STREAM TERRACES IN THE CRITICAL ZONE – LOWER GORDON GULCH, COLORADO

A Thesis
Presented to
The Academic Faculty

By

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In Partial Fulfillment
Of the Requirements for the Degree Designation
Research Option in Earth and Atmospheric Sciences

Georgia Institute of Technology

May, 2011

STREAM TERRACES IN THE CRITICAL ZONE – LOWER GORDON GULCH, COLORADO

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ACKNOWLEDGMENTS

First, I would like to thank my thesis adviser, Dr. Kurt Frankel, for his support and encouragement throughout my years at Georgia Tech. He has been an unbelievable inspiration to me, and I would not be where I am without his guidance. I also want to thank my field advisers, Drs. David Dethier and Will Ouimet, for helping me with this project while I was in Colorado. This project would not have been possible without their help. I would also like to thank the National Science Foundation and Keck Geology Consortium for giving me the opportunity to go to the Front Range in Colorado to do research. I would also like to thank the Boulder Creek CZO for allowing me to contribute to their ongoing research. I would also like to thank Dr. Rutt Bridges for providing me with a fellowship to do my research at Georgia Tech. My extensive field work would have not been possible without the help of my fellow Keck students Corey Shircliff (Beloit College), Erin Camp (Amherst College), Cianna Wyshnytzky (Amherst College), Reece Lyerly (Furman University), Hayley Corson-Rikert (Wesleyan University), and Ellie Maley (Smith College). I would also like to thank my friends and family for their support. Finally, I would like to thank Dr. Josef Dufek for reading my thesis and providing me with his input.

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LIST OF SYMBOLS AND ABBREVIATIONS

B	bank-full width
CZ	Critical Zone
D_{84}	84^{th} percentile size of the channel sediment
g	gravity
Ga	billion years (Giga anna)
H	channel depth at bankfull
ka	thousand years (kilo anna)
Ma	million years (Mega anna)
ρ_s	sediment density
ρ_w	water density
Q_s	annual sediment flux
τ_c	shear stress ($\tau_c = \rho_w gHS$)
θ	Shields stress
θ_c	critical Shields stress
R	hydraulic radius
S	slope
s	specific gravity of sediment
T_s	sediment removal timescale
t	unitless time interval
V_s	volume of sediment in basin
v	velocity

SUMMARY

As bedrock weathers into soil, erosional processes often carry loose sediment down slope into a stream channel. Higher weathering rates produce larger amounts of erodible soil, which then causes sediment in the stream to build up and raise the base level of the stream. Changes in climate and land use may cause changes in the stream's carrying capacity and result in stream incision. As the stream adapts to changes in climate and land use over time, a complex series of fill terraces may form. These terraces can store large amounts of sediment, and it may take thousands of years for the stream to remove this sediment.

Gordon Gulch, a small catchment in Colorado's Front Range, is a prime example of a series of complex fill terraces. In this study, five terraces have been thoroughly mapped and characterized. The volume of sediment stored in the terraces is 50,000 cubic meters, and a time span for removal of this sediment is 1,300 years by the model developed by Mueller and Pitlick, (2005). The reliability of the results from this model are also discussed and contrasted with ^{14}C dates obtained from the terraces.

CHAPTER 1. INTRODUCTION

Systems of stream terraces provide insight into the history of a stream and how the surrounding landscape has changed throughout geologic history. Stream terraces are an integral part of the Critical Zone, which is the area in the Earth's crust where rocks meet life. The development of the Critical Zone is important to understand because it is the basis of all terrestrial life. The Boulder Creek Critical Zone Observatory encompasses three catchments that work together to better understand how the Critical Zone develops in alpine, sub-alpine and montane environments [*Murphy, 2006*].

1.1 Background

1.1.1 The Critical Zone

The Critical Zone (CZ) is defined as the boundary layer that extends from the buried, unweathered bedrock up through the weathered rock and regolith to the soil where terrestrial life thrives [*Anderson et al., 2007*]. The CZ is the vital place on Earth's surface where rocks, soil, atmospheric gasses, and meteoric water interact. The CZ is separated into distinguishable layers of weathered rock, regolith, and soil; the characteristics of these layers vary throughout different environments where the balance of weathering mechanisms varies.

The CZ has been described as a “feed-through reactor” that transforms solid bedrock into soil and sediment, as seen in Figure 1 [*Anderson et al., 2007*]. This reactor model applies in areas of

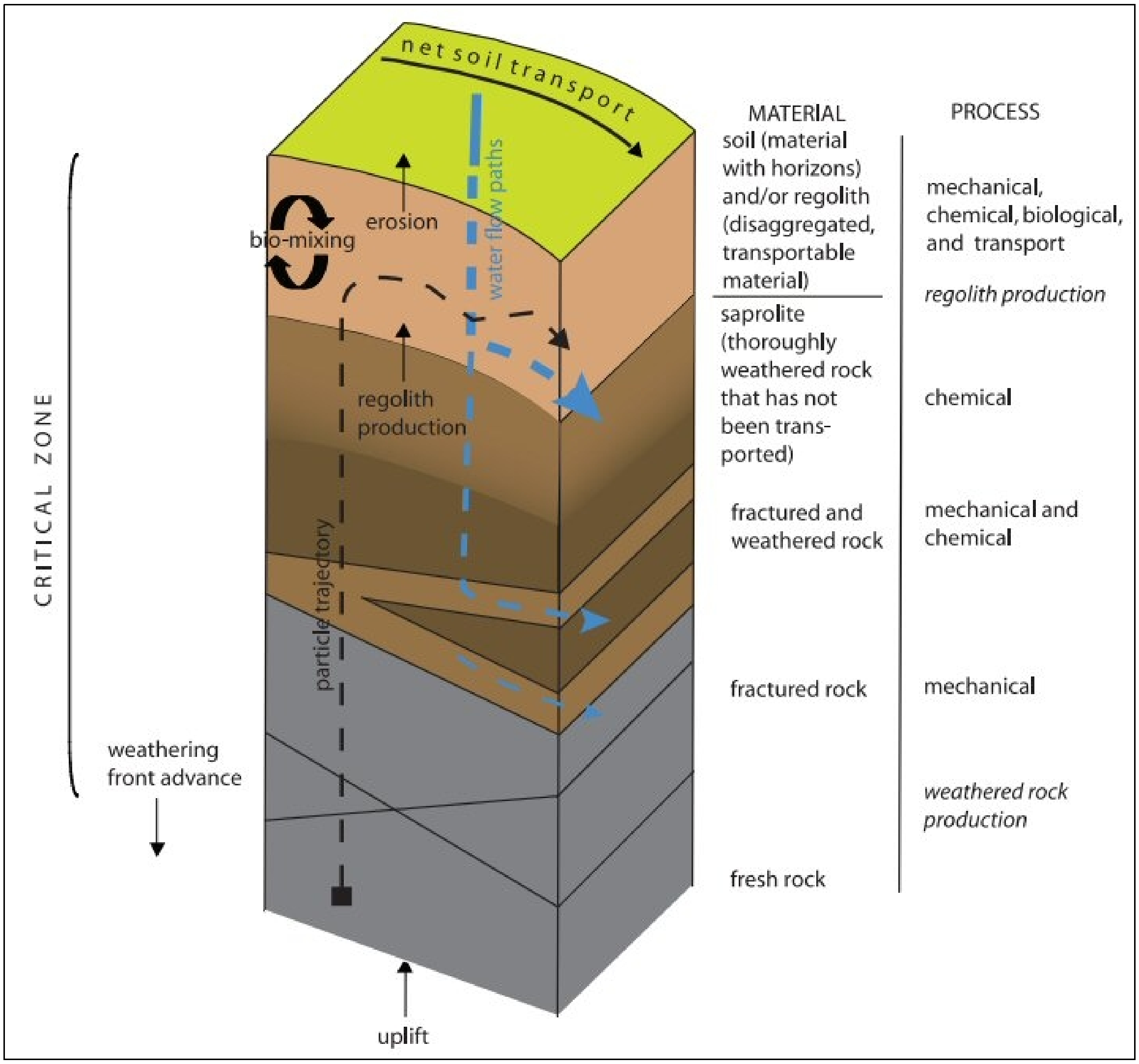

Figure 1. The Critical Zone reactor model, which shows the path of a sediment particle (in black) and the path of water (in blue) (Anderson et al., 2007).

steady state topography, meaning erosion is balanced by uplift. The raw material enters the reactor through the bottom as unweathered bedrock, and is increasingly weathered until it reaches the top of the reactor as soil. The thickness of the CZ is a manifestation of the rates of downward weathering and erosion. The amount of chemical weathering varies with depth according to the solubility of minerals and rate of water flow [*Anderson et al., 2007*]. Rates of weathering and erosion are not always in balance. In some areas erosion is not sufficient to balance the amount of weathering, and a net accumulation is the result.

1.1.2 Streams and Terraces

Streams are often surrounded by a floodplain, which is the low, flat surface flanking a stream that accommodates excess water in a stream channel. The morphology of a stream and its floodplain is the result of a delicate balance of driving and resisting forces. Sediment entrainment and deposition in a stream is driven by the velocity, depth and slope of that stream; it is resisted by the channel configuration, sediment size and sediment concentration [*Ritter et al., 2002*]. Excess deposition can cause a stream to aggrade, or build up sediment and increase the elevation of the channel bottom. Excess erosion can cause a stream to incise its channel and decrease the elevation of the stream.

