5	390173.2	7113144.0	278.5	35627.8
6	390172.4	7113154.5	278.5	35637.8
7	390171.7	7113165.5	278.5	35648.4
8	390170.9	7113176.5	278.5	35658.9
9	390170.2	7113187.0	278.6	35669.0
10	390169.5	7113198.0	278.6	35679.5
11	390168.7	7113209.0	278.7	35690.0
12	390168.0	7113219.5	278.7	35700.1
13	390167.2	7113230.5	278.7	35710.6
14	390166.5	7113241.5	278.8	35721.2
15	390165.8	7113252.0	278.8	35731.2
16	390165.0	7113263.0	278.7	35741.8
17	390164.3	7113274.0	278.7	35752.3
18	390163.5	7113284.5	278.5	35762.4
19	390162.8	7113295.5	278.4	35772.9
20	390162.0	7113306.5	278.2	35783.5
21	390161.3	7113317.0	278.2	35793.5
22	390160.6	7113328.0	278.1	35804.1
23	390159.8	7113339.0	278.0	35814.6
24	390159.1	7113349.5	278.0	35824.7
25	390158.3	7113360.5	278.0	35835.2
26	390157.6	7113371.5	278.0	35845.8
27	390156.8	7113382.0	278.0	35855.8
28	390156.1	7113393.0	278.0	35866.4
29	390155.3	7113404.0	278.0	35876.9
30	390154.6	7113414.5	278.0	35887.0
31	390153.9	7113425.5	278.0	35897.5
32	390153.1	7113436.5	278.0	35908.1
33	390152.4	7113447.0	277.9	35918.1
34	390151.7	7113458.0	277.8	35928.7
35	390150.9	7113469.0	277.7	35939.2
36	390150.2	7113479.5	277.5	35949.3
37	390149.4	7113490.5	277.3	35959.8
38	390148.7	7113501.5	277.1	35970.4
39	390147.9	7113512.0	277.0	35980.5
40	390147.2	7113523.0	276.8	35991.0
41	390146.5	7113533.5	276.6	36001.1
42	390145.7	7113544.5	276.4	36011.6
43	390145.0	7113555.5	276.2	36022.2
44	390144.2	7113566.0	276.0	36032.3
45	390143.5	7113577.0	275.8	36042.8
46	390142.8	7113588.0	275.7	36053.3
47	390142.0	7113598.5	275.5	36063.4
48	390141.3	7113609.5	275.3	36074.0
49	390140.5	7113620.5	275.2	36084.5

0	389820.8	7113920.5	279.9	36479.0
1	389784.3	7114005.0	281.8	36571.0
2	389747.7	7114090.0	281.1	36663.5
3	389711.1	7114174.5	280.3	36755.5
4	389674.6	7114259.0	280.3	36847.5
5	389638.0	7114343.5	279.7	36939.5
6	389601.4	7114428.0	280.1	37031.5
7	389564.9	7114513.0	279.8	37123.9
8	389528.3	7114597.5	279.5	37215.9
9	389491.8	7114682.0	279.2	37307.9
10	389455.2	7114766.5	278.9	37399.9
11	389418.7	7114851.0	278.0	37491.9
12	389382.1	7114936.0	276.6	37584.4
13	389345.5	7115020.5	273.0	37676.4
14	389309.0	7115105.0	269.9	37768.4
15	389272.4	7115189.5	268.4	37860.4
16	389235.8	7115274.5	267.8	37952.9
17	389199.3	7115359.0	267.4	38044.9
18	389162.7	7115443.5	267.5	38136.9
19	389126.2	7115528.0	266.8	38228.9
20	389089.6	7115612.5	266.6	38320.9
21	389053.1	7115697.5	266.0	38413.3
22	389041.9	7115787.0	264.8	38500.8
23	389041.9	7115879.5	263.1	38587.1
24	389041.9	7115971.5	261.1	38672.9
25	389041.9	7116063.5	259.5	38758.8
26	389041.9	7116156.0	258.0	38845.1
27	389041.9	7116248.0	256.0	38931.0
28	389041.9	7116340.0	254.7	39017.0
29	389036.3	7116431.0	253.1	39104.0
30	388993.3	7116512.5	253.2	39195.5
31	388950.2	7116594.0	252.6	39287.0
32	388907.1	7116675.5	253.3	39378.5
33	388864.0	7116757.0	254.0	39470.0
34	388820.9	7116838.5	255.6	39561.5
35	388777.8	7116920.0	256.9	39653.0
36	388734.8	7117001.5	258.9	39744.5
37	388699.9	7117085.0	260.6	39835.0
38	388696.6	7117177.0	259.3	39922.1
39	388693.2	7117269.5	258.5	40009.7
40	388689.8	7117361.5	257.5	40096.9
41	388686.5	7117453.5	257.4	40184.0
42	388683.1	7117545.5	258.0	40271.3
43	388679.7	7117637.5	258.9	40358.5
44	388676.3	7117730.0	259.5	40446.2
45	388673.0	7117822.0	260.2	40533.5
46	388669.6	7117914.0	261.0	40620.8
47	388666.3	7118006.0	261.7	40708.1
48	388662.9	7118098.0	262.2	40795.4
49	388659.5	7118190.5	261.6	40883.3
50	388656.1	7118282.5	261.3	40970.6
0	386843.6	7121346.0	227.0	44478.6
1	386746.1	7121436.0	226.1	44597.8
2	386648.5	7121525.5	225.5	44716.7

