THE EVOLUTION OF GRAND VALLEY IN THE UPPER COLORADO RIVER BASIN: A DILUVIAL HYPOTHESIS FOR THE GENESES OF ALPINE TERRACES

A Dissertation

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

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December 2020

Major Subject: Geology

ABSTRACT

Rivers are thought to form fluvial terraces. The geneses of terraces depend on climatic changes because of the variations of riverbed slopes and sediment fluxes. Particularly, generating erosional-strath terraces requires beveling a surface, depositing a laterally extant sedimentary layer, and abandoning, accompanied by vertical incisions. Amounting, much evidence now suggests that large flows of water and sediments are necessary for strath terrace geneses. Thus, one can ask: is the solely fluvial explanation sufficient for the geneses of terraces? I invoke catastrophic diluvial processes as an alternative explanation for the geneses of alpine terraces, drawing the evidence from those in the Grand Valley area of the upper Colorado River Basin.

For decades, researchers suggested that the terraces of the upper Colorado River are of fluvial origin. Unfortunately, their conclusions lacked age control and the link to climate changes, and analyses of the matrices of the terraces. This study offers such data and a new interpretation on the terraces. Five Colorado River terrace/floodplain matrices were examined, using electrical resistivity tomography (ERT) method, the bedrock Mancos Shale at depths (< 25 Ω-m) and the overlying terrace clasts were identified (>100–1000's Ω-m). The terraces consist of aggregates of river gravels, cobbles, and even boulders, indicating that the formative discharges exceeded those of seasonal floods or river flows. New luminescence dates for the fill/depositional terraces in the tributaries concur that episodic jökulhlaups from Grand Mesa occurred between 85 and 58 ka, post-dating Bull Lake (MIS 6) and pre-dating Pinedale glaciations (MIS 2).

Arguably, contemporaneous to the fill terraces, the strath terraces formed under the repeated cycles of 1) *rapid beveling of the substrate*, 2) *lateral deposition of gravels and boulders*, and 3) *rapid vertical incision and abandonment,* resulting in the Holocene-modern floodplains. Hence, the suggestion that the terraces in the area formed by episodic glacial floods instead of fluvial processes.

My suggestion for terrace geneses through glacial outburst flooding is supported by similar data from other jökulhlaup-prone places in addition to the Rocky Mountains. Conceivably, with more investigations of alpine fluvial terraces elsewhere, a wide recognition of diluvial, rapid terrace formation will result.

DEDICATION

This dissertation is dedicated to seven very special individuals in my life. The first person is the Messiah, my Lord Christ, who invisibly but most vitally guided and will guide my life. In him I live, move, and have my being (Acts 17:28). To him belong all honor despite all my shortcomings. The second and third are my wife and our child in her womb—Hyun Ji O. Jeon and Ephe Jeon. I am glad that I dedicate this dissertation to my wife now as I am with her as I had done my Master's thesis years before meeting her; I find this is quite romantic.

Considering my newly established family, I cannot forget to mention my parents; this dissertation is dedicated also to my parents in Seoul, South Korea. They loved me sacrificially and unconditionally since my conception and guided me throughout my life. I will be and do the same, if not more, to their grandchildren for their sake, in honor of them.

Lastly, I dedicate this manuscript to two other special individuals in Palisade, Colorado, Mr. Brent Goff and Ms. Kim Goff, who "adopted" me into their family over a decade and a half ago. Now, with this dissertation in their hands, they can imagine how much water might have flowed out of De Beque Canyon, when they look to the right as they get out of their driveway!

ACKNOWLEDGEMENTS

I thank my wife Hyun Ji O. Jeon for her support in every way. She agreed to enter into the covenant of marriage with me despite my shortcomings and though I had not established a career yet to provide well for my family. She has helped me finish my doctorate before hers and bore our first child Ephe growing in the womb now as I write this. I will relieve you of the duty after my defense and graduation because providing for our family is my duty till the end of our time in this world. Likewise, I would like to thank my parents and grandmother and honor them for being the channels of my life and being the nurturer of my life, and my sister Yeonkyung and my brother-in-law's family for being honest and faithful to keep me challenged and encouraged.

Aside from my family, I am most grateful to professor J. Rick Giardino for his unceasing encouragement, wisdom, guidance, and trust in me—not only for studies but also for life in general. I am exceptionally grateful for professor Andres Aslan for offering me time, guidance, field help, and, more than anything, tremendous insights on the geomorphology of the Grand Valley and Grand Mesa areas. I thank Kaytan Kelkar for enjoying talking with me about catastrophic processes including landslides and megafloods. I thank Adam Nawacki, my field aid and friend, who was always so eager to help out with the recon trip and the electrical resistivity tomography surveys. With the mention of ERT, I thank professor Mark Everett for suggesting the method for my study, and his graduate student J. Michael Martin who helped me learn the method. Also, I thank Dr. D.K. Lee in Seoul who remotely gave me useful lessons for dissertation in general and ERT interpretation in particular. Thanks go to professor Tammy Rittenour and her lab

colleagues at the Utah State University. Relatedly, I thank Colorado Scientific Society for generous funding that helped me not owe money to Luminescence Lab! I also thank Mr. Brad Brophy for allowing me to survey on his orchard. I sincerely thank professor Victor Baker for inspiring me in catastrophism. I thank M.O. and R. N. for their existence.

I am grateful also for those I have known since my time in Texas, including professor Moo-Hyun Kim (Civil/Ocean Engineering), Mr. Jaeman Lee, Mr. Bill Hoesch, professor Eui-Hyeok Yang, Dr. Choonghyun Lee, professor Heechen Cho, professor Robert Gustafson, Mr. Yohan Lee, James and Anna Ensley, pastor Jason Pickard’s family, pastor Titus Bagby’s family, pastor Randall Bard, and pastor Paul Hoemann, pastor Stephen Powell’s family, pastor Brent Bullard, pastor Hye-il Kim and Ms. Myungduk Oh, music professors Scott LaGraff (Voice), James and Abby Held (Voice and Oboe), Chris Kaatz (Band), Greg Grabowski (Conducting), Mr. Walt Hufford, Dr. Deogsang Bae, Mr. Shinwoo Ha, Dr. ‘John’ Han Park, Mr. Hayoun Jung, Dr. Dong Hyun Suh, CPT Jonathan Tsujimura, MAJ Troy Emery, Rachel Vining, and Mike Kappen. I had better thank the pseudonymous gentleman “Dr. Dino”. For sure, Dr. Jeff Fitzgerald and Dr. John T. Bryant for letting me work for and with them immediately after defending my dissertation.

I am grateful for the special friends and mentors since my time in South Carolina, starting with Dr. William H. Bates, Dr. Keith Cook and Ms. Elisabeth Cook, Bob and Tammy Kabakjian, pastor Joseph Park, pastor Luke Rhyee, Paul LeDuc, Dr. Eunseok Seo, John Burnett and Mary-Stewart Burnett, Dr. Durgesh Kumar, Joong-bae Kim, George Kim, Dr. Jessica Chassereau Sullivan, Jaehoon Choe, CPT Hyun-Jin Jang (Ret.), Mr. Glenn Wellsford and Ms. Wellsford, Mr. Ken Wingate and Ms. Cathy Wingate.

Furthermore, I am thankful for the friends and mentors since my time in Pennsylvania, including Justin Hughes (Marianna Hughes and the newly born Matthew), Matt Dodds, Ben Rupert, Dr. Jeremy Walter, professor Richard B. Alley (for mentoring me for my bachelor's thesis on glaciology), professor Eric Kirby for his geomorphology class, Robert Fuller my geomorphology TA who became a friend and a source of wisdom, Mr. Andy Cimbala and his father professor John Cimbala, Kyle and Mitch Kostreva, Mr. Anuj Christian, Dr. Boyi Gao, Dr. Jie 'Dan' Luo, Dr. D. C. Fialho, Mr. Tim Henderson, Rob Stitchick, Josh Gonzalez, Tim Sanville, Mike Staub, Joey Schweighardt, Lyndon Unger, Ryan and Shanna Modzelewski, and Mike Jonas.

Additionally, I thank the special individuals that entered my life since my time in and before Binghamton, New York, starting with Mr. David Mayner and Ms. Elizabeth Mayner, pastor Chris Tracey, Kevin Ozmon, Aleks Kalashnik, Mr. Eugene Bai, professor John Bridge and his wife, professors Rebecca Kissling, Joe Graney, and David Jenkins. They would be proud as they were when I thanked them when I ran into them at major conferences. Let me also thank Mr. Pil-sung Cho, Neal Morse, Matt Smith of Theocracy for their faith and music; Mike LePond of Symphony X for his political stance.