Terraces are the abandoned floodplains that were formed when a stream flowed at a higher elevation than its present elevation [*Ritter et al., 2002*]. Multiple terrace levels may occur as a

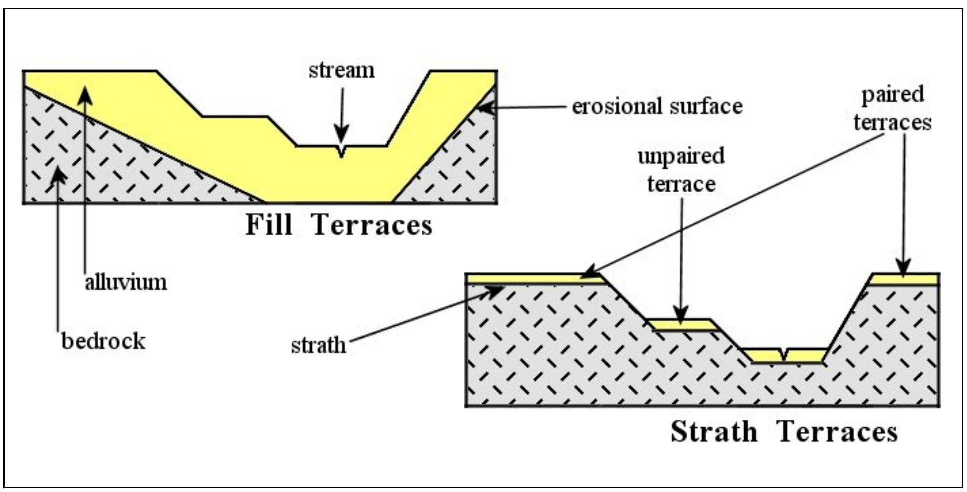

Figure 2. Diagram of fill terraces and strath terraces

series of planar surfaces at different elevations flanking a stream (Fig. 2). The terraces may be paired, where there is a matching terrace surface on each side of the stream, or unpaired. Terraces can be categorized as strath or fill: a strath terrace is one in which the abandoned floodplain is composed of bedrock whereas a fill terrace is one in which the abandoned floodplain is composed of aggraded material. Fill terraces are especially important in the CZ because they store eroded sediment and biomass from the surrounding hillslopes.

The formation of strath terraces is due to a fall in base-level. Base-level is the lowest level to which a stream grades. Since all streams flow into the ocean, the most basic drop in base-level is a drop in sea level. Strath terraces can also be caused by the uplift of surrounding rocks [*Wegmann et al., 2002*].

The mechanisms that cause fill terraces to form can be quite varied and complex. There must be a reversal in stream incision to cause aggradation [*Bull, 1990*]. Changes in the discharge of a stream can cause a shift from incision to aggradation; smaller discharge is associated with aggradation and larger discharge is associated with incision [*Hancock and Anderson, 2002*]. Foster et al. [*2009*] studied a terrace system in Lancashire, England, in which a period of aggradation is attributed to changes in land use. The introduction of farming to the area (1000 B.P.) created an increased sediment supply (and thus aggradation). A period of wetter climate has been correlated with stages stream incision and terraces [*Foster et al., 2009*]. A relationship between valley aggradation and upstream glaciation has also been studied by Baker et al. [*2009*]; glacial erosion can cause an increase in sediment flux and resulting aggradation. Terrace ages along the Río Diamante can be directly related to periods of glaciation [*Baker et al., 2009*].

1.2 Objectives

In an effort to better understand the linkage between the Critical Zone (CZ) and fluvial terraces, a detailed study of the landscape has been made. The goals of this study are:

1. to determine the fluvial history of Gordon Gulch by mapping the terraces surrounding the stream;
2. to approximate the age and amount of sediment stored in the terraces; and
3. to approximate the time it would take to completely erode the sediment stored in the terraces.

The results of this study will help to better understand the complicated and intertwined relationships between the CZ and fluvial terrace morphology and development. The CZ is an essential part of any landscape, as all life stems from this "reactor" that transforms bedrock into loose, nutrient-rich soil.

CHAPTER 2. STUDY AREA

Colorado's Front Range extends 50 kilometers west from the base of the Flatirons to the Continental Divide, as seen in Figure 3 [*Anderson et al., 2006*]. The Boulder Creek catchment extends through the Front Range and onto the plains where it joins the South Platte River (Fig. 3). Within the Boulder Creek catchment are three CZO research sites: Green Lakes Valley, Betasso Gulch, and Gordon Gulch, each representing a characteristic area of the Front Range. Green Lakes Valley lies at the edge of the Continental Divide and encompasses the headwaters of North Boulder Creek; the site contains six reservoirs that provide water for the city of Boulder. Green Lakes Valley is an alpine environment where the geology has been heavily influenced by the glaciation that retreated about 12,000 years ago [*Schildgen et al., 2002*]. Betasso Gulch is a catchment in the foothills region of the Front Range, and has the lowest elevation of the three sites. In the past 5 million years, Betasso Gulch has undergone a rejuvenation in bedrock channel incision, which has created a steep fluvial canyon [*Anderson et al., 2006*]. Gordon Gulch lies between Green Lakes Valley and Betasso Gulch and has a mild, montane climate. Gordon Gulch has low relief compared to Green Lakes Valley and Betasso Gulch and is thought to represent slow, steady erosion (Fig. 5).

The study area for this project is the 3.76 square kilometer Gordon Gulch catchment in Boulder County, Colorado. Gordon Gulch is a tributary of North Boulder Creek; it joins North Boulder Creek about 16 kilometers downstream from its headwaters. Elevations in Gordon Gulch range from 2,400 meters to 2,700 meters. Gordon Gulch is separated informally into two sections –

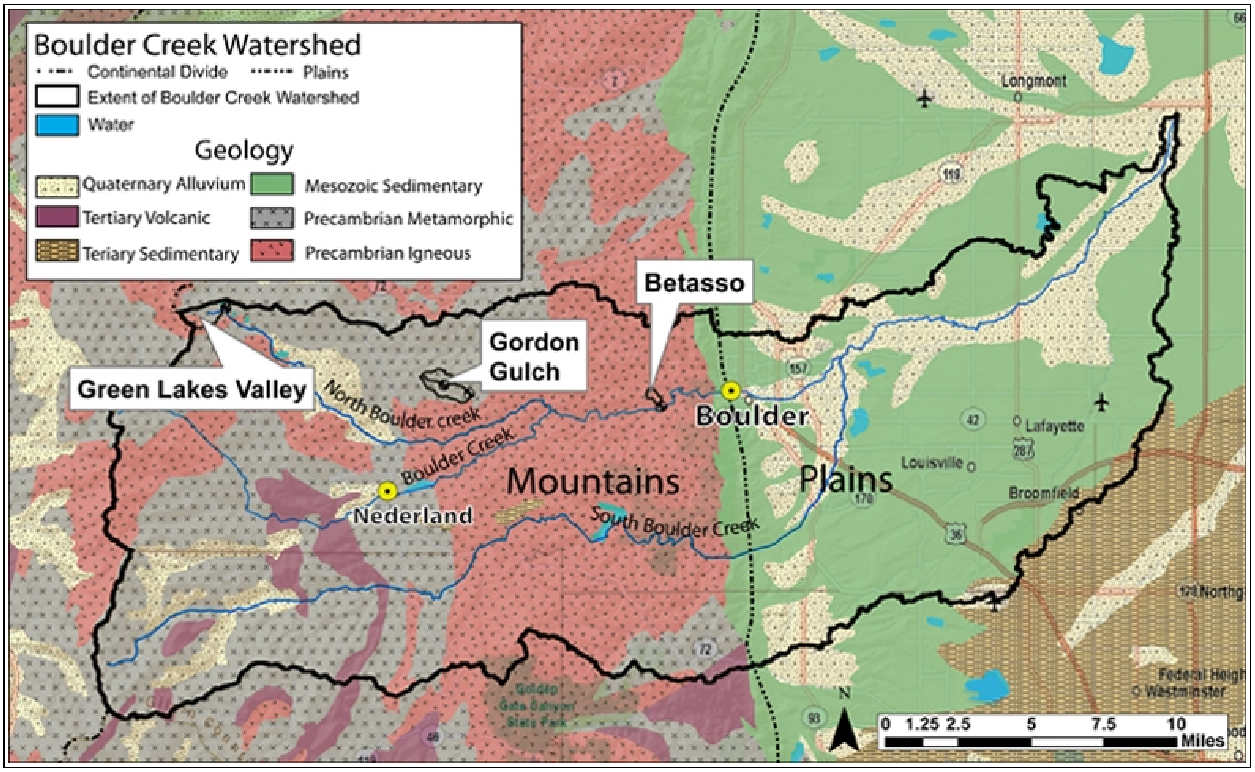

Figure 3. Map of the Boulder Creek catchment, which shows the three sites of the Boulder Creek CZO [from Boulder Creek CZO].

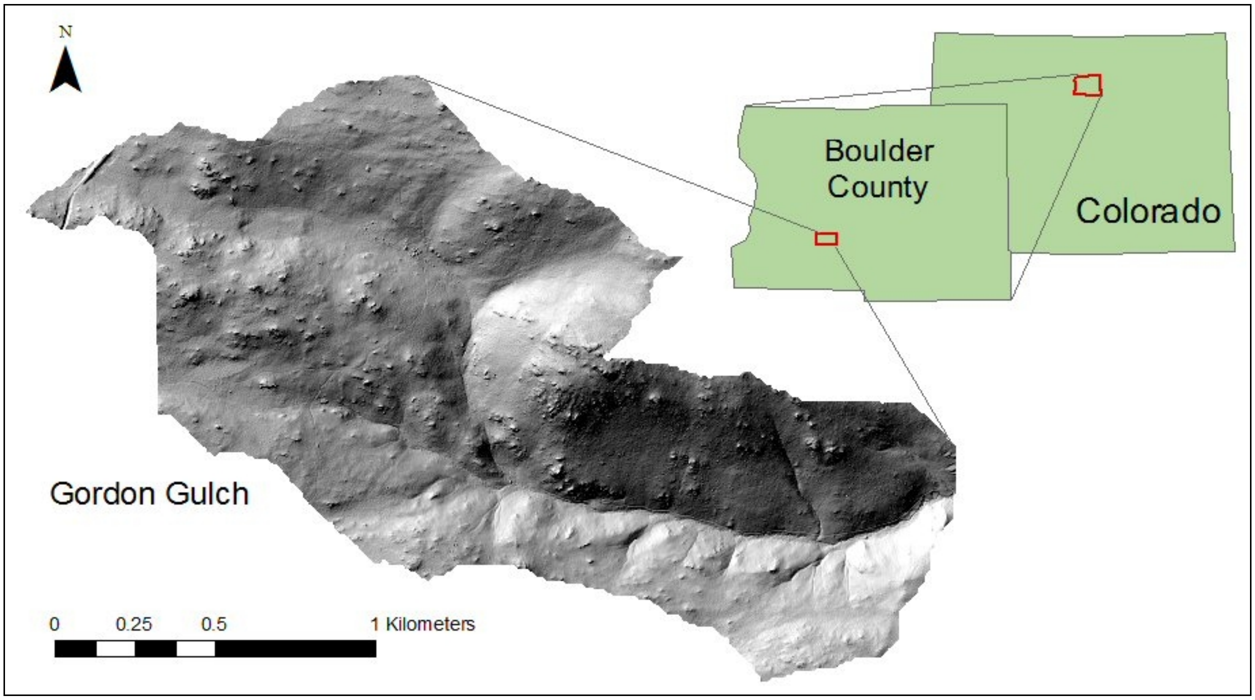

Figure 4. Map of Gordon Gulch showing location in Boulder County and Colorado. Map of Gordon Gulch is a hillshade derived from lidar flown in August 2010 with a pixel size of 1 m^2.

lower Gordon Gulch and a large tributary that constitutes upper Gordon Gulch. A large knickpoint lies between lower and upper Gordon Gulch (Fig. 4). The stream in upper Gordon Gulch is intermittent; however the majority of the stream in lower Gordon Gulch contains water in most years.