3	386550.9	7121615.0	224.3	44835.7
4	386453.4	7121704.5	223.9	44954.7
5	386355.8	7121794.0	222.3	45073.8
6	386258.3	7121883.5	222.0	45193.0
7	386160.7	7121973.5	220.8	45312.7
8	386063.2	7122063.0	220.0	45432.0
9	385965.6	7122152.5	219.0	45551.4
10	385868.0	7122242.0	218.0	45670.9
11	385770.5	7122331.5	216.1	45790.4
12	385672.9	7122421.0	214.7	45910.0
13	385575.4	7122511.0	213.1	46030.2
14	385477.8	7122600.5	212.0	46149.9
15	385380.3	7122690.0	211.3	46269.7
16	385282.7	7122779.5	210.0	46389.6
17	385185.2	7122869.0	209.4	46509.6
18	385087.6	7122958.5	208.5	46629.6
19	384990.0	7123048.5	207.9	46750.1
20	384892.5	7123138.0	206.6	46870.3
21	384794.9	7123227.5	205.7	46990.5
22	384697.3	7123317.0	204.1	47110.8
23	384599.8	7123406.5	203.3	47231.1
24	384502.3	7123496.0	202.2	47351.6
25	384404.7	7123586.0	201.0	47472.5
26	384307.1	7123675.5	200.0	47593.0
27	384209.6	7123765.0	198.0	47713.6
28	384112.0	7123854.5	197.1	47834.3
29	384014.4	7123944.0	196.2	47955.0
30	383916.9	7124034.0	196.0	48076.3
31	383819.3	7124123.5	195.0	48197.1
32	383721.8	7124213.0	194.2	48318.0
33	383624.2	7124302.5	193.7	48439.0
34	383526.7	7124392.0	193.0	48560.0
35	383429.1	7124481.5	192.0	48681.1
36	383331.6	7124571.5	191.9	48802.7
37	383234.0	7124661.0	191.0	48923.9
38	383136.4	7124750.5	190.0	49045.2
39	383038.9	7124840.0	189.0	49166.5
40	382941.3	7124929.5	188.0	49287.9
41	382843.8	7125019.0	187.4	49409.3
42	382746.2	7125109.0	186.1	49531.3
43	382648.7	7125198.5	185.5	49652.8
44	382551.1	7125288.0	184.1	49774.4
45	382453.5	7125377.5	183.6	49896.1
46	382356.0	7125467.0	183.0	50017.8
47	382258.4	7125556.5	183.0	50139.6
48	382160.9	7125646.5	183.0	50261.8
49	382063.3	7125736.0	183.0	50383.7

Table E-4. Terrace profile data for Healy age terraces east of the Nenana River. All data is derived from USGS digital elevation models. All measurements are in meters. Each individual terrace segment begins with sample # 0.