Lastly, the significant individuals I would like to conclude by thanking my family that adopted me and teachers and friends from my time in Colorado including Mr. Brent Goff and Ms. Kim Goff ("Brent-dad" and "Kim-mom") and their children Deanne, Jim, and Nikki; Ms. Stephanie Rush, pastor Jason McManus, Mr. Vogt, my dear friends from Palisade High School Cody Barley, David McManus, Dustin Marriott, and Isaac Taylor.

CONTRIBUTORS AND FUNDING SOURCES

The student completed all the research included in this dissertation, otherwise noted. The work was supported by Professor John R. Giardino (Chair), Professor John D. Vitek, Professor Mark E. Everett of Geology and Geophysics Department, Professor Kevin R. Gamache of the George Bush School of Government and Public Service at Texas A&M University, and Professor Andres Aslan of the Physical and Environmental Sciences Department at Colorado Mesa University.

This work was funded indirectly and partially by the Halbouty Scholarship of the Geology and Geophysics Department, the educational stipend received as a Repsol Student Award, and funded directly and partially by a research grant from the Colorado Scientific Society. The author had saved up and channeled his Army ROTC stipend and the income from the Army Reserve to further supplement the research. However, the author is solely responsible for the contents and conclusions of this dissertation, and do not necessarily represent the official views of the direct and indirect funding sources.

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CHAPTER I

INTRODUCTION

1.1 Introduction

Research during the last fifty years has suggested that the Colorado River terraces are entirely of fluvial origin (e.g., Sinnock, 1978; 1981a; 1981b; Cole and Sexton, 1981; Yeend, 1969; Cole and Young, 1983). Unfortunately, these studies lacked extensive assessment of the internal morphology of the terraces, age controls of the deposits, and a link to the climatic history of the region (Jarrin et al., 2017; Johnson et al., 2017; Aslan et al., 2019). To address terrace genesis, a geophysical instrument and a geochronological method were employed in this dissertation. The examination of the main river-terrace matrices using electrical resistivity methods identified the possible presence of boulders and cobbles as well as river gravels (all with high Ω-m) overlying the Mancos Shale (low Ω-m). Furthermore, I obtained numeric dates using optically stimulated luminescence method (OSL). The obtained luminescence ages for the terraces indicate multiple stages of glacial flooding (85–74 ka, 67 ka, 63–61 ka, and 58 ka) having occurred between Bull Lake (MIS 6) and Pinedale glaciations (MIS 2) of Grand Mesa.

The internal structures of the terraces suggest high discharges exceeding normal fluvial or seasonal flood processes. The timing of glacial flooding in the tributaries and the composition and structure of the terraces along the upper Colorado River suggest rapid deposition, followed by abandonment and incision within the past 100 ka. Thus, I suggest that these terraces, as well as terraces located in upper tributaries were all formed by glacial flooding as opposed to solely fluvial processes.

Fluvial terraces are abandoned floodplains situated along river valleys (e.g., Bucher, 1932; Schumm et al., 1987; Bull, 1990; Wegmann and Pazzaglia, 2002; Pan et al., 2003; Pazzaglia, 2013). Terrace genesis viewed from a strictly fluvial view is bimodal: erosional (strath) and depositional (fill) processes. The strath terraces in Grand Valley in the upper Colorado River Basin are accordingly interpreted as solely fluvial in origin. However, field observations of fill terraces in the vicinity causes one to question the fully fluvial explanation and ask: how did Grand Valley evolve? Is there an alternative explanation that accounts for the coexistence of both types of terraces? Data reported in this dissertation suggest that fluvial processes are inadequate for explaining terrace genesis and thus the geomorphic evolution of Grand Valley. The composition and subsurface morphologies of the terraces seems to indicate large amounts of energies and water were necessary for beveling of substrates and depositing large amounts of sediments—altogether beyond the abilities of fluvial processes. In this dissertation, I suggest that the series of terraces in the upper Colorado River basin are the result of glacial outwash floods from Grand Mesa as opposed to solely river flows.

1.2 Problem Statement

The main question raised in this dissertation is "How did Grand Valley evolve?" The commonly held view is that the Colorado and Gunnison rivers are solely responsible for the development of the respective terraces and Grand Valley (Sinnock, 1978; 1981a; 1981b; Aslan and Hanson, 2009; Aslan et al., 2009; Aslan et al., 2019). The view has been maintained for decades, though these studies seem to recognize that major modifications of the pre-Cenozoic landscapes require bedrock beveling, and rapid incision and abandonment of floodplains are necessary for terrace development. My dissertation research was driven by the question: is this the correct geomorphic interpretation? Rather than fully fluvial in its evolution, however, I suggest that multiple glacial outwashes from Grand Mesa played a substantial role in the development of the terraces, and thus, the current geomorphology of Grand Valley.

1.3 Goal and Objectives

The goal of this dissertation is to demonstrate that episodic meltwaters from Grand Mesa were a necessary driver of the geomorphic evolution in the Grand Mesa-Grand Valley system.

The main objectives are mainly two-fold:

- To establish chronology of sedimentary processes in the tributaries to the main channels of the Colorado and the Gunnison Rivers.
- To examine the internal structures of floodplains in Grand Valley, both modern and ancient (terraces), to distinguish diluvial (outwash-related) terraces from fluvial counterparts.

1.4 Outline of Dissertation

Following Chapter I: Introduction, Chapter II describes the location, general physiography, drainage basin, river profiles (longitudinal and cross-section), climate, vegetation, geological history (lithology and tectonics), and geomorphology. After the stage is set, the optically stimulated luminescence method (OSL) and electrical resistivity tomography (ERT) methods used for this investigation are discussed in Chapter III. The data and information from Chapter III and other published research data are presented in Chapter IV. An analytical discussion of the data along with interpretations are presented in Chapter V. In this chapter, a new hypothesis is proposed to explain the origin and evolution of the Grand Valley and Grand Mesa area. The concluding chapter, Chapter VI, summarizes and suggest and alternate process for the formation of terraces.

CHAPTER II

STUDY SITE

2.1 Location

The Grand Mesa–Grand Valley system investigated in this study is located in west-central Colorado, near the border with Utah (Figure 2.1). Grand Valley generally spans from Montrose, Colorado to Price, Utah, in the widest definition (e.g., Sinnock, 1978; 1981). However, the range of my study area includes the parts of Grand Valley that generally spans the main drainage system around Grand Mesa, the upper Colorado and the lower Gunnison Rivers, and downstream from their confluence to the Utah border. The upper Colorado River flows from the headwaters in the Rocky Mountains into the northeastern part of the Colorado Plateau. The Gunnison River likewise flows southwesterly, around Grand Mesa before joining the Colorado River in Grand Valley. The confluence of Colorado and Gunnison rivers occurs in the town of Grand Junction (N 39.090°, W 108.557°). The study area is in the Mesa and Delta Counties of Colorado. The landform system consists of the main part of Grand Valley bounded by the Uncompahgre Plateau in the west, the Book Cliffs in the north, and Grand Mesa in the east. The surface of Grand Valley is comprised primarily of two youngest fluvial terraces and the modern floodplain. Also, Grand Mesa and the Plateau and Surface Creeks in the flanks of Grand Mesa, which are two tributaries of the Colorado and Gunnison rivers, are the main subjects of this geomorphic investigation.