Throughout Gordon Gulch prominent bedrock outcrops on the crests of hillslopes, called tors, can be found. Differential weathering and erosion leads to the creation of tors [*Anderson et al., 2006*]. Large masses of rock that have become separated from these tors can be found along the stream. Alluvial fans are also prominent features found throughout Gordon Gulch. An alluvial fan is a depositional feature caused by a change in a stream channel; in Gordon Gulch all of the alluvial fans are the result of tributary streams joining the main channel [*Ritter et al., 2002*]. When the tributary meets the main channel, the channel experiences a decrease in slope and velocity, and is thus able to carry less sediment. The alluvial fans of Gordon Gulch are of different ages, and many have been eroded into by the main channel.

Gordon Gulch is dominated by a mixture of vegetation. Aspen (*Populus tremuloides*) are common in the meadows and on alluvial fans around the main stream. Lodgepole pines (*Pinus contorta*) dominate the catchment, and are especially dense on the north-facing slope. Ponderosa pines (*Pinus ponderosa*) and Douglas fir (*Pseudotsuga menziesii*) are found around the main stream. They are less common throughout the catchment due to their inability to compete with the Lodgepole pines following fires that destroyed most of the vegetation in the catchment in the late 1800s [*Goldblum and Veblen, 1992*]. The north-facing slopes are more densely vegetated

Figure 5. Photo of Gordon Gulch, looking from a south-facing slope to a north-facing slope.

than the south-facing slopes due to the larger amount of precipitation received on north-facing slopes (Fig. 5).

2.1 Geologic History of the Front Range

The bedrock that provides the raw material for the CZ reactor has a large influence on the type and composition of soil formed, which in turn affects the erosion rates of the hillslopes. The bedrock of much of the Front Range consists of a core of Precambrian igneous and high-grade metamorphic rocks [*Birkeland et al., 2003*]. The oldest rocks are Precambrian Era biotite and horneblende gneiss which were intruded by 1.7 Ga Boulder Creek Granodiorite and 1.4 Ga Silver Plume Granite [*Birkeland et al., 2003*]. During the Paleozoic Era the plains region was covered by a shallow sea, which deposited sedimentary strata; later in the Paleozoic Era the whole region was uplifted in an event that formed the ancestral Rocky Mountains [*Kellogg et al.,* *2008*]. Sea level rise in the Mesozoic Era led to the plains region being covered by a sea once again, which deposited the sedimentary strata that is found on the plains today [*Kellogg et al., 2008*]. The Laramide orogeny began during the Early to Middle Eocene, causing the ocean to withdraw from the area and eventually leading to the creation of the modern day Rocky Mountains [*Dickinson et al., 1988*]. Extensive faulting, erosion and volcanism was common during this time [*Birkeland et al., 2003; Kellogg et al., 2008*].

Throughout the Quaternary, the area surrounding Gordon Gulch has been subject to periods of glaciation as well as changes in land use and vegetation. Two periods of glaciation occurred: the Bull Lake glaciation occurred 100 ka ago and the Pinedale glaciation occurred 32-10 ka ago [*Schildgen et al., 2002*]. The Bull Lake glaciation was significantly larger than the Pinedale glaciation, and ice extended farther down in elevation [*Schildgen et al., 2002*]. These periods of glaciation resulted in pulses of sediment introduced into the river systems. More recently during the late 1800s to early 1900s as miners settled the area, land use changed drastically. The introduction of mining generated a large amount of sediment that was transported into stream (by biological activity, runoff, etc.). The frequency of fires in the region drastically increased as well, which resulted in an increase in erosion in the catchment [*Goldblum and Veblen, 1992; Moody and Martin, 2001*].

2.2 Related Work in the Boulder Creek CZO

Schildgen et al. [*2002*] studied fill terraces in Boulder Canyon, adjacent to Gordon Gulch, using cosmogenic Al-26, Be-10 and C-14 dating. This study found three distinct terrace levels: terraces from the Bull Lake glaciation, 15-20m above the current stream; terraces from the Pinedale Glaciation, 4-15m above the current stream; terraces of Holocene age, less than 4m above current stream [*Schildgen et al., 2002*].

Current work in the Boulder Creek CZO has been focused on many subjects. Anderson et al. [*2006*] studied the profiles of rivers downstream glaciers and found that the profiles display a convex shape. This is not the typical profile of a river, and is likely due to the excess sediment deposited by glaciers [*Anderson et al., 2006*]. Leopold et al. [*2010*] have studied changes in permafrost in the alpine regions of the CZO and related these changes to climate change.

Terrace studies have never been applied to the Gordon Gulch catchment. Gordon Gulch is a tributary of Middle Boulder Creek, the terraces of which were studied by Schildgen et al. [*2002*]. Because the headwaters of Gordon Gulch are of much lower elevation than those of Boulder Creek, the processes controlling the development of terraces are much different than those controlling Boulder Creek. Terrace formation in Boulder Creek is dominated by glaciation, whereas terrace formation in Gordon Gulch is dominated by climate, land use and vegetation. To further understand the processes of the CZO, the terraces of Gordon Gulch must be understood.

CHAPTER 3. METHODS

3.1 Field

3.1.1 Base Map Creation

Before a map of the terraces could be made, a detailed base map of the stream was needed. A laser rangefinder was used to take measurements of vertical and horizontal distance and azimuthal angle. A laser rangefinder uses a built in laser with a known velocity and a separate reflector to measure the distance between the rangefinder and reflector (Fig. 6). The rangefinder then calculates the horizontal and vertical distances using the slope angle. The rangefinder also has a built in compass that measures the compass angle (between 000 and 360 degrees). To ensure accurate measurements, the rangefinder and reflector have the same height above the ground. They also must be held level and obstacles between the rangefinder and reflector must

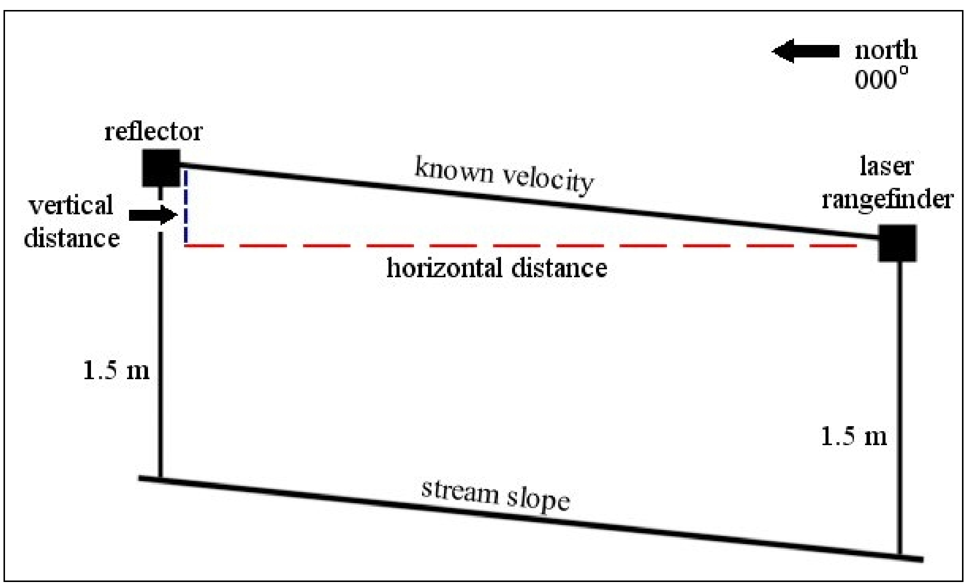

Figure 6. Laser rangefinder configuration: distance between rangefinder and reflector is ~4 meters.