sample #	easting	northing	elevation	distance from Garner
0	404452.9	7085013.5	528.4	5338.5
1	404439.4	7085039.0	527.7	5359.2
2	404425.8	7085064.5	526.8	5380.0
3	404412.2	7085090.0	525.6	5400.8
4	404398.6	7085115.5	524.5	5421.8
5	404385.1	7085141.0	523.5	5442.8
6	404371.5	7085166.5	522.6	5463.8
7	404357.9	7085192.0	521.6	5485.0
8	404344.3	7085217.5	521.0	5506.2
9	404330.8	7085243.0	520.4	5527.5
10	404317.2	7085268.5	519.8	5548.9
11	404303.6	7085294.5	519.5	5570.8
12	404290.0	7085320.0	519.1	5592.3
13	404276.5	7085345.5	518.6	5613.9
14	404262.9	7085371.0	518.2	5635.5
15	404249.3	7085396.5	518.0	5657.2
16	404235.7	7085422.0	517.9	5678.9
17	404222.2	7085447.5	517.6	5700.7
18	404208.6	7085473.0	517.2	5722.6
19	404195.0	7085498.5	517.3	5744.6
20	404181.4	7085524.0	517.5	5766.6
21	404167.8	7085550.0	517.6	5789.1
22	404154.3	7085575.5	517.1	5811.3
23	404140.7	7085601.0	516.9	5833.4
2	404182.9	7086334.0	521.2	6560.6
3	404162.0	7086376.0	523.2	6598.1
4	404141.1	7086418.5	524.3	6636.1
5	404120.2	7086460.5	525.4	6673.7
6	404099.2	7086502.5	526.4	6711.5
7	404078.3	7086545.0	527.4	6749.9
8	404057.4	7086587.0	529.4	6787.9
9	404036.5	7086629.5	530.8	6826.5
10	404015.6	7086671.5	531.6	6864.7
11	403994.6	7086714.0	532.4	6903.5
12	403973.7	7086756.0	533.3	6942.0
13	403952.8	7086798.0	533.9	6980.5
14	403931.9	7086840.5	534.0	7019.6
15	403911.0	7086882.5	533.3	7058.4
16	403890.0	7086925.0	532.5	7097.7
17	403869.1	7086967.0	530.7	7136.6
18	403848.2	7087009.5	529.0	7176.2
19	403827.3	7087051.5	527.4	7215.3
20	403806.4	7087093.5	525.7	7254.5
21	403785.4	7087136.0	524.1	7294.3
22	403764.5	7087178.0	523.0	7333.7
23	403743.6	7087220.5	523.0	7373.7
24	403722.7	7087262.5	522.7	7413.3
25	403701.8	7087305.0	522.8	7453.4

0	401533.8	7090347.5	499.3	10555.1
1	401526.8	7090358.5	499.3	10566.9
2	401519.8	7090369.5	499.2	10578.8
3	401512.8	7090380.5	499.1	10590.6
4	401505.8	7090391.5	499.1	10602.5
5	401498.9	7090402.5	499.2	10614.3
6	401491.9	7090413.5	499.3	10626.2
7	401484.9	7090424.5	499.3	10638.0
8	401477.9	7090435.5	499.2	10649.9
9	401470.9	7090446.5	499.1	10661.8
10	401463.9	7090457.0	499.0	10673.1
11	401456.9	7090468.0	498.9	10685.0
12	401449.9	7090479.0	498.8	10696.9
13	401442.9	7090490.0	498.7	10708.8
14	401435.9	7090501.0	498.7	10720.6
15	401428.9	7090512.0	498.7	10732.5
16	401421.9	7090523.0	498.6	10744.4
17	401414.9	7090534.0	498.6	10756.3
18	401407.9	7090545.0	498.5	10768.2
19	401400.9	7090556.0	498.5	10780.1
20	401394.0	7090567.0	498.6	10792.0
21	401387.0	7090578.0	498.9	10803.9
22	401380.0	7090589.0	499.2	10815.8
23	401373.0	7090600.0	499.5	10827.7
24	401366.0	7090611.0	499.9	10839.6
25	401359.0	7090622.0	500.2	10851.5
26	401352.0	7090633.0	500.6	10863.4
27	401345.0	7090643.5	500.7	10874.8
28	401338.0	7090654.5	500.5	10886.7
29	401331.0	7090665.5	500.5	10898.7
30	401324.0	7090676.5	500.4	10910.6
31	401317.0	7090687.5	500.4	10922.5
32	401310.0	7090698.5	500.6	10934.4
33	401303.0	7090709.5	500.7	10946.4
34	401296.0	7090720.5	500.7	10958.3
35	401289.1	7090731.5	500.7	10970.2
36	401282.1	7090742.5	500.7	10982.2
37	401275.1	7090753.5	500.7	10994.1
38	401268.1	7090764.5	500.7	11006.0
39	401261.1	7090775.5	500.7	11018.0
40	401254.1	7090786.5	500.7	11029.9
41	401247.1	7090797.5	500.7	11041.9
42	401240.1	7090808.5	500.7	11053.8
43	401233.1	7090819.0	500.7	11065.3
44	401226.1	7090830.0	500.6	11077.3
45	401219.1	7090841.0	500.6	11089.2
46	401212.1	7090852.0	500.6	11101.2
47	401205.1	7090863.0	500.6	11113.1
48	401198.1	7090874.0	500.6	11125.1
49	401191.1	7090885.0	500.6	11137.1
50	401184.1	7090896.0	500.7	11149.0
51	401177.2	7090907.0	500.9	11161.0
52	401170.2	7090918.0	500.9	11173.0
53	401163.2	7090929.0	500.8	11185.0