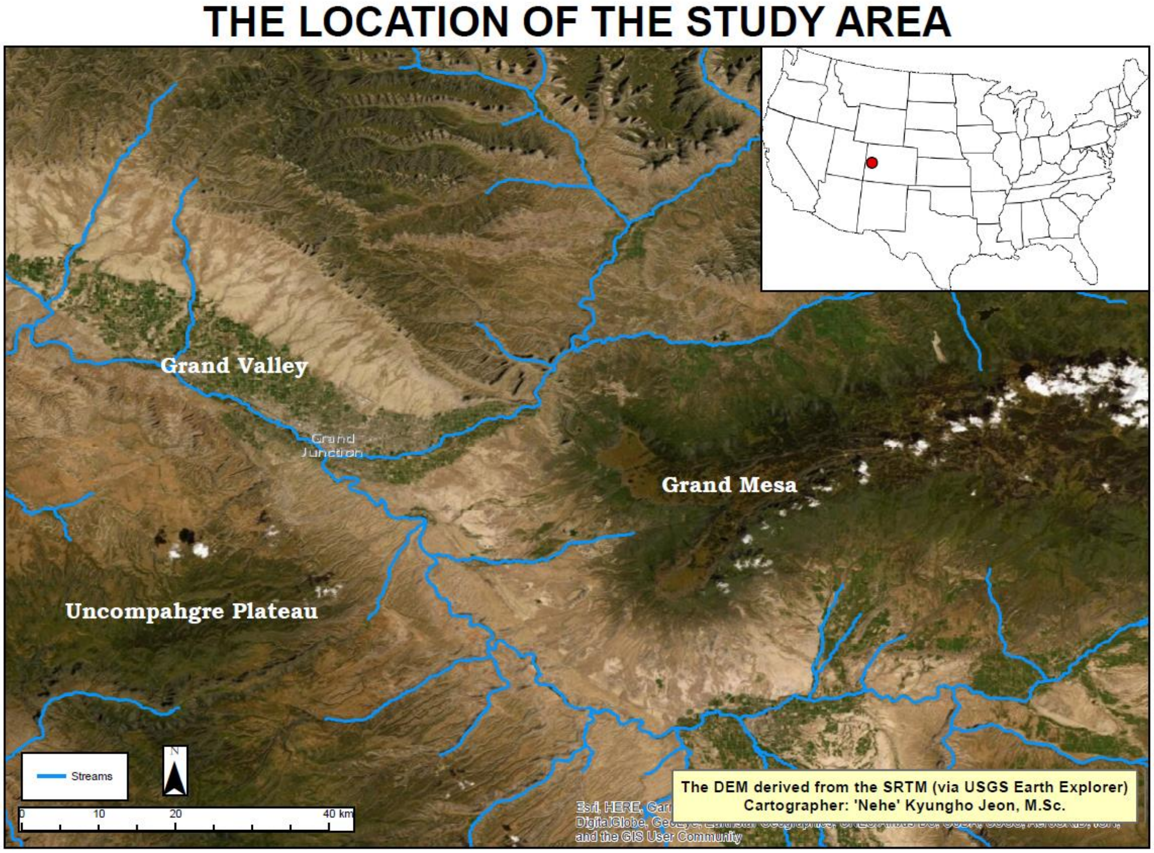


Figure 2.1 Map of the Study Area in Central-Western Colorado, U.S.A. Grand Valley and Grand Mesa.

2.2 General Merits of Characteristics

2.2.1 The Colorado Plateau

Grand Valley is located in the northeastern margin of the Colorado Plateau, which spans Colorado, Utah, Arizona, and New Mexico (e.g., Fillmore, 2011). The uplift of the Plateau is closely linked to the various sub-regional orogenies that gave rise to the Ancestral Rockies since the Pennsylvanian times (Kluth and Coney, 1981). The best-known geological feature on the Colorado Plateau is probably the Grand Canyon, with the sheer size testifying to the immense erosion in the Colorado River Basin during the uplifts of the Colorado Plateau in the Cenozoic (e.g., Pederson et al, 2002; Karlstrom et al., 2008; Ranney, 2011). During the Mesozoic, the uplift rate has been outpaced by sea-level rise that formed the Western Interior Seaway through much of the Colorado Plateau. In the Cenozoic, the Laramide orogeny continued the uplift of the Colorado Plateau. In the northeastern corner of the Colorado Plateau, the Uncompahgre Plateau was uplifted, which now forms the southwestern boundary of Grand Valley (Kluth and Coney, 1981).

2.2.2 The Uncompahgre Plateau and the San Juan Mountains

The Uncompahgre Plateau and the San Juan Mountains are notable topographic features in the Grand Valley region (as a subset of the Colorado Plateau; Sinnock, 1981b; Steven, 2002; Aslan et al. 2008; 2011; Sohregan et al., 2015, etc.). The uplifted regions were inundated during the Cretaceous, especially because of active tectonics in ocean basins raising the global sea level. This led to widespread deposition of marine sediments, including the Mancos Shale throughout the Four Corners states, including the Grand Valley areas (e.g., Noe, 2010; Filmore, 2011).

As the Laramide orogeny renewed the rising of the Colorado Plateau and the Rocky Mountains during the Cenozoic, the regions surrounding Grand Valley, other uplifts resumed for the Uncompahgre Plateau and the San Juan Mountains regions (e.g., Epis and Chapin, 1975; Steven, 2002; Stanley, 2009; Fillmore, 2011). The San Juan Mountains underwent extensive volcanism in the Tertiary times, and the Uncompahgre Plateau much canyon incision so as to attract investigators for historical reconstruction of the area, riddled with geomorphic interactions between tectonic and fluvial processes.

Ancient Colorado and/or Gunnison Rivers evidently have flowed through the Uncompahgre Plateau during its uplift, incising the Unaweep Canyon (e.g., Sinnock, 1978;

1981a; 1981b; Aslan et al. 2009; Soreghan, 2015, etc.). The channel flows have subsequently been diverted to the current courses, circumnavigating the Uncompahgre Plateau, with their confluence at Grand Junction, on their way farther downstream into Utah and to Grand Canyon.

2.2.3 The Book Cliffs

The Book Cliffs, which are 100–600 m high buttes marked by overall south-facing cliffs extending some 400 km from near Price, Utah, mark the northern periphery of Grand Valley (e.g. McCaroll, 2019). The eastern edge of the Cliffs coincides with the northeastern boundary of the Valley. Although the base of the Book Cliffs is composed of the highly erodible Mancos Shale, the tops are capped by erosion-resistant sandstones, such that lateral erosion dominates over vertical denudation (e.g., Schmidt, 1984; 1996; 2009; McCaroll, 2019; Glade, 2019). This erosional tendency is discussed in the latter part of this dissertation, alongside the implications of the main hypothesis on the geneses of terraces.

2.2.4 Grand Mesa and the Drainages

Located in the eastern part of Grand Valley, Grand Mesa is the largest flat-topped mountain in the world (e.g., Retzer, 1954; Yeend, 1969; Cole and Sexton, 1981). Grand Mesa is capped with Tertiary basalt, contemporaneous with the volcanism in the San Juan Mountains; much of it has been shed and eroded by debris flows and glacial floods (e.g., Baker et al., 2002; Brunk, 2010; Blakeley, 2014). Presumably, climate and precipitation have taken a significant role in the landform history. Transitions between glacial and interglacial times especially would pertain closely to geomorphic phenomena throughout the Cenozoic.

Together with the upper Colorado River, the Gunnison River and the tributaries serve as major storages and vehicles of sediments in the region. The Colorado River flows into the study area from the northeast, in the Rocky Mountains. The stream flows by the northwestern Grand Mesa, joined by the Plateau Creek. Likewise, the Gunnison River flows around the southern and southwestern flanks of Grand Mesa. The Gunnison River then merges with the upper Colorado River in Grand Valley. Nevertheless, upon exiting the study site, Colorado River then continues to flow into Utah and Arizona and through the Grand Canyon.

2.2.5 Summary

In summary, the prominent mountain ridges including Grand Mesa, the low-lying Grand Valley, and the drainage systems constitute a geomorphic system. The physiography of Grand Valley and the surrounding alpine landscape render a region for an interplay between lithology, climate, hydrology, and geomorphology through time. Fluctuating discharges in the stream channels in response to climate changes in the Quaternary times would have played important roles in geomorphic work. This study will shed light on the landform evolution, which may be applicable to modern settings in providing insights on disaster management, especially on alpine river flooding in light of the globally warming climate.

2.2.6 Literature Review

The geomorphic history of the Grand Valley and Grand Mesa areas, along with the Colorado and Gunnison Rivers received much attention over the past five decades (e.g., Sinnock, 1978; 1981a). Here, relevant works in the region dealing with geomorphology, geochronology, and climate are reviewed.

The Rocky Mountains were glaciated in the Pleistocene times (Pierce, 2003; Johnson et al., 2017). Moraines in high elevations such as the San Juan and the Elk Mountains have yielded numeric ages that are consistent with the glacial cycles of MIS 6 (Bull Lake, 200 ka–130 ka) and MIS 2 (Pinedale, 110 ka–12 ka; Ives, 1938; Gosse and Phillips, 2001). Multiple terraces are situated in Grand Valley (Sinnock, 1978; 1981a) and in nearby upland regions (Yeend, 1969; Cole and Young, 1983) that are presumably tied to the same glacial times. Others suggested that the Colorado, the Gunnison, and the Uncompahgre Rivers, have migrated incessantly across the valleys, never having been anchored to the present locations since the Cenozoic times (e.g., Sinnock, 1981b). The regions lacked the age control of glaciations except those inferred from features of glacial geomorphology; only recently have there been suggestions that outwash terraces near Grand Valley that are contemporaneous to those in Grand Valley (Jarrin et al., 2017; Aslan et al., 2019).