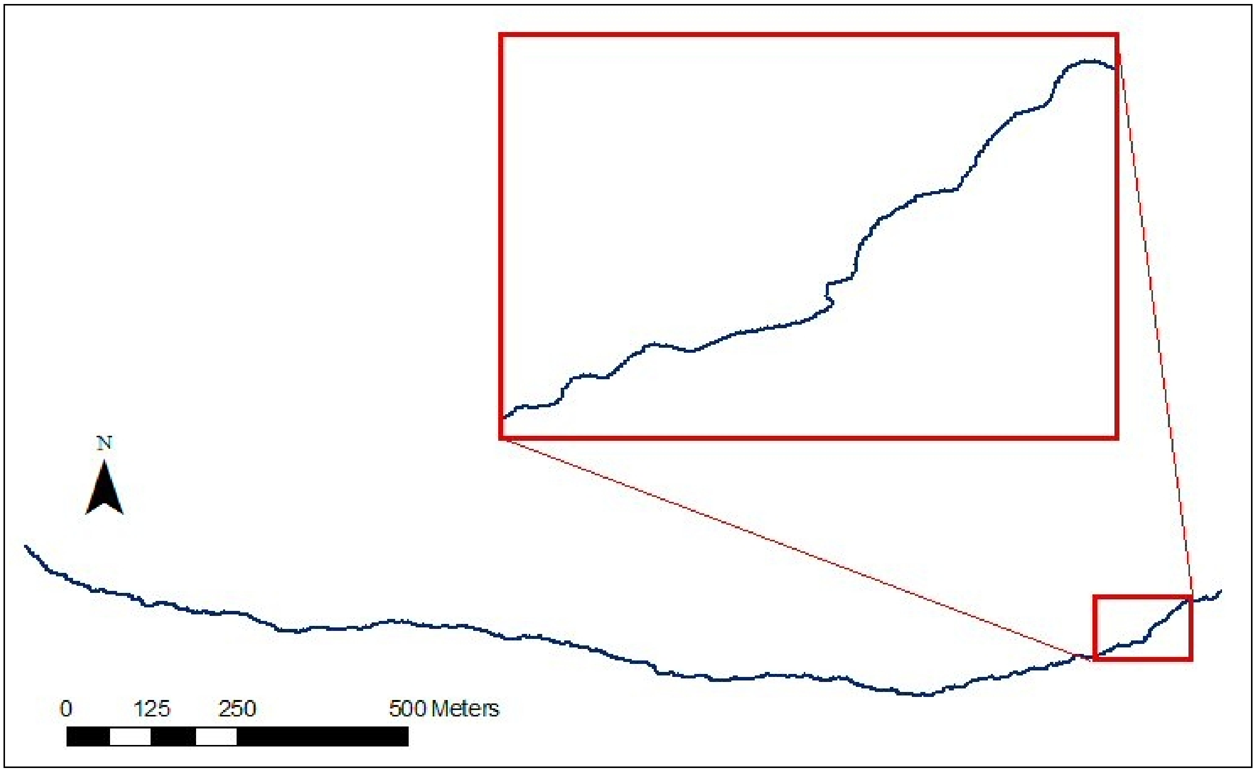

Figure 7. Base map of Gordon Gulch with inset showing detail

be removed. The rangefinder has an accuracy of ±0.30 meters for slope distance, ±0.25 degrees for slope angle, and ±1 degree for azimuthal angle. A series of 38 markers were also placed along the stream and their locations were noted on the base map. GPS points were taken at the beginning and ending location of the base map stream extent.

The compass angle was used in conjunction with the horizontal distance measurements to produce x and y coordinates. A base-level elevation measurement was made with a GPS, and a z coordinate was calculated using the base-level and vertical distance measurements. The final base map can be observed in Figure 7.

3.1.2 Stream Terrace Mapping

The base map was then used to map the stream terraces. Stream morphology and a series of makers placed along the stream were used to mark the terraces on the map relative to their location along the stream. The laser rangefinder was used to measure the height of each terrace above the stream channel, which was then recorded on the map. A clean version of the map was then made and the terrace heights were interpreted into five distinct terrace levels depending on their heights as well as other features, including alluvial fans and tors.

3.1.3 Cross Section Measurements and Sediment Sample Collection

A series of eight evenly-spaced cross sections were made along the mapped section of the stream using the laser rangefinder. The cross section locations were strategically placed to represent characteristic sections of the valley and terrace morphology. Each cross section location was marked with a GPS point. These cross sections were used to estimate the bank-full width as well as the basin volume estimates.

At each cross section location, a sample of stream sediment from the active channel was taken. The size of the samples ranged from 0.121 kilograms to 0.640 kilograms. These sediment samples were stored in Ziploc bags until they were later processed for grain size. Seven sediment samples were also collected from profiles that were dug into two alluvial fans along the stream.

3.1.4 Tree Core Collection

Seventy-five tree cores were collected from trees growing on the terraces. By counting the number of rings in the tree core, the approximate age of the tree can be obtained. The ages provide a minimum age for each terrace, as the terrace must have been in existence before the tree started growing. The location of each tree was marked both by a GPS point and on the terrace map. The species and diameter of each tree were also recorded. The tree core data are listed in Appendix B.

3.2 Laboratory

3.2.1 Terrace Plotting and Sediment Volume Estimates in ArcMap

A scanned copy of the terrace map was imported into ArcMap in tiff format. GPS points were used to orient the map into the correct location and scale in ArcMap. The method was adapted from Oskin [*2009*]. Each terrace polygon was manually traced into a workable ArcMap shapefile.

Basin volume was estimated using a series of eight detailed cross sections that were measured along the stream using the rangefinder (Fig. 8C). Valley-wide cross sections extracted from a high resolution digital elevation model to estimate the slope of the bedrock in surrounding hillslopes (Fig. 8B). Riemann sums were used to calculate cross sectional area of sediment between the bedrock slope and terrace cross section (Fig. 8C). The area was multiplied by the distance upstream to the next cross section, and all volumes were summed to obtain the total volume of sediment stored in the terraces (V_s).

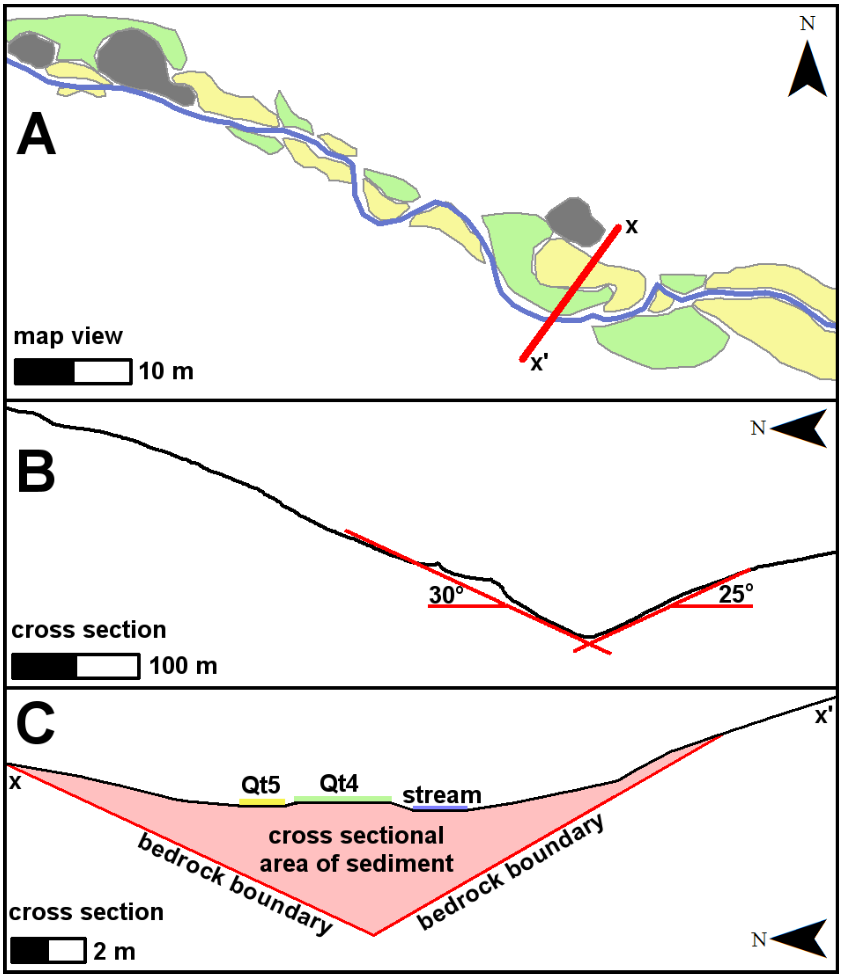

Figure 8. (A) Map view of terraces at KW-ST-10 with cross section X-X' marked. Tors (Qt) are shown. (B) Valley-wide cross section derived from lidar showing estimated slope angles of the bedrock boundary. (C) Cross section and map view of stream terrace map at location KW-ST-10 showing terraces Qt4 and Qt5 and the cross sectional area of sediment.

3.2.2 Stream Sediment Grain Size

The grain size of the sediment samples was needed for the Shields stress calculations (see section 3.2.3). The stream sediment samples were dried in an oven for at least 48 hours. The samples were then sieved into seven grain size classes and each grain size class was weighed. The grain size analyses data are listed in Appendix C.

3.2.3 Shields Stress Calculation

A stream transports the greatest amount of sediment at its bankfull depth, which is the greatest depth that a stream attains. To determine if a stream is capable of transporting all of the sediment in its channel at bankfull depth, Shields stress needs to be calculated. Shields stress is the threshold for bed movement, a dimensionless ratio of bed shear stress to grain size [*Cronin et al., 2007*]. Shield's stress is defined as:

$$\theta = \frac{\tau_c}{(\rho_s - \rho_w)\, g\, D_{84}} \quad \textbf{\textit{(1)}}$$

where τ_c is the critical shear stress ($\tau_c = \rho_w gHS$), ρ_s and ρ_w are the sediment and water densities, g is gravity, D_{84} is the median grain size of the channel sediment, h is the channel depth at bankfull, and S is decimal slope (Cronin et al., 2007). Slope was measured from the base map at each sample location. When θ is equal to 0.03, the stream is capable of transporting all the sediment in its bed. Below this value, the stream cannot transport all of its sediment. When θ is above 0.07 the stream is capable of carrying more sediment than its bed contains and ultimately results in stream incision. The Shields stress will be used to calculate the annual sediment flux.

3.2.4 Sediment Removal Timescale Calculation

To calculate the timescale for sediment removal, the annual sediment flux must be known first. The model developed in Mueller and Pitlick [*2005*] will be used to calculate the annual sediment flux. The equation derived for sediment flux (Q_s) in meters cubed per second is:

$$Q_s = 11.2 \frac{(\theta - \theta_c)^{4.5}}{\theta^3} [(s-1)\, g\, D_{84}^3]^{0.5} B \quad \textbf{\textit{(2)}}$$

where θ is the Shields stress, θ_c is the critical Shields stress (approximated at 0.03), s is the specific gravity of the sediment, g is gravity, D_{84} is the 84th percentile grain size, and B is the bank-full width. The cross sections were used to determine bank-full width (B) and hydraulic radius (R) of the active stream. Hydraulic radius is:

$$R = \frac{HB}{2\mathrm{H} + B} \quad \textbf{(3)}$$

where H is bankfull depth, defined as:

$$H = \frac{Q_w}{Bv} \quad \textbf{(4)}$$

where Q_w is maximum discharge of water in the stream, and v is velocity of the stream. Bankfull velocity was approximated at 0.5 m/s. Maximum discharge of water from Gordon Gulch was calculated as the 90th percentile of daily discharge data from the stream gauge over the year 2009.