54	401156.2	7090940.0	500.9	11196.9
55	401149.2	7090951.0	500.9	11208.9
56	401142.2	7090962.0	500.8	11220.9
57	401135.2	7090973.0	500.8	11232.9
58	401128.2	7090984.0	500.9	11244.9
59	401121.2	7090994.5	500.9	11256.4
60	401114.2	7091005.5	500.9	11268.4
61	401107.2	7091016.5	500.8	11280.4
62	401100.2	7091027.5	500.7	11292.4
63	401093.2	7091038.5	500.7	11304.4
64	401086.2	7091049.5	500.6	11316.4
65	401079.2	7091060.5	500.5	11328.4
66	401072.3	7091071.5	500.5	11340.4
67	401065.3	7091082.5	500.6	11352.4
68	401058.3	7091093.5	500.6	11364.4
69	401051.3	7091104.5	500.4	11376.4
70	401044.3	7091115.5	500.2	11388.5
71	401037.3	7091126.5	500.1	11400.5
72	401030.3	7091137.5	499.9	11412.5
73	401023.3	7091148.5	499.7	11424.5
74	401016.3	7091159.5	499.5	11436.6
75	401009.3	7091170.0	499.4	11448.1
76	401002.3	7091181.0	499.2	11460.1
77	400995.3	7091192.0	499.1	11472.1
78	400988.3	7091203.0	498.9	11484.2
79	400981.3	7091214.0	498.6	11496.2
80	400974.3	7091225.0	498.5	11508.3
81	400967.3	7091236.0	498.3	11520.3
82	400960.3	7091247.0	498.2	11532.3
83	400953.3	7091258.0	498.0	11544.4
84	400946.3	7091269.0	497.8	11556.4
85	400939.3	7091280.0	497.6	11568.5
86	400932.4	7091291.0	497.4	11580.5
87	400925.4	7091302.0	497.2	11592.6
88	400918.4	7091313.0	497.0	11604.7
89	400911.4	7091324.0	496.8	11616.7
90	400904.4	7091335.0	496.4	11628.8
91	400897.4	7091345.5	495.9	11640.3
92	400890.4	7091356.5	495.3	11652.4
93	400883.4	7091367.5	494.6	11664.5
94	400876.4	7091378.5	494.3	11676.5
95	400869.4	7091389.5	493.9	11688.6
96	400862.4	7091400.5	493.3	11700.7
97	400855.4	7091411.5	492.6	11712.8
98	400848.4	7091422.5	491.8	11724.8
99	400841.4	7091433.5	491.1	11736.9
100	400834.4	7091444.5	490.3	11749.0
0	400402.3	7091888.0	480.4	12268.1
1	400366.3	7091980.0	479.7	12365.6
2	400330.3	7092072.5	478.0	12463.6
3	400294.3	7092165.0	476.9	12561.6
4	400258.3	7092257.0	475.1	12659.2
5	400222.3	7092349.5	473.2	12757.3
6	400186.3	7092441.5	470.6	12854.8