Most other studies of the region either dealt with adjacent landforms, pertained to longer time scales than the recent glaciations, and/or concerned particularly with the Cenozoic tectonics. Recent studies addressed the incision histories of the Black Canyon (e.g., Sandoval et al., 2011), the ancestral Colorado and Gunnison Rivers (e.g., Aslan et al., 2011), the Uncompahgre Plateau and the Unaweep Canyon inside it, along with the evolution of the drainage patterns in the region (e.g., Soreghan et al., 2015; Aslan et al., 2008; Lohman, 1981). However, that the incision rate estimates in these studies presume much longer time scales (~ 10 Ma) and are averaged over longer time periods (m/Ma) necessarily precludes acquiring age limits for the episodic glacial flooding events that would have occurred sporadically since ~ 200 ka (e.g. Aslan et al., 2019).

Sinnock (1978; 1981a; 1981b) addressed the geomorphic origin of Grand Valley in the Quaternary with a preliminarily fluvial scenario. Sinnock (1978; 1981a) surveyed the Uncompahgre Plateau, Grand Valley, and the associated rivers, identifying four sets of fluvial terraces and suggested that incisions resulted from gentle glacial outwashes between and after MIS 6 (Bull Lake) and MIS 2 (Pinedale) times. Presumably contemporaneous to those in Grand Valley, fluvial terraces have been recognized in the uplands of central Colorado (e.g., Nelson and Shroba, 1998) and in Utah (e.g., Richmond, 1962). Only recently have there been a few numeric ages assigned to the terraces in Grand Valley to link the timing to the processes (Aslan and Hanson, 2009; Aslan et al., 2019). Sinnock (1981b) hypothesized an evolutionary scenario of Grand Valley involving a complex interplay between the exhumation of the Uncompahgre Plateau and the channel-drainage evolutions, invoking fluidity of channel migrations across the landscape. Regrettably, the proposed scenarios involved a hypothetical timescale of 0.5 Ma, whereas numerical ages of younger features were unavailable. Furthermore, the internal structures of terraces were left uninvestigated for the purported channel behavior since the work of Sinnock (1978). Thus, the decades of research on the geomorphic evolution in the region left room for more definitive investigations of Grand Valley to test the historical framework, invoking post-orogenic (of the Uncompahgre Plateau) glaciofluvial events from Grand Mesa.

Accordingly, recent investigations of paleohydrology of alpine rivers around the world are relevant to this dissertation. There is an increasing importance of catastrophic processes in altering landforms drastically. For example, discharge events of low-frequency and high-magnitude, particularly glacial outburst floods, play an essential role in unusual channel processes and valley morphogenesis (e.g., Baker, 2013). Places around the world, including Asia (e.g., Baker et al., 1993; Montgomery et al., 2004; Reuther et al., 2006), Europe (e.g., Grosswald and Rudoy, 1996), as well as in the Appalachians (Kochel et al., 2009) and the Andes (Pacifici, 2009) are but a few exemplary places whose geomorphology have been influenced by glacial floods and outwashes.

Furthermore, this study relates to a global concern, because contemporary warming of the planet will lead to more frequent glacial and snowmelt flooding in mountains, and hence raising risks for alpine residents. The critical implications of the present study are highlighted in the latter part of this dissertation.

2.3 Elevation Ranges and the Sizes of the Area

The elevation ranges between Grand Valley and the surrounding ridges are drastic. Figure 2.2 shows the digital elevation model based on Shuttle Radar Topography Mission (SRTM) data. The highest elevation 4,372 m is located in Grand Mesa, shown in white, and the lowest point 1,318 m in black, along with the rest of Grand Valley in the west and northwest of Grand Mesa. The Grand Mesa and Grand Valley are two nearly flat terrains separated by an average elevation difference of 2000 m (for surface slopes, see Figure 2.19 in Section 2.6 below). The area of Grand Mesa is about 1,402 km^2 (346,555 acres, United States Forest Service, 2007), whereas Grand Valley along the Colorado River is around 1,200 km^2, or 1,500 km^2, if incorporating the areas of the Gunnison River course that circumvents the south and southwest of Grand Mesa. The vast, gently sloped areas of

Grand Mesa and Grand Valley are adjacent to each other and are connected by the drainages.

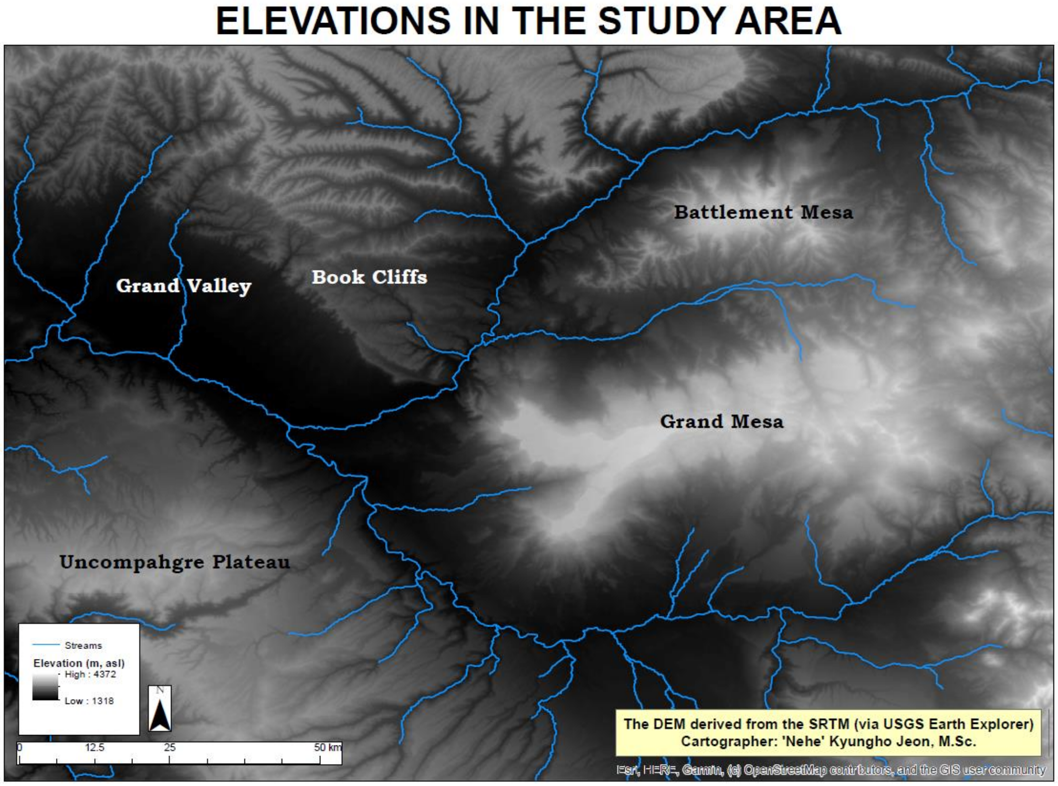


Figure 2.2 Elevations in the Study Area. The Elevations represented by the Digital Elevation Model (Shuttle Radar Topography Mission). Note Grand Valley, the Book Cliffs, Grand Mesa, Uncompahgre Plateau along with the main drainage patterns.

2.4 Drainage Basin

The drainage basin consists of a section of the upper Colorado River Basin, the lower Gunnison River and local tributaries to both rivers (Figure 2.3). The Colorado River flows into Grand Valley through the De Beque Canyon, generally trending southwest. The

Gunnison River generally flows west until it is joined by Uncompahgre River that flows northwest; downstream from the confluence, they continue northwest, passingby Grand Mesa in the northeast.

Of numerous side channels present in the study area, the Plateau, Kannah, and Surface Creeks are the three major side channels draining Grand Mesa. In particular, the Plateau Creek is a direct tributary to the Colorado River that drains the northern flank of Grand Mesa; and the Surface Creek, stemming from the southern flank of Grand Mesa, feeds into the Gunnison River. The last tributary, Kannah Creek, uninvestigated in this dissertation, drains the western flank of Grand Mesa.