The sediment removal time-scale *(T_s)* for the valley is:

$$T_s = \frac{V_s}{Q_s} t \quad \textbf{(5)}$$

where t is a unitless time interval, defined as:

$$t = \frac{total\ years\ of\ Q_w\ data}{total\ years\ of\ Q_w\ exceeding\ 90^{th}\ percentile} \quad \textbf{(6)}$$

This calculation assumes stream flow patterns remain constant over thousand year timescales. The value for sediment flux can be converted into meters cubed per year to estimate the annual sediment flux. From this value it is a simple calculation to determine the sediment removal time scale using the estimated sediment volume and annual sediment flux.

CHAPTER 4. RESULTS

4.1 Fluvial Terrace Characterization

Terraces along 1.6 km of lower Gordon Gulch were characterized into five distinct levels, which are listed in Table 1. Terrace Qt1 is the oldest terrace in the valley; terrace Qt5 is the current floodplain and was vegetated by mostly grasses and young plants. There was no discernible difference in vegetation on terraces Qt1 through Qt4. Figure 9 shows a section of lower Gordon Gulch in which all five terrace levels interact with alluvial fans (Qa).

Morphology of terraces in Gordon Gulch varies along the stream. Downstream, there are more terraces flanking the stream in complex patterns. The majority of terraces are not paired. The north bank of the stream often contains few or no terraces. Terraces on the south bank are more extensive. In some locations (Fig. 9) it is possible to find all five terraces in one location. Upstream there may be only one or two terraces flanking the stream (Fig. 8A). No bedrock is visible in the mapped stream channel. Tor deposits are more common upstream. The overall width of upstream terraces is half that of downstream terraces.

Terrace	h_{min}	h_{max}	area	n_{units}	age_{min}	n_{cores}
Qt1	2.2	3.3	97	2	83	1
Qt2	1.2	2.1	908	8	134	6
Qt3	0.9	1.7	2751	33	158	18
Qt4	0.4	1.2	3043	92	162	33
Qt5	0.1	0.7	1465	164	120	7

Table 1. Characterization of Gordon Gulch stream terraces, with Qt1 being the oldest and Qt5 being the current floodplain. h_{min} and h_{max} are minimum and maximum heights of terraces above the stream channel in meters, area is total area of all units in square meters, n_{units} is number of units mapped for each terrace, age_{min} is minimum age obtained from tree coring in years, n_{cores} is number of tree cores obtained for each terrace.

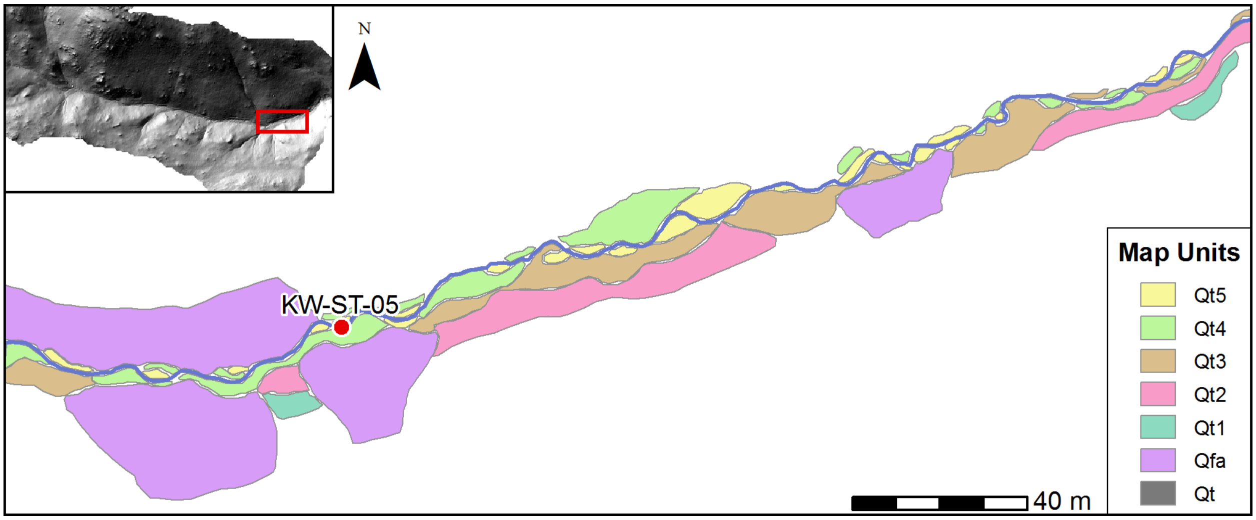

Figure 9: Section of stream terrace map near location KW-ST-05 (red dot). Terraces range from Qt1 (oldest) to Qt5 (youngest). Alluvial fan units (Qfa) are visible. Tor deposits (Qt) are not visible.

4.2 Sediment Volume and Removal Timescale Estimates

The total volume of sediment stored in the terraces of lower Gordon Gulch (V_s) was calculated to be 50,000 m^3 in the mapped 1.6 km of the stream (Table 2).

The time interval t was calculated using discharge data from Boulder Creek over the past 24 years provided by the US Geological Survey. Of the 24 years of data, two years of maximum discharge values exceeded the 90th percentile of the Boulder Creek data. Thus, the time interval between maximum discharge events in the catchment is 12 years.

Parameters for the calculation of Q_s are listed in Table 2. For the 90th percentile discharge (3,500 m^3/day from Boulder Creek CZO stream gauge data), the median θ value was 0.29, more than sufficient to mobilize terrace sediment. The θ values were used to calculate sediment flux at

Sample ID	Dist	D_{84}	S	H	R	B	τ	θ	Q_s
KW-ST-04	0.00	0.002	0.08	0.09	0.075	0.9	59	1.80	710
KW-ST-06	0.19	0.020	0.08	0.10	0.081	0.8	63	0.20	360
KW-ST-05	0.39	0.002	0.08	0.20	0.100	0.4	79	2.40	500
KW-ST-01	0.64	0.020	0.09	0.27	0.096	0.3	85	0.26	260
KW-ST-07	0.77	0.010	0.09	0.09	0.075	0.9	66	0.41	650
KW-ST-08	0.99	0.020	0.09	0.17	0.098	0.5	87	0.27	450
KW-ST-09	1.27	0.020	0.11	0.27	0.096	0.3	100	0.32	390
KW-ST-10	1.41	0.020	0.10	0.07	0.061	1.2	60	0.18	470
							Median	0.29	460

Table 2. Shields stress and sediment flux for Gordon Gulch. Dist. is distance upstream from the beginning of the mapped section in meters, D_{84} is grain size in meters, S is decimal slope, H is bank-full depth in meters, R is hydraulic radius in meters, B is bank-full width in meters, τ is shear stress in Newtons per square meter, θ is Shields stress (unitless), Q_s is modeled sediment flux in cubic meters per 12 year cycle.

each sample location, with the median sediment discharge value being 460 m^3 of sediment transported from Gordon Gulch every 12 years. Median values were used to avoid sensitivity to outliers.

At the current rates of water and sediment discharge, this model estimates that it would take 1,300 years to evacuate the sediment currently in the basin.

Two radiometric ^{14}C dates were obtained from buried wood in Qt4 terrace sediments. The first sample was 30 cm above the current stream channel and was dated 1,110 ± 50 years before present. The second sample was 10 cm above the current stream channel and was dated 1,520 ± 40 years before present.

CHAPTER 5. DISCUSSION

As streams go through periods of aggradation and degradation a complex system of terraces may form. In Gordon Gulch, five terrace levels have formed from this process.

5.1 Terrace morphology of Gordon Gulch

Variations in terrace morphology along Gordon Gulch can be attributed to valley morphology. Water downstream carries more sediment, as drainage area is directly related to distance from the headwaters. Thus, more sediment is carried into the stream by erosional processes. Increased sediment is counteracted by decreased slope of the stream. The combined effect of these factors is that a larger amount of sediment accumulated in downstream terraces versus upstream terraces. Sediments in the terraces accumulated within the past 1,600 years, prior to the incision and creation of Qt1 through Qt4. Qt5 may be the result of a combination of current accumulation and incision into past accumulation.

Ages obtained from tree coring are largely varied and do not accurately reflect terrace ages. This may be the result of logging and forest fires that cleared many of the trees in the past 200 years. The oldest tree was a 162 year old Ponderosa Pine on Qt4. Thus, terraces Qt1 through Qt4 stabilized at least 162 years ago.

5.2 Sediment Removal Timescale of Gordon Gulch

Shields stress (θ) values for maximum stream discharge in Gordon Gulch have a large variation. Maximum stream discharge is more than sufficient ($\theta > 0.07$) in all sample locations to transport all sediment in the stream. In two locations (KW-ST-04 and KW-ST-05), the θ value for maximum stream discharge is very high (θ > 1.5) due to decreased grain size. These locations also have a high Q_s value. In locations with a large D_{84} grain size ($D_{84} \geq 20$ mm), θ values were below 0.40 and Q_s values were below or near the median Q_s value. Increased slope also resulted in increased θ and Q_s values. Grain size appears to have the largest control on θ and Q_s values

The sediment removal timescale for terraces in Gordon Gulch calculated by this model is 1,300 years. Evacuating the sediment in this timescale would be unlikely, as the sediments have been in place for over 1,500 years. If the prediction of the model were correct, these sediments would have already been eroded. The model does not take into account forces holding sediments together, which include roots, buried logs and other biologic factors, as well as compaction forces of buried sediments. The model also does not account for sediment currently being added to the stream by erosion on hillslopes and from addition of sediment upstream of the mapped area. Incorporating these factors into the model would likely increase the sediment removal timescale.