7	400150.3	7092534.0	469.3	12952.9
8	400114.3	7092626.5	468.0	13051.1
9	400078.3	7092718.5	467.1	13148.7
10	400042.3	7092811.0	466.0	13246.8
11	400006.3	7092903.0	465.6	13344.5
12	399970.3	7092995.5	465.0	13442.7
13	399934.3	7093088.0	464.1	13540.9
14	399898.3	7093180.0	463.2	13638.6
15	399862.2	7093272.5	461.6	13736.9
16	399826.2	7093364.5	460.5	13834.6
17	399790.2	7093457.0	459.2	13932.9
18	399754.2	7093549.5	458.6	14031.1
19	399718.2	7093641.5	457.3	14128.9
20	399682.2	7093734.0	455.6	14227.2
21	399646.2	7093826.0	453.9	14325.0
22	399610.2	7093918.5	452.8	14423.4
23	399574.2	7094011.0	449.5	14521.7
24	399538.2	7094103.0	446.4	14619.6
25	399502.2	7094195.5	440.6	14717.9
0	398829.3	7095225.0	430.8	15882.0
1	398811.6	7095349.5	429.5	16006.8
2	398793.9	7095474.5	428.2	16132.1
3	398776.2	7095599.0	427.3	16257.0
4	398758.4	7095723.5	423.1	16381.9
5	398740.7	7095848.0	418.7	16506.8
6	398723.0	7095972.5	416.4	16631.7
7	398705.3	7096097.0	415.2	16756.6
8	398687.6	7096221.5	414.5	16881.5
9	398669.8	7096346.5	414.0	17006.9
10	398652.1	7096471.0	414.0	17131.9
11	398634.4	7096595.5	414.2	17256.9
12	398616.7	7096720.0	414.0	17381.8
13	398598.9	7096844.5	413.0	17506.8
14	398581.2	7096969.0	412.0	17631.8
15	398563.5	7097093.5	410.0	17756.8
16	398546.1	7097218.5	408.1	17882.2
17	398531.9	7097343.5	406.8	18006.9
18	398517.7	7097468.5	405.5	18131.6
19	398503.5	7097593.5	403.9	18256.2
20	398489.3	7097718.5	401.6	18380.9
21	398475.2	7097843.5	400.9	18505.6
22	398461.0	7097968.5	400.0	18630.4
23	398446.8	7098093.5	399.1	18755.1
24	398432.6	7098218.5	398.8	18879.8
0	398407.7	7101778.5	379.9	22357.4
1	398355.7	7101906.0	378.0	22492.9
2	398303.7	7102033.0	376.8	22627.8
3	398251.7	7102160.5	375.9	22763.3
4	398199.7	7102287.5	373.5	22898.3
5	398147.7	7102415.0	370.9	23033.9
6	398095.7	7102542.0	368.2	23168.9
7	398043.7	7102669.0	366.0	23304.0
8	397991.7	7102796.5	364.6	23439.6
9	397939.7	7102923.5	363.5	23574.8