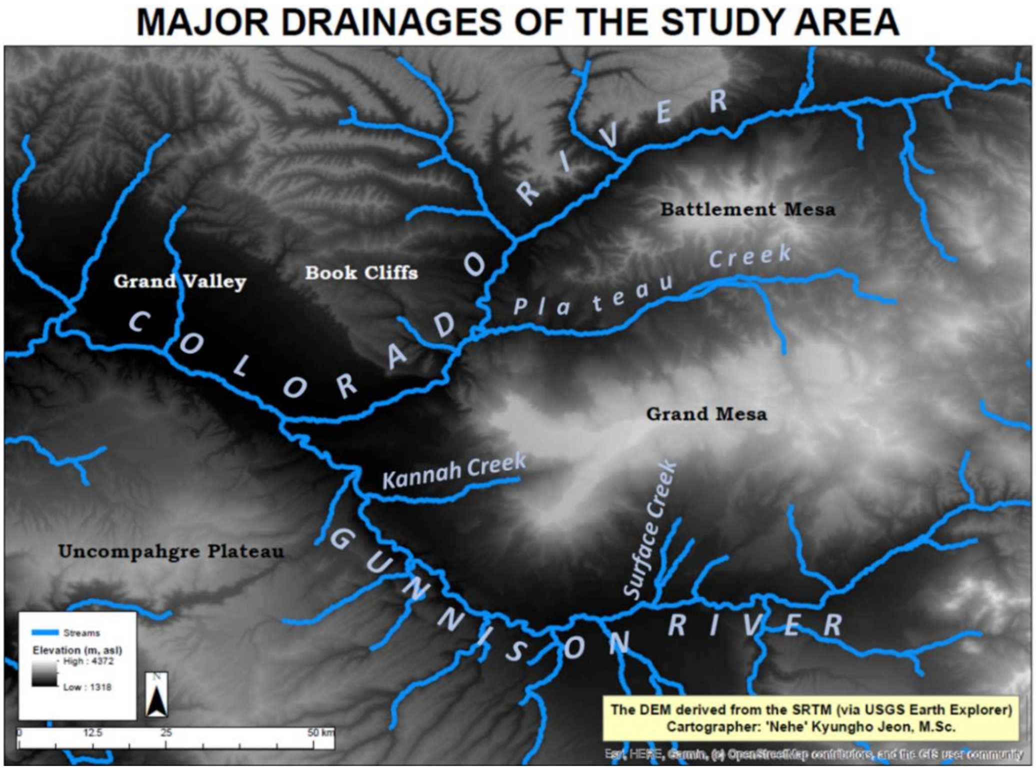
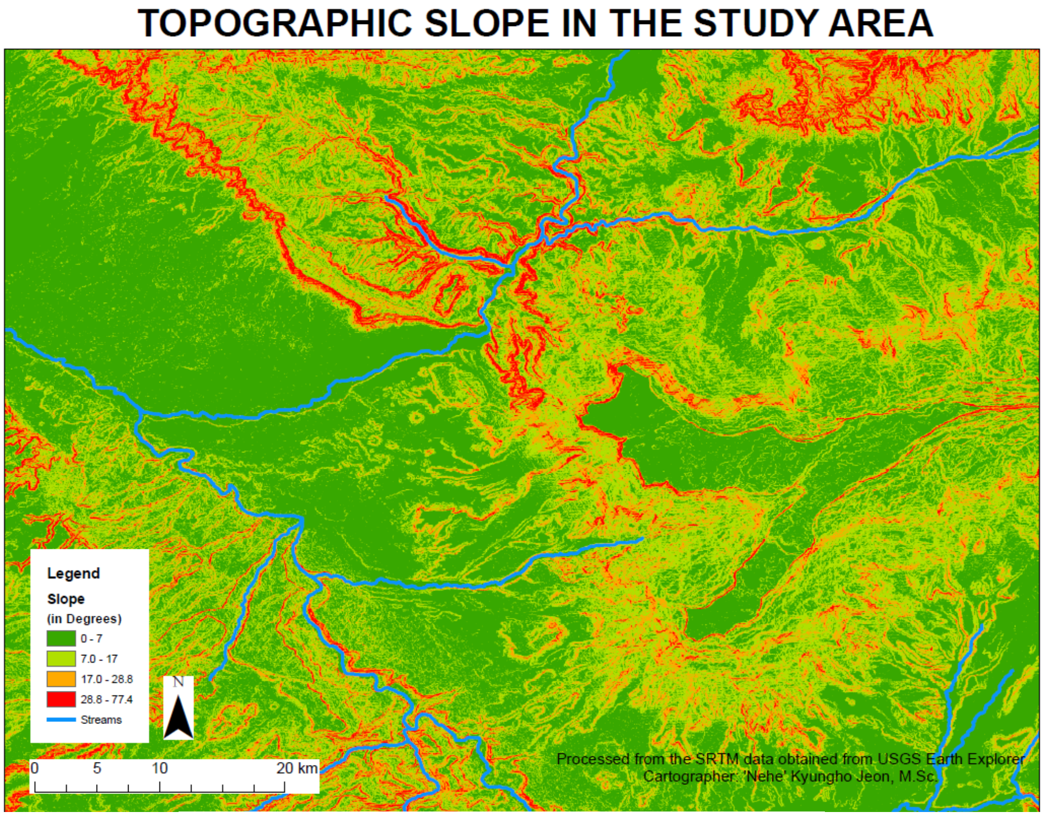


Figure 2.3 Major Drainages in the Study Area. The Colorado and the Gunnison Rivers, and side channels draining the study area. All side channels feed into the main stems of either of the rivers, and the Gunnison River merges with the former.

2.5 Topographic Slopes

As noted in discussion of Figure 2.1, the elevation difference between Grand Valley and the surrounding topography, especially that of Grand Mesa, is around 2,000 m. More notably, the variations in topographic gradient shows distinct features of the study area. The slope values appeared as four distinct lumps (Figure 2.4; from green, yellow, and orange to red, in increasing slope). Figure 2.4 shows low, generally flat terrains (Grand Valley and Grand Mesa) in green and some yellow, with relatively abrupt transitions between them and other valleys, represented as steep sides of mountains in red and orange. Although the Figure 2.1 showed a stark contrast between Grand Valley in the west and Grand Mesa in the east separated by sloped areas, the slope map presents both Valley and Mesa in the same legend element indicating that both terrains are nearly equal in sloping gently. Marked contrasts also are shown at the boundaries between the terrains with high slope values. Namely, the peripheries of Grand Mesa, and the promontories of the Book Cliffs immediately along the northeast of Grand Valley have slope values above 28° from the horizontal.



Processed from the SRTM data obtained from USGS Earth Explorer
Cartographer: 'Nehe' Kyungho Jeon, M.Sc.

Figure 2.4 Topographic Slopes in the Study Area.

2.6 Climate

Linked only by river channels and because the low-gradient terrains of both Grand Valley and Grand Mesa are separated by the stark elevation difference, the climate regimes for the two adjacent landforms correspond to the differences in elevation. The climate of Grand Mesa is sub-alpine, Dfc (snow; fully humid; cool summer) in Koppen classification (Kotteck et al., 2006). Based on data recorded from 1963 to 2016 (for precipitation, to 2012; at Bonham Reservoir on Grand Mesa) the annual temperature is -0.5° C (31.1° F) with maximum 6.4° C (43.5° F) and minimum -7.4° C (18.6° F), whereas the average precipitation is 833.1 mm (32.8 inches), with maximum and minimum 1135 mm (44.7 inches) and 642.6 mm (25.3 inches), respectively. A concise overview of mean annual precipitation in the Mesa County that includes the entirety of our study area (Figure 2.5) indicates that higher grounds including Grand Mesa receive substantially more precipitation than those of lower elevation including the Grand Valley area (Western Regional Climate Center, 2020).