CHAPTER 6. CONCLUSIONS

The Gordon Gulch terrace system includes five complex terrace levels that are closely related to valley morphology. Downstream terraces are wider and more complex due to aggradation from increased sediment concentration and decreased slope. Sediment stored in terraces has been accumulating for over 2,000 years. Total volume of sediment stored in the terraces was approximated to be 50,000 cubic meters. Hydrologic models applied to calculate sediment flux estimate that it would take 1,300 years to evacuate terrace sediment from Gordon Gulch. This value underestimates the time it will take to remove sediment stored in the terraces, largely because the model does not take into account biologic factors and erosional input from the headwaters and hillslopes.

Future research should focus on quantifying inputs of sediment into the stream by erosion on hillslopes and upstream of the mapped area. Incorporating these factors into the model would provide a closer approximation of the sediment removal timescale. Future research should also quantify the effects of biologic factors and compaction on erosion of terrace sediments. Understanding these factors would also provide better understanding of how the complex relationships of the CZ affect sediment flux. Volume of sediment should be better estimated using geophysical methods (ground penetrating radar) to measure the depth to bedrock below the terraces.

CHAPTER 7. REFERENCES

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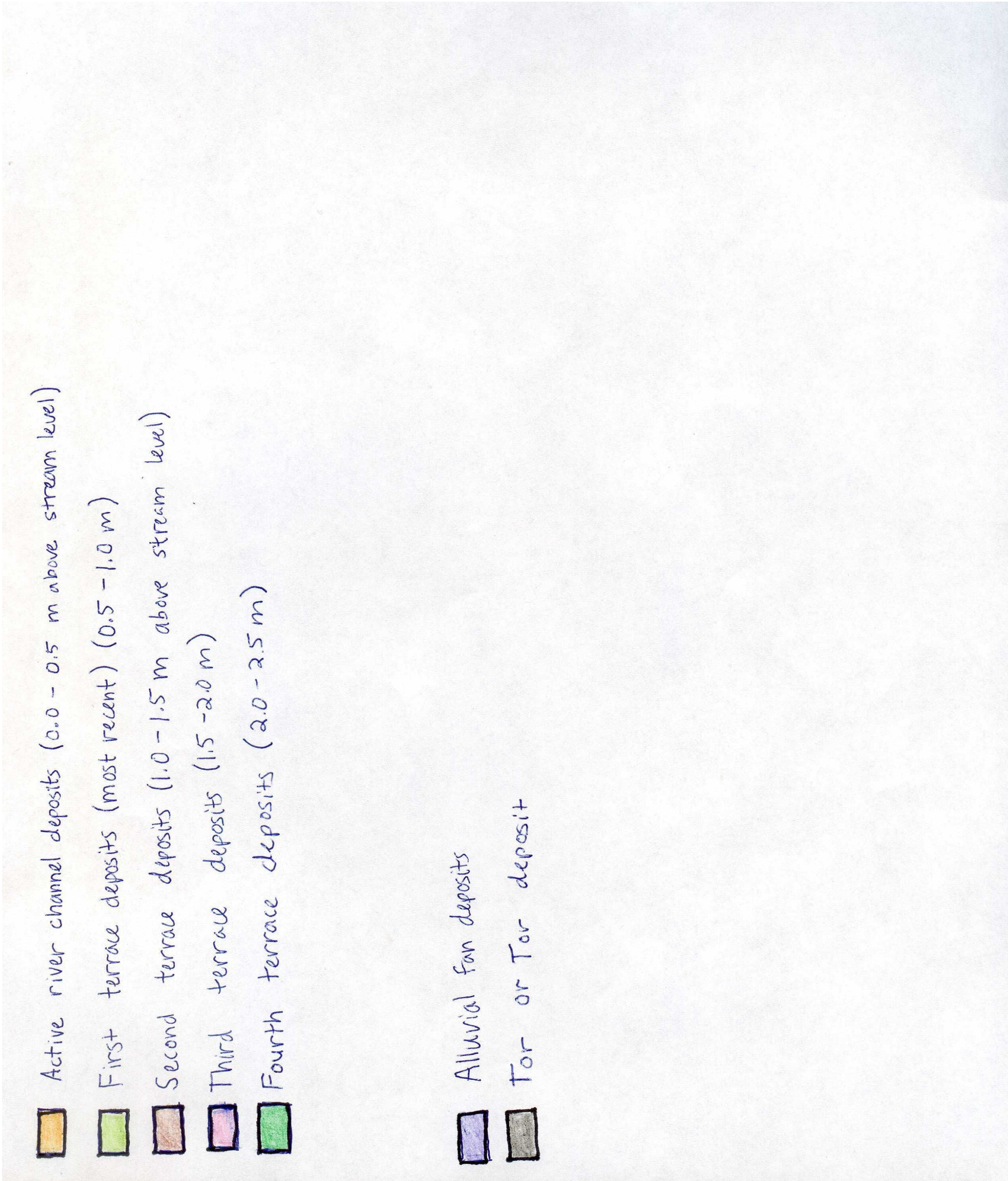
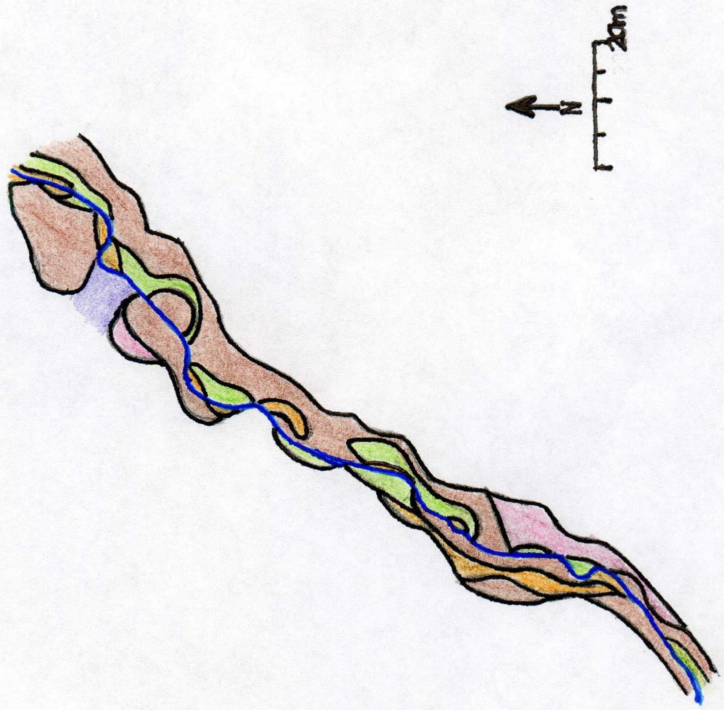
APPENDIX A – Stream Terrace Maps




20m
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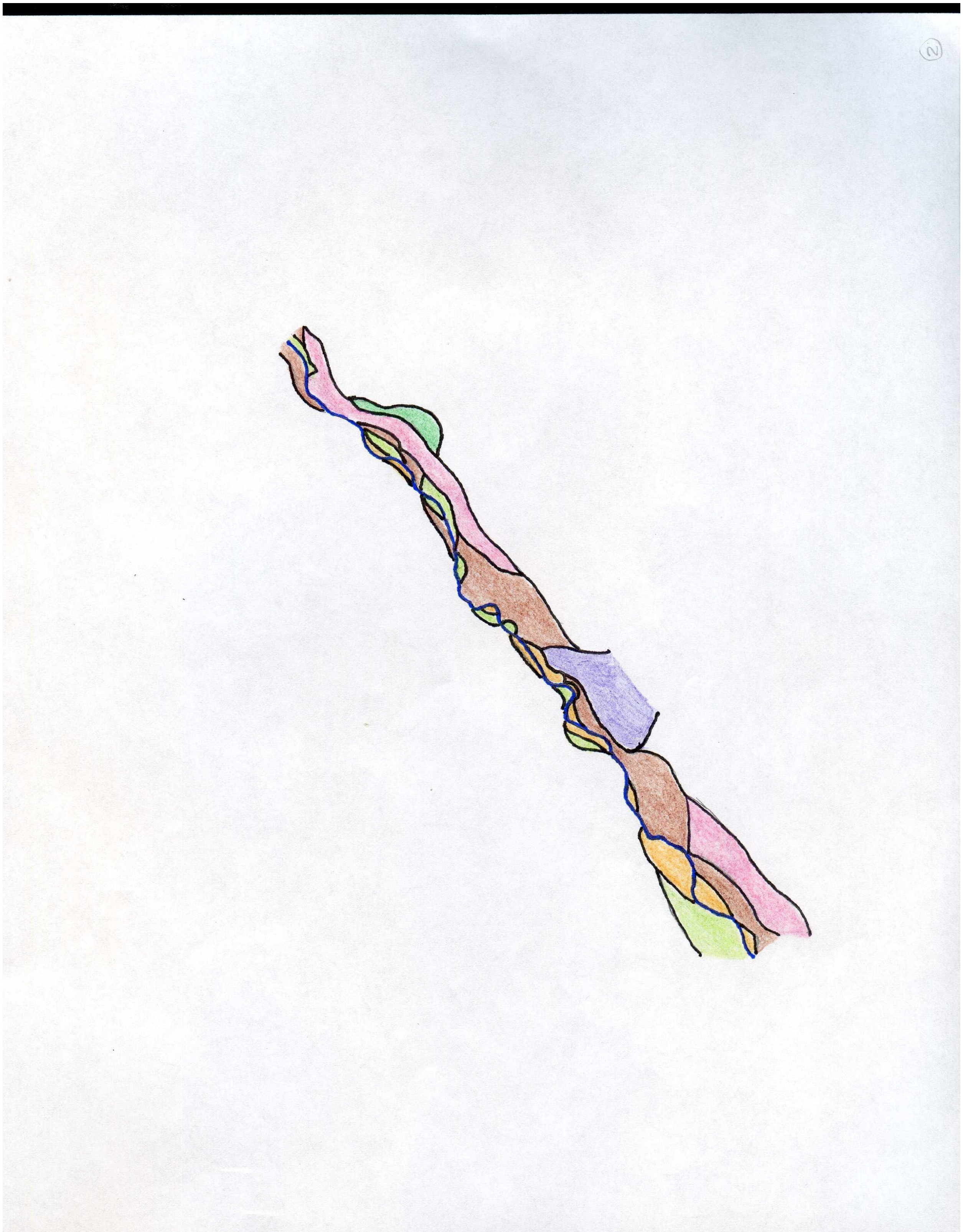