10	397887.7	7103051.0	362.0	23710.5
11	397835.7	7103178.0	361.9	23845.6
12	397783.7	7103305.0	361.5	23980.9
13	397731.7	7103432.5	360.3	24116.6
14	397679.7	7103559.5	358.9	24251.8
15	397627.7	7103687.0	357.5	24387.6
16	397575.7	7103814.0	356.6	24522.9
17	397523.7	7103941.0	357.3	24658.2
18	397471.7	7104068.5	358.7	24794.1
19	397419.7	7104195.5	355.6	24929.4
20	397367.7	7104323.0	354.2	25065.3
21	397315.7	7104450.0	357.4	25200.7
22	397263.7	7104577.0	357.9	25336.2
23	397211.7	7104704.5	357.4	25472.1
24	397159.7	7104831.5	354.8	25607.6
0	390532.6	7119452.0	265.6	41468.2
1	390529.9	7119627.5	264.0	41636.5
2	390527.2	7119803.5	263.0	41805.3
3	390524.5	7119979.0	261.2	41973.7
4	390521.9	7120155.0	259.5	42142.6
5	390519.2	7120330.5	257.7	42311.1
6	390516.5	7120506.5	256.1	42480.2
7	390513.8	7120682.0	254.2	42648.8
8	390511.1	7120857.5	252.3	42817.5
9	390508.4	7121033.5	251.1	42986.7
10	390505.8	7121209.0	249.3	43155.5
11	390503.1	7121385.0	248.0	43324.8
12	390500.4	7121560.5	246.7	43493.7
13	390497.7	7121736.0	244.9	43662.6
14	390495.0	7121912.0	241.4	43832.1
15	390492.3	7122087.5	238.3	44001.1
16	390489.7	7122263.5	235.3	44170.7
17	390612.2	7122388.0	231.2	44255.8
18	390737.2	7122511.5	228.0	44339.8
19	390862.3	7122635.0	227.0	44424.3
20	390987.3	7122758.5	226.0	44509.4
21	391112.3	7122882.0	225.9	44595.0
22	391237.3	7123005.5	226.0	44681.1
23	391362.3	7123129.0	226.1	44767.8
24	391487.3	7123252.5	225.9	44854.9
25	391612.4	7123376.0	225.9	44942.6
26	391737.4	7123499.5	225.0	45030.8
27	391862.4	7123623.0	224.8	45119.5
28	391987.4	7123746.5	223.8	45208.7
29	392112.5	7123870.0	223.0	45298.5
30	392237.5	7123993.5	222.0	45388.7
31	392363.3	7124116.0	221.5	45478.3
32	392489.1	7124238.5	221.0	45568.3
33	392615.0	7124361.5	220.2	45659.4
34	392740.9	7124484.0	220.0	45750.4
35	392866.8	7124606.5	219.0	45842.0
36	392992.6	7124729.0	218.1	45934.0
37	393118.5	7124852.0	218.0	46027.0
38	393244.4	7124974.5	217.0	46120.0

39	393370.3	7125097.0	216.1	46213.5
40	393496.1	7125220.0	216.1	46307.9
41	393622.0	7125342.5	215.0	46402.4
42	393747.8	7125465.0	214.1	46497.3
43	393873.7	7125587.5	213.0	46592.7
44	393999.6	7125710.5	210.9	46689.0
45	394125.5	7125833.0	208.9	46785.3
46	394251.3	7125955.5	206.8	46882.1
47	394377.2	7126078.0	204.7	46979.3
48	394503.1	7126201.0	202.7	47077.5
49	394629.0	7126323.5	200.6	47175.6
50	394754.8	7126446.0	196.3	47274.2

Table E-5. Terrace profile data for Riley Creek age terraces west of the Nenana River. All data is derived from USGS digital elevation models. All measurements are in meters. Each individual terrace segment begins with sample # 0.

sample #	easting	northing	elevation	distance from Garner
0	400444.8	7087890.0	411.3	8386.3
1	400408.7	7087923.0	411.9	8428.7
2	400372.5	7087956.0	412.1	8471.1
3	400336.4	7087989.0	412.1	8513.6
4	400300.3	7088022.0	412.0	8556.1
5	400264.1	7088055.0	412.0	8598.8
6	400228.0	7088088.5	411.9	8641.9
7	400191.8	7088121.5	412.0	8684.7
8	400155.7	7088154.5	411.9	8727.5
9	400119.6	7088187.5	411.9	8770.4
10	400083.4	7088220.5	411.4	8813.3
11	400047.3	7088253.5	409.7	8856.4
12	400011.2	7088286.5	408.7	8899.4
13	399975.0	7088319.5	408.2	8942.6
14	399938.9	7088353.0	407.1	8986.2
15	399902.8	7088386.0	405.5	9029.5
16	399866.6	7088419.0	404.6	9072.8
17	399830.5	7088452.0	404.3	9116.1
18	399794.3	7088485.0	404.0	9159.6
19	399758.2	7088518.0	404.3	9203.0
0	398101.1	7091217.0	401.1	12325.1
1	397961.1	7091440.5	398.9	12585.8
2	397821.0	7091664.5	399.0	12847.0
3	397681.0	7091888.0	395.5	13107.9
4	397540.9	7092111.5	395.6	13369.0
5	397436.4	7092350.0	390.4	13629.4
6	397373.0	7092606.5	382.8	13889.7
7	397309.5	7092862.5	388.1	14149.6
8	397246.1	7093118.5	387.0	14409.8
9	397182.6	7093374.5	385.2	14670.0
10	397163.0	7093637.5	383.9	14919.7
11	397146.0	7093900.5	379.7	15168.9
12	397107.9	7094161.0	373.9	15424.3
13	397051.3	7094418.5	370.8	15684.1
14	396995.8	7094676.5	368.7	15944.1
15	396941.3	7094935.0	369.2	16204.3
16	396886.8	7095193.0	369.6	16464.1
17	396832.3	7095451.0	368.8	16724.1
18	396780.4	7095710.0	367.5	16984.2
19	396728.7	7095968.5	366.3	17243.8
20	396677.0	7096227.0	365.8	17503.6
0	394435.1	7103806.5	327.7	25390.6
1	394362.5	7103953.0	328.5	25552.9
2	394290.0	7104099.0	328.7	25714.8
3	394217.4	7104245.5	328.7	25877.2
4	394144.9	7104392.0	329.9	26039.6
5	394072.4	7104538.0	329.2	26201.5
6	393999.8	7104684.5	329.4	26364.0