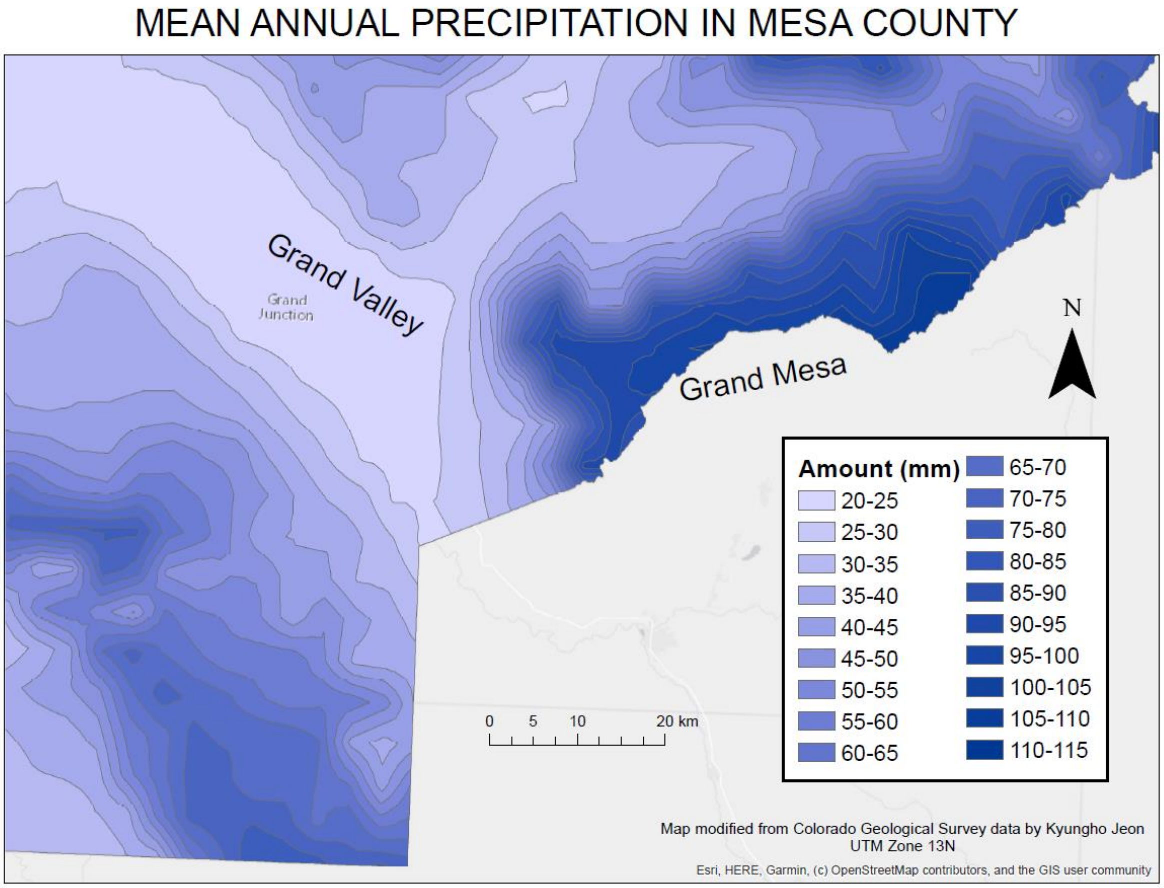


Figure 2.5 The Average Annual Precipitation Map of the Study Area. The dataset was obtained from Colorado Geological Survey.

The Grand Valley area corresponds to a warmer zone, being about 1,800 m below Grand Mesa. With the Köppen and Geiger classification BSk (that is, arid-steppe-cold arid), Grand Junction is climatically a local steppe (Kotteck et al., 2006). Based on records from between 1963 and 2016, the average annual temperature is 11.8°C (53.3 °F) with the annual minimum and maximum temperatures 4.7° C (40.5° F) and 18.9° C (66.1° F), respectively. From 1963 to 2012, the annual precipitation 223.5 mm (8.8 inches) and annual precipitation minimum and maximum 145 mm (5.7 inches) and 381.5 mm (15.0 inches; Western Regional Climate Center, 2020; US Climate Data, 2020).

2.7 Vegetation

The climate allows for the Grand Valley area, broadly encompassing Fruita, Grand Junction, and Palisade, to have the longest growing season in the state of Colorado (Robbins, 1910), rendering it the status of American Viticultural Area (CFR, 1991).

The overall vegetation of Mesa County consists broadly of six types (Lyon et al., 1996; Doyle et al., 2002). Generally, moving from higher to lower elevations (from Grand Mesa to Grand Valley) the following vegetative populations occur: 1) coniferous forests, 2) aspen forests; 3) mountain shrublands, 4) pinyon-juniper woodlands, 5) sage brush; 6) semi-desert shrublands. The last type characterizes the lowlands of the study site. Sadscale (*Atriplex confertifolia*), saltbush (*Atriplex* spp.), and greasewood (*Sarcobatus vermiculatus*) thrive in the dry climate and soil (Lyon et al., 1996; Doyle et al., 2002). Thus, vegetative distribution is consistent with the distribution of the precipitation amount around Mesa County, as discussed in Section 2.7.

2.8 Geology

The oldest rocks from pre-Cambrian through Paleozoic times are located primarily in the Uncompahgre Plateau area in the southwest, and younger Mesozoic units (the Mesaverde Group) sparsely in the southeast of Grand Valley and west of Grand Mesa, as well as more commonly in the upland regions, upstream from the De Beque Canyon in the north. Much of the Cenozoic rocks are distributed as volcanics composing the youngest sections of Grand Mesa, and spread throughout Grand Valley in the portion where the Colorado River flows through. The next section deals with the general stratigraphy in the chronological order in more detail.

2.8.1 Lithological Chronology

The preserved lithology in the study site span from pre-Cambrian to today (Figure 2.6; e.g. Scott et al., 2002). Remnants of early Proterozoic rocks exist as meta-igneous and meta-sedimentary rocks. In the Phanerozoic, an imperfect record of Paleozoic through Cenozoic times is represented in the study area.

With the Paleozoic rocks (543 Ma—248 Ma) essentially absent, the lithological history transitions abruptly from Proterozoic to the Triassic of Mesozoic. From the Mesozoic Era (248 Ma—65 Ma), the only Triassic rocks are from the Chinle Formation and the equivalent Dolores Formation exposed in the Uncompahgre Plateau area, particularly the Colorado National Monument (e.g., Fillmore, 2011). The lower to middle Jurassic Period is commonly represented by distinctively sandy units such as the Wingate Sandstone, Kayenta Formation, and Slick Rock Member, all of which likewise are exposed on the monoclinic ridge that consists the Colorado National Monument in the southwest of the map (Fillmore, 2011). The famous Morrison Formation of upper Jurassic, famous for its abundance of dinosaur remains is represented near the southwestern edge of the study area. The Cretaceous rocks representing the deep waters of the Western Interior Seaway, are Burro Canyon Formation, the Dakota Formation, and the Mancos Shale (e.g. Noe, 2010; Fillmore, 2011).

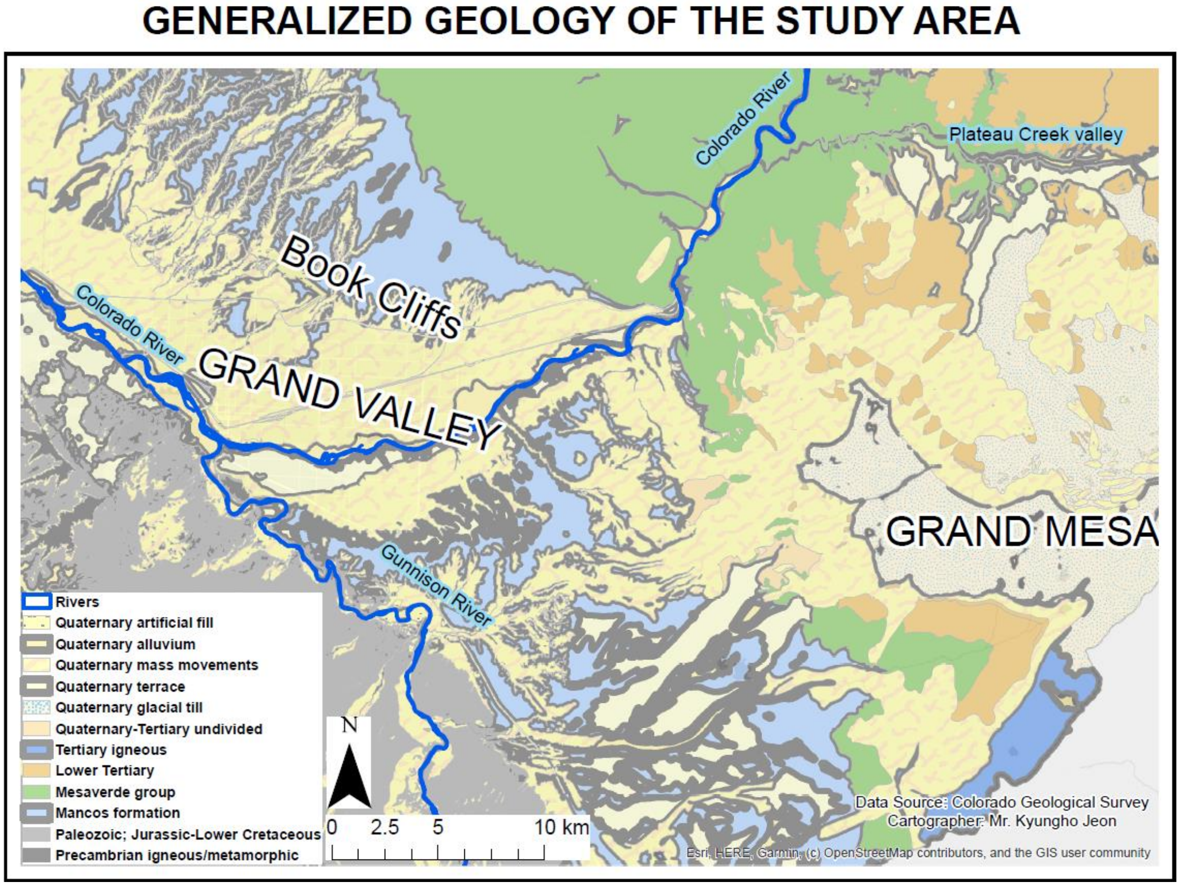


Figure 2.6 A Geologic Map of the Study Area.