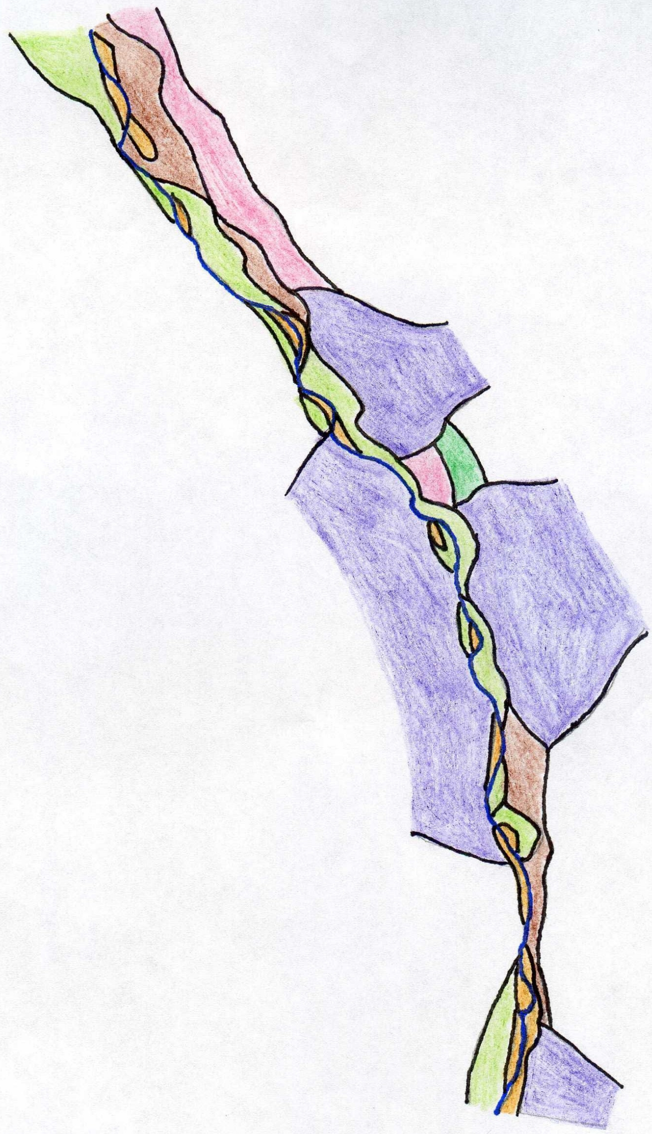

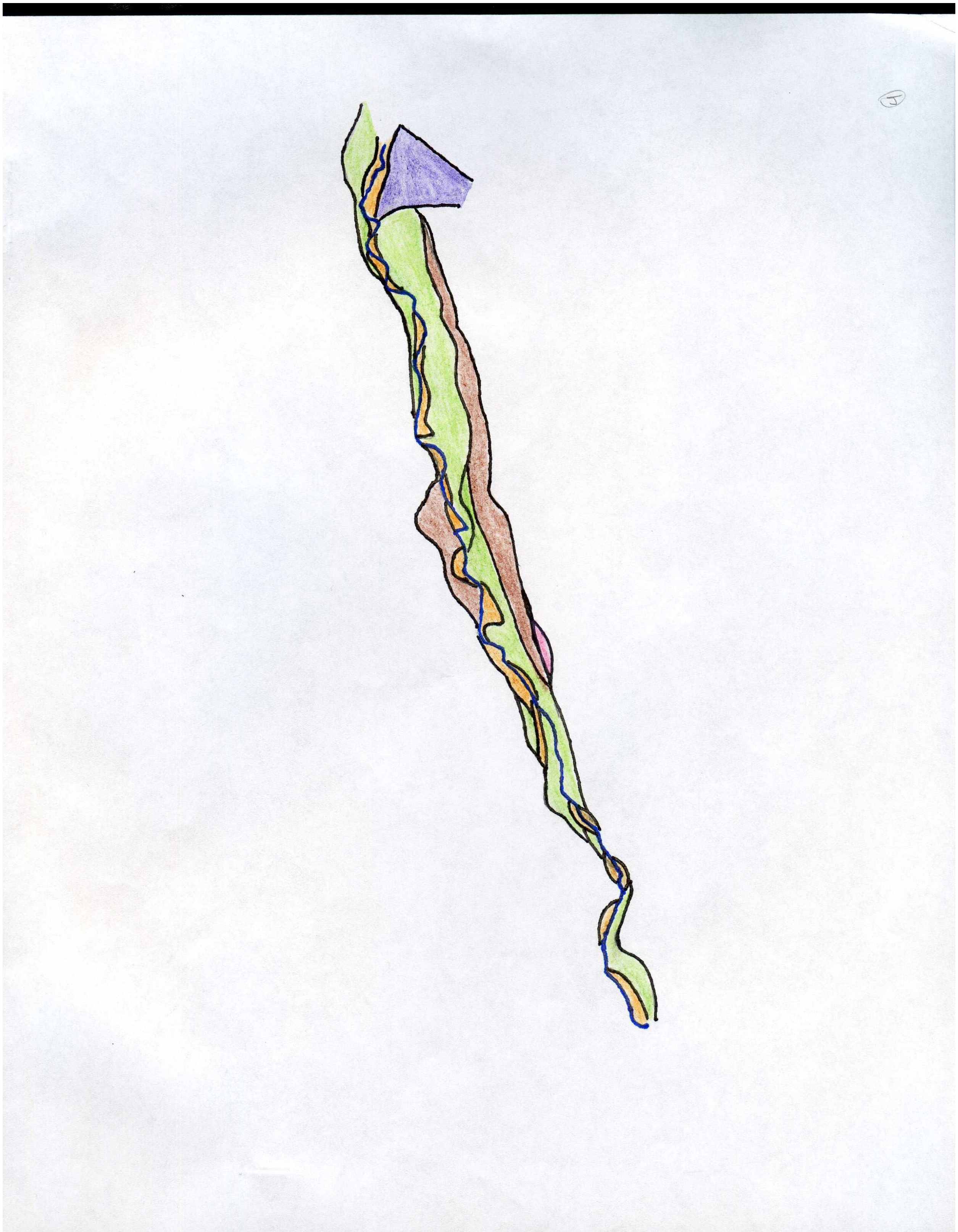

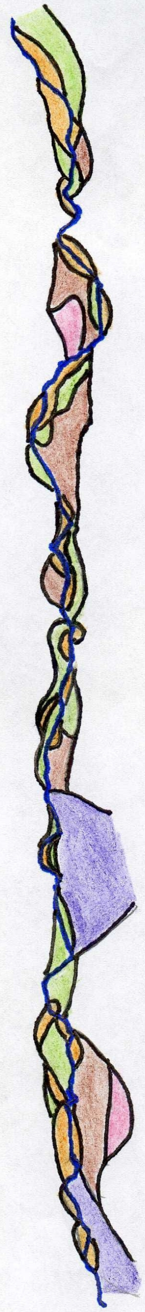

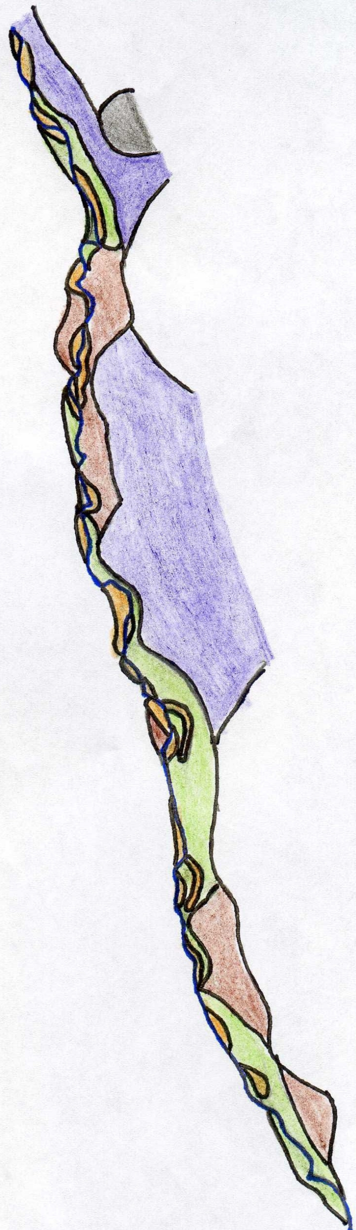

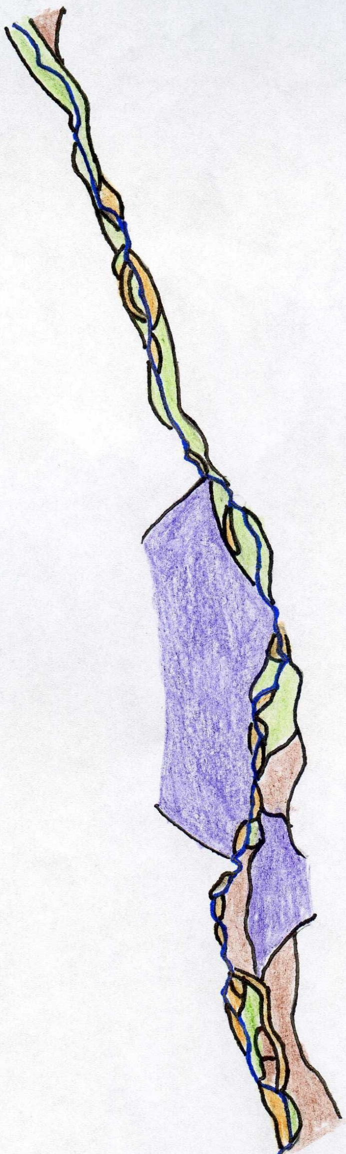

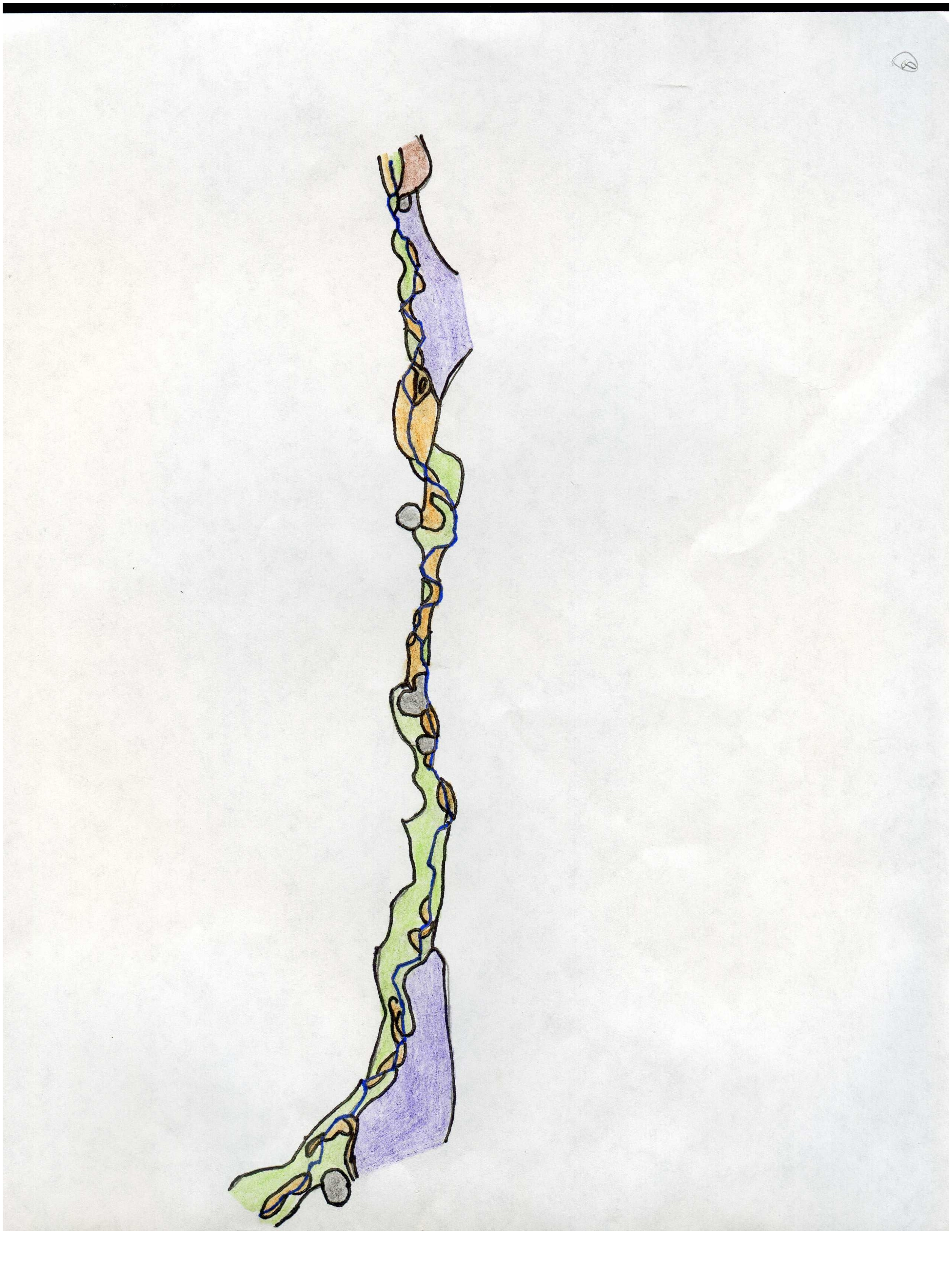

APPENDIX B – Tree Core Data

Core	Age	Diameter	Species	Terrace
36	145	195	Ponderosa	Qaf
47	113	129	Lodgepole	Qaf
30	111	176	Ponderosa	Qaf
17	108	130	Lodgepole	Qaf
57	75	113	Lodgepole	Qaf
42	120	90	Lodgepole	Qt5
26	90	130	Ponderosa	Qt5
6	75	130	Douglass	Qt5
1	70		Ponderosa	Qt5
70	69	104	Lodgepole	Qt5
8	55	130	Douglass	Qt5
76	52	90	Lodgepole	Qt5
48	162	166	Ponderosa	Qt4
46	160	120	Lodgepole	Qt4
67	150	143	Ponderosa	Qt4
35	146	110	Lodgepole	Qt4
27	145	85	Lodgepole	Qt4
62	142	148	Lodgepole	Qt4
31	140	129.5	Ponderosa	Qt4
25	135	203	Ponderosa	Qt4
45	133	128	Lodgepole	Qt4
44	130	169	Ponderosa	Qt4
43	125	105.5	Lodgepole	Qt4
37	117	120	Lodgepole	Qt4
75	114	138	Ponderosa	Qt4
19	108	133	Ponderosa	Qt4
7	100	195	Ponderosa	Qt4
39	100	105	Lodgepole	Qt4
64	99	177	Ponderosa	Qt4
69	98	134	Ponderosa	Qt4
10	90	120	Lodgepole	Qt4
21	85	95	Ponderosa	Qt4
29	85	90	Lodgepole	Qt4
74	85	165	Lodgepole	Qt4
71	77	108	Douglass	Qt4
24	75	145.5	Ponderosa	Qt4
40	75	177	Lodgepole	Qt4
16	69	110	Lodgepole	Qt4
28	66	110	Lodgepole	Qt4

Core	Age	Diameter	Species	Terrace
68	65	112	Lodgepole	Qt4
73	58	107.5	Douglass	Qt4
34	50	96.5	Douglass	Qt4
38	45	70	Douglass	Qt4
41	45	106	Lodgepole	Qt4
22	27	37.5	Lodgepole	Qt4
20	158	197	Ponderosa	Qt3
4	136	217	Ponderosa	Qt3
5	130	154	Lodgepole	Qt3
33	128	133	Lodgepole	Qt3
66	124	167	Lodgepole	Qt3
49	123	188	Douglass	Qt3
18	120	172	Ponderosa	Qt3
11	115	180	Lodgepole	Qt3
9	110	179	Ponderosa	Qt3
14	110	227	Douglass	Qt3
2	105	120	Ponderosa	Qt3
15	105	185	Douglass	Qt3
61	84	121	Ponderosa	Qt3
32	83	99.5	Lodgepole	Qt3
56	83	115	Douglass	Qt3
58	78	126	Lodgepole	Qt3
65	65	102	Lodgepole	Qt3
72	57	97	Lodgepole	Qt3