7	393927.3	7104831.0	329.0	26526.4
8	393854.7	7104977.0	328.4	26688.4
9	393782.2	7105123.5	328.5	26850.9
10	393709.7	7105270.0	328.0	27013.3
11	393637.1	7105416.0	327.8	27175.4
12	393566.8	7105563.5	326.9	27338.0
13	393507.1	7105715.5	326.2	27501.3
14	393447.3	7105867.5	325.4	27664.6
15	393387.6	7106019.5	323.9	27827.8
16	393327.9	7106171.5	322.5	27991.1
17	393268.2	7106323.5	321.9	28154.4
18	393208.4	7106475.5	321.8	28317.6
19	393148.7	7106627.5	321.1	28480.9
20	393089.0	7106779.5	320.9	28644.2
0	387778.7	7121394.0	229.1	44193.5
1	387729.9	7121659.0	226.8	44459.1
2	387681.2	7121923.5	224.0	44724.4
3	387632.4	7122188.5	222.0	44990.1
4	387583.6	7122453.5	219.9	45255.9
5	387534.8	7122718.0	217.0	45521.3
6	387486.0	7122983.0	215.6	45787.2
7	387437.3	7123247.5	213.4	46052.6
8	387388.5	7123512.5	212.0	46318.5
9	387335.2	7123776.5	210.0	46585.1
10	387277.4	7124039.0	209.0	46851.8
11	387219.7	7124302.0	207.0	47119.0
12	387162.0	7124565.0	205.3	47386.2
13	387104.3	7124828.0	204.0	47653.4
14	387046.5	7125091.0	202.8	47920.6
15	386988.8	7125354.0	201.0	48187.9
16	386934.7	7125618.0	200.0	48454.9
17	386883.2	7125882.0	198.1	48721.1
18	386831.6	7126146.5	196.3	48987.8
19	386780.0	7126410.5	194.1	49254.1

Table E-6. Terrace profile data for Riley Creek age terraces east of the Nenana River. All data is derived from USGS digital elevation models. All measurements are in meters. Each individual terrace segment begins with sample # 0.

sample #	easting	northing	elevation	distance from Garner
0	400444.8	7087890.0	411.3	8386.3
1	400408.7	7087923.0	411.9	8428.7
2	400372.5	7087956.0	412.1	8471.1
3	400336.4	7087989.0	412.1	8513.6
4	400300.3	7088022.0	412.0	8556.1
5	400264.1	7088055.0	412.0	8598.8
6	400228.0	7088088.5	411.9	8641.9
7	400191.8	7088121.5	412.0	8684.7
8	400155.7	7088154.5	411.9	8727.5
9	400119.6	7088187.5	411.9	8770.4
10	400083.4	7088220.5	411.4	8813.3
11	400047.3	7088253.5	409.7	8856.4
12	400011.2	7088286.5	408.7	8899.4
13	399975.0	7088319.5	408.2	8942.6
14	399938.9	7088353.0	407.1	8986.2
15	399902.8	7088386.0	405.5	9029.5
16	399866.6	7088419.0	404.6	9072.8
17	399830.5	7088452.0	404.3	9116.1
18	399794.3	7088485.0	404.0	9159.6
19	399758.2	7088518.0	404.3	9203.0
0	398101.1	7091217.0	401.1	12325.1
1	397961.1	7091440.5	398.9	12585.8
2	397821.0	7091664.5	399.0	12847.0
3	397681.0	7091888.0	395.5	13107.9
4	397540.9	7092111.5	395.6	13369.0
5	397436.4	7092350.0	390.4	13629.4
6	397373.0	7092606.5	382.8	13889.7
7	397309.5	7092862.5	388.1	14149.6
8	397246.1	7093118.5	387.0	14409.8
9	397182.6	7093374.5	385.2	14670.0
10	397163.0	7093637.5	383.9	14919.7
11	397146.0	7093900.5	379.7	15168.9
12	397107.9	7094161.0	373.9	15424.3
13	397051.3	7094418.5	370.8	15684.1
14	396995.8	7094676.5	368.7	15944.1
15	396941.3	7094935.0	369.2	16204.3
16	396886.8	7095193.0	369.6	16464.1
17	396832.3	7095451.0	368.8	16724.1
18	396780.4	7095710.0	367.5	16984.2
19	396728.7	7095968.5	366.3	17243.8
20	396677.0	7096227.0	365.8	17503.6
0	394435.1	7103806.5	327.7	25390.6
1	394362.5	7103953.0	328.5	25552.9
2	394290.0	7104099.0	328.7	25714.8
3	394217.4	7104245.5	328.7	25877.2
4	394144.9	7104392.0	329.9	26039.6
5	394072.4	7104538.0	329.2	26201.5
6	393999.8	7104684.5	329.4	26364.0

7	393927.3	7104831.0	329.0	26526.4
8	393854.7	7104977.0	328.4	26688.4
9	393782.2	7105123.5	328.5	26850.9
10	393709.7	7105270.0	328.0	27013.3
11	393637.1	7105416.0	327.8	27175.4
12	393566.8	7105563.5	326.9	27338.0
13	393507.1	7105715.5	326.2	27501.3
14	393447.3	7105867.5	325.4	27664.6
15	393387.6	7106019.5	323.9	27827.8
16	393327.9	7106171.5	322.5	27991.1
17	393268.2	7106323.5	321.9	28154.4
18	393208.4	7106475.5	321.8	28317.6
19	393148.7	7106627.5	321.1	28480.9
20	393089.0	7106779.5	320.9	28644.2
0	387778.7	7121394.0	229.1	44193.5
1	387729.9	7121659.0	226.8	44459.1
2	387681.2	7121923.5	224.0	44724.4
3	387632.4	7122188.5	222.0	44990.1
4	387583.6	7122453.5	219.9	45255.9
5	387534.8	7122718.0	217.0	45521.3
6	387486.0	7122983.0	215.6	45787.2
7	387437.3	7123247.5	213.4	46052.6
8	387388.5	7123512.5	212.0	46318.5
9	387335.2	7123776.5	210.0	46585.1
10	387277.4	7124039.0	209.0	46851.8
11	387219.7	7124302.0	207.0	47119.0
12	387162.0	7124565.0	205.3	47386.2
13	387104.3	7124828.0	204.0	47653.4
14	387046.5	7125091.0	202.8	47920.6
15	386988.8	7125354.0	201.0	48187.9
16	386934.7	7125618.0	200.0	48454.9
17	386883.2	7125882.0	198.1	48721.1
18	386831.6	7126146.5	196.3	48987.8
19	386780.0	7126410.5	194.1	49254.1

APPENDIX F

Procedures for extraction of terrace profile data. I used MapINFO v. 7 for this procedure since I could not extract the actual data from the profile graphs in ArcGIS v. 8.3.

1. Open the USGS DEMs for the region covered by the terrace map.
2. Import the terrace map so that it overlies the DEMs.
3. Use the Interpolate Line tool to draw a line along an individual terrace surface.
4. Select the Cross-Section tool to make the profile graph along this line.
5. Right-click on the graph for options. Select Export, and save as a text document.
6. The data can now be opened in Excel or Grapher for inspection and plotting.