The Mancos Shale by itself needs further elaboration for its significance in the regional geomorphology. The unit consists chiefly of dark-gray fissile shale that turns lighter when weathered (Scott et al., 2002). Marine fossils, especially trace fossils, are common, and although some volcanic ash and bentonite contents are also present. The expansive shale renders the unit highly erodible, especially by debris flows and landslides, as commonly observed on the Colorado River bluffs. The precise thickness of the unit throughout the study site is unknown, although it is usually bounded on top by unconsolidated sediments from the Cenozoic Era (Scott et al., 2002; cf. Carrara, 2000; 2001).

The Cenozoic times (66 Ma—today), largely divided into Tertiary (Paleogene and Neogene) and Quaternary (Pleistocene and Holocene) are characterized by much volcanism, glacial cycles, and fluvial activities in the region. The study area lacks any Tertiary volcanic rocks that originated in it, but they are introduced into the study site via Quaternary erosional processes, evidenced by the Colorado River gravels. Volcanism from Oligocene through Pliocene covered the San Juan Mountains 1-km thick (Bove et al., 2001; Blair et al., 1996).

Much alluvium comprises the Quaternary sediments in the study area. The provenance of the floodplain deposits is in the uplands including Grand Mesa, the San Juan Mountains, and the Elk Mountains. Significantly, the sedimentary compositions of the Pleistocene floodplains in the area inform us with regard to their provenance. Above the confluence, the Colorado River gravels consist mostly of basalt, quartzite, granite, and fine-grained mica-sandstones derived mostly from Grand Mesa, the side channels, and along the upstream Colorado River; downstream from the confluence, the alluvium includes some andesite and dacite that originate from other volcanic sources outside the study area, for which the Gunnison River was a conveyer of the sediments (Scott et al., 2002).

Finally, deposits from Holocene to modern times include various mass movement deposits on pediments surfaces, especially near the Book Cliffs (Whitney, 1981) as well as floodplain sediments of the Colorado and the Gunnison Rivers and side channels, and artificial fills (Scott et al., 2002).

2.8.2 Tectonics

Most of the tectonic activities relevant to the study area of this dissertation took place in three different eras in the geological history of the Colorado Plateau (e.g., Fillmore, 2011). The first major movements occurred in the Pennsylvanian period (upper half of the Carboniferous period) of the Paleozoic, although the majority of the Paleozoic rocks are absent in the study area. The Ancestral Rockies and the Uncompahgre Plateau were initially uplifted during this time (Kluth and Coney, 1981).

The second episode of massive tectonic activity took place during the Mesozoic. Particularly during the Cretaceous period, the sea level rose dramatically, upon opening up of the Western Interior Seaway, as evidenced by the widespread Mancos Shale throughout the four-corners states today (e.g., Noe, 2010).

The early Cenozoic times saw the majority of tectonic activity in the region, related particularly to the renewed and continued uplift of the Colorado Plateau and the Rocky Mountains during the Laramide Orogeny (Epis and Chapin, 1975; Fillmore, 2011). In a more local and temporal context, the uplifts since the Cretaceous continued through the Tertiary times, resulting in the San Juan Uplift, Gunnison Uplift, Grand Hogback, Sawatch

Uplift, along with further raising the Uncompahgre Plateau, which led to developments of monoclines of Colorado National Monument adjacent to Grand Valley (e.g., Steven, 2002). The Uncompahgre Plateau and the Tertiary volcanism discussed previously have attracted numerous researchers for tectonics and geomorphology as well as the Quaternary geology in general.

2.8.3 Glaciation

As the volcanic and tectonic activities in the Tertiary times resulted in higher peaks and plateaus of the Rocky Mountains, the region became subject to glaciations (e.g. Pierce, 2003). Glaciation in the western Colorado in general took place in the San Juan Mountains, the La Sal Mountains (Atwood and Mather, 1932; Richmond, 1954; 1962; Mather and Wengerd, 1965), arguably the Uncompahgre Plateau (Cole and Young, 1984), and Grand Mesa (e.g., Retzer, 1954; Yeend, 1969; Cole and Sexton, 1981). At least three glacial times have been inferred by the presence of tills in the uplands and outwash terraces down-glaciers—loosely, pre-Bull Lake, Bull Lake, and Pinedale (Yeend, 1969; Richmond, 1954; Sinnock, 1981). However, MIS 4/3 and MIS 2 have lately been suggested to be more prominent glacial times in the region (Jarrin et al., 2017; Johnson et al., 2017)

2.8.4 Geomorphology

The evolution of landforms in the study area during the Quaternary times are an interplay between the lithospheric, atmospheric, and various Earth surface processes. The resumed uplift of the Uncompahgre Plateau, various Tertiary volcanisms gave rise to landscapes to be storages of geomorphic agents and subjects to erosion. For example, the plateaus, mesas, and peaks would serve as storages and channels for glaciers during glacial times; and transitioning into interglacial times, meltwaters feeding streams, other fluvial and mass movement processes served as prominent agents of landform evolution. Of particular interest for geomorphic investigations concerns with the interactions between the regional tectonics (the uplift of the Uncompahgre Plateau in the context of the Colorado Plateau) and the evolutions of the channels and drainages (the Colorado, the Gunnison and the Uncompahgre Rivers). Figure 2.7 shows the outcrop that exemplifies the Mancos Shale eroded and overlain by gravels from an ancient Colorado River, and the modern Colorado River channel that flows next to the outcrop.

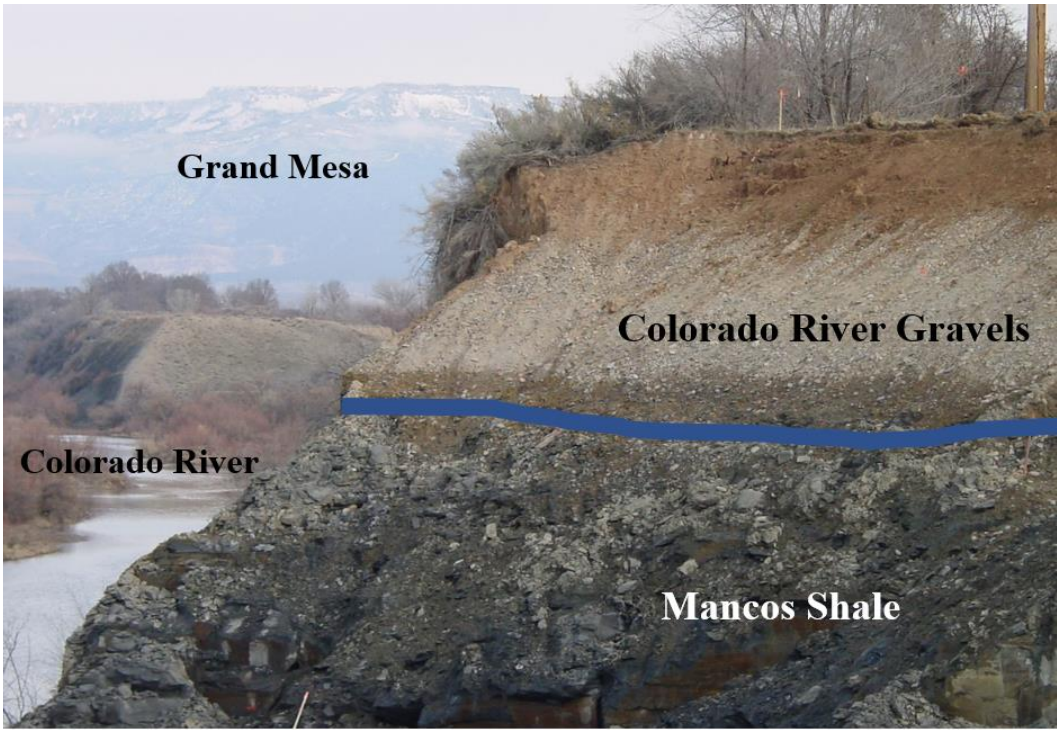


Figure 2.7 An Outcrop of the Mancos Shale and the Colorado River Gravels. The mountain in the back is Grand Mesa. Note the wooden pole on the top of the terrace for scale. Photo courtesy of A. Aslan.

Grand Mesa has been glaciated and eroded by subsequent events (Yeend, 1969). Tills, pediments, and terraces have been identified in associated glacial and fluvial conduits in Grand Valley, Uncompahgre Plateau, and the adjacent areas (Sinnock, 1978; 1981a; 1981b; Cole and Young 1983; Jarrin et al., 2017) have been surveyed for pediments, terraces, channel incisions, diversions. Various transportive processes such as glacial and fluvial activities, and mass movements, oscillatory geomorphic phenomena as counter forces, eroded the landscapes.

2.8.5 Glaciation of Grand Mesa

Central to the hypothesis of this dissertation involves icecaps on Grand Mesa in the Pleistocene and the geomorphic processes related to melting of the glaciers. Multiple glaciations covered parts and entirety of Grand Mesa at various times (Henderson, 1923; Retzer, 1954; Yeend, 1969; Cole and Sexton, 1981). Bull Lake glaciation lasted from 140 ka to 70 ka, and Pinedale from 30 ka to 12 ka. Four sets of tills are identified in the Grand Mesa and its immediate surroundings (Yeend, 1969). Tills predating Bull Lake are confined to the Chalk Mountain in the east of Grand Mesa; those from Bull Lake are distributed on the western end of Grand Mesa (Land’s End Formation). Lastly two sets of Pinedale-age tills (Grand Mesa Formation) are found widely, including in the side channels on the flanks of Grand Mesa, and in the adjacent towns of Collbran and Mesa. Although numeric ages of tills in the Grand Mesa area are absent, and even generally for the Rocky Mountains region, few numeric dates for Bull Lake or pre Bull Lake tills, there now exist firmly established the dates of the Pinedale (MIS 2) glaciation general Rocky Mountain areas (Benson et al., 2005; Brugger, 2007; Jarrin et al., 2017). The extents of the glaciers were conservatively estimated in this study, as demonstrated in the subsequent sections.

CHAPTER III

METHODS

3.1 Introduction

My geomorphic investigation in the tributary valleys of Grand Mesa (the Plateau and Surface Creeks) and the main channel floodplains in Grand Valley involved geospatial analyses, sedimentology, geochronology, and geophysics, as an overview is provided in the following.

The geospatial analyses were twofold, related to the river channels and an estimation of glaciation of the Grand Mesa area. First, the river profiles of the Colorado and the Gunnison Rivers were extracted using the SRTM Digital Elevation Model. Both longitudinal profiles and cross-sectional profiles were extracted to assess the river channels and respective valleys in the Grand Valley area. Second, the extents and volume of glaciers on Grand Mesa and Battlement Mesa were estimated using the same DEM dataset. Recently published and unpublished surface geologic maps were used to locate glacial deposits on top of Grand Mesa, and infer the areal extents of the glaciers, and thereby estimating the volume of the glaciers (White, 2018; White and Palkovic, 2019; Chesnutt et al., 2019).

As for on-site field surveys were concerned, three field trips were taken for three methods of data collection. First, dimensional measurements were made of glacial flood and debris flow sediments bearing basalt clasts from Grand Mesa to confirm the previous work by others (Yeend, 1969; Cole and Sexton, 1981; Brunk, 2010; Noe and Zawaski, 2013). The survey sites were chosen to complement other studies conducted in the higher up-valley regions and the southern flank of Grand Mesa. Relatedly, given that few studies sparsely reported numeric control of ages in the genetically related areas, optically stimulated luminescence (OSL) method was then employed for age estimations of the deposits in the Plateau and the Surface Creek valleys. Lastly, a 2D subsurface imaging of modern and ancient floodplains in Grand Valley was conducted using the electrical resistivity method (ERT). This survey was conducted to explore the internal matrices of the terraces and a modern floodplain, in search of clues for the genesis of strath terraces in Grand Valley.

The justification for each method, along with the principle and theoretical basis, is given in more detail in this chapter.

3.2 River Profiles

The Colorado and the Gunnison River were assessed using the Digital Elevation Model (DEM) derived from the Shuttle Radar Topography Mission. Long profiles and cross-sectional profiles of both rivers were extracted, and significant morphological changes along and across the channels were observed. The Colorado River profile is a stretch of about 49 km from the immediately upstream from the Plateau Creek confluence, espousing Grand Mesa, to the Grand Junction where the confluence with the Gunnison River is located. For the longitudinal profile of the Gunnison River, a longer river-distance was analyzed because of the larger distance between the Surface Creek confluence and the Colorado River confluence. A channel length of 97 km was surveyed. As for cross sections, six (6) cross sections were analyzed along the Colorado River course, and eight (8) along the Gunnison River, totaling fourteen (14) cross sections.

3.3 Estimating the Glaciers on Grand Mesa

The glacio-diluvial hypothesis for the evolution of Grand Valley is naturally linked to the availability and feasibility of the volumes of water that would have been locked in Grand Mesa. An observation of available surficial geologic maps of Mesa Lakes, Hells Kitchen, and Lands End (White, 2018; Chesnutt et al., 2019; White and Palkovic, 2019) indicate that moraines and lakes co-occur on the surface of Grand Mesa. Although a few lakes are artificial, they are thought to be drained natural lakes that originated from previous glaciations. Thus, the vertical locations of lakes were used to infer the extents of the glaciers, which was then used to estimate the volume of the ice.

Two estimates were made for the glacial extents and volumes. A conservative estimate of glacial extent was made from the lakes of the Pinedale glaciation indicated by the positions of end moraines. A relatively more realistic estimate of glacial extents was made using the lakes that pre-date the Pinedale glacial times, namely those proposed in this dissertation and those of the Bull Lake times indicated by White (2018), Chesnutt et al. (2019), and White and Palkovic (2019). The maximum extents of the glacial ice had been suggested to be beyond the cliffs of the modern Grand Mesa and in the Plateau Creek Valley (Henderson, 1923; Yeend, 1969). Unfortunately, although the concept is feasible, the actual locations of the glaciations are absent in the region, rendering the analysis impossible. Thus, in this dissertation, a conservative estimate based on the Pinedale moraine positions, and a realistic estimate determined from the presence of tills from the pre-Pinedale glaciations.

3.4 Basalt clasts on flanks of Grand Mesa

The first field survey was a field observation of basalt clasts that occur in the northern flank of Grand Mesa. The Plateau Creek valley, a tributary to the Colorado River, is the northern counterpart of erosional and sedimentary archive of the southern flank of Grand Mesa. This field survey was conducted to extend the investigations by others (Yeend, 1969; Baker et al., 2002; Brunk et al., 2009; Brunk, 2010; Blakeley and Giardino, 2013; Blakeley, 2014); whereas Brunk (2010) and Blakeley (2014) studied the glacial flood deposits in the Surface Creek valley in the southern flank of Grand Mesa, I examined the Plateau Creek valley in the northern flank of Grand Mesa. Significantly, glacial flooding and debris flows prevalent in the slopes and foothills of Grand Mesa (Brunk, 2010; Blakeley, 2014) show striking resemblance in sedimentology and stratigraphy to the modern and ancient glacial flooding events reported by others (e.g., Benvenuti and Martini, 2002; Russell and Knudsen, 2002; Blair, 2002).

Located in the Plateau Creek valley, adjacent to Colorado State Highway 65, a wall of basalt clasts crops out (Figure 3.1). A total of thirty (30) clasts were measured over a hundred meters along the outcrop. The concise survey of the northern flanks of Grand Mesa involved a use of a tape measurer and the Bruton compass for strikes and dips of imbricated basalt clasts (Jeon et al., 2018). The use of tape measurer was to ensure the interval of clast selection horizontally along the outcrop. The Bruton compass reading for the dips of the clasts was for a proxy of imbrication, by assigning numbers.

Figure 3.1 A Basalt Clast Outcrop in the Northern Flank of Grand Mesa.

3.5 The OSL dating for Fill Terraces

3.5.1 The Principle

Optically stimulated luminescence (OSL) method is used for dating the time of burial, by estimating the last time when the minerals such as quartz were exposed to light (cf. in case of thermo-luminescence method, heat, instead of light; e.g., Rittenour, 2008; Preusser et al., 2009; Rhodes, 2011). In principle, naturally ionizing radiation from the environment (e.g., K, U, Th, and Rb) and cosmic rays builds latent luminescence inside defects of crystal lattices of quartz minerals as electrons (e.g., Prescott and Hutton, 1994). Sediments are sampled in a gingerly manner such that the subject is protected from exposure to light until in a meticulous laboratory setting. In a darkroom lab, the latent luminescence can be stimulated and measured precisely to compute the time elapsed since the burial of the sediment, with respect to the environmental dose rate and burial duration.

The main caveat is that because the luminescence signal can be reset ("bleached") when exposed to any light, heat, or even high pressure, causing the emission of the latent luminescence, unknown and uncontrolled setting may give rise to