55	134	139	Lodgepole	Qt2
51	100	163	Lodgepole	Qt2
60	90	147	Lodgepole	Qt2
52	85	144	Lodgepole	Qt2
54	75	104	Douglass	Qt2
53	60	91	Lodgepole	Qt2
63	83	116	Lodgepole	Qt1
59	140	144.5	Lodgepole	Hillslope
23	24	42.5	Lodgepole	Hillslope

APPENDIX C – Grain Size Analyses Data

Sample ID	D16 (m)	D50 (m)	D84 (m)
KW-ST-01	2.00E-003	2.00E-002	2.00E-002
KW-ST-04	2.50E-004	7.10E-004	2.00E-003
KW-ST-05	5.00E-004	2.00E-003	2.00E-003
KW-ST-06	2.00E-003	2.00E-002	2.00E-002
KW-ST-07	5.00E-004	2.00E-003	1.00E-002
KW-ST-08	1.00E-003	2.00E-003	2.00E-002
KW-ST-09	2.00E-003	1.00E-002	2.00E-002
KW-ST-10	1.00E-003	2.00E-003	2.00E-002

KW-ST-01

Start Weight 552 g

Class	**Weight (g)**
>20mm	295
20-10mm	75
10-2mm	119
2mm-1mm	28
1mm-710um	8
710um-500um	7
500um-250um	8
250um-125um	2
<125um	3

KW-ST-04

Start Weight 215 g

Class	**Weight (g)**
>20mm	0
20-10mm	0
10-2mm	44
2mm-1mm	60
1mm-710um	28
710um-500um	31
500um-250um	39
250um-125um	7
<125um	1

KW-ST-05

Start Weight 121 g

Class	**Weight (g)**
>20mm	0
20-10mm	7
10-2mm	51
2mm-1mm	22
1mm-710um	10
710um-500um	11
500um-250um	11
250um-125um	2
<125um	1

KW-ST-06

Start Weight 360 g

Class	**Weight (g)**
>20mm	202
20-10mm	55
10-2mm	53
2mm-1mm	27
1mm-710um	6
710um-500um	4
500um-250um	3
250um-125um	1
<125um	1

KW-ST-07

Start Weight 636g

Class	Weight (g)
>20mm	50
20-10mm	55
10-2mm	202
2mm-1mm	103
1mm-710um	52
710um-500um	61
500um-250um	70
250um-125um	11
<125um	4

KW-ST-08

Start Weight 622 g

Class	Weight (g)
>20mm	203
20-10mm	77
10-2mm	194
2mm-1mm	70
1mm-710um	25
710um-500um	22
500um-250um	17
250um-125um	3
<125um	2

KW-ST-09

Start Weight 565 g

Class	Weight (g)
>20mm	231
20-10mm	112
10-2mm	132
2mm-1mm	33
1mm-710um	12
710um-500um	12
500um-250um	17
250um-125um	5
<125um	4

KW-ST-10

Start Weight 338 g

Class	Weight (g)
>20mm	74
20-10mm	85
10-2mm	78
2mm-1mm	32
1mm-710um	16
710um-500um	15
500um-250um	14
250um-125um	3
<125um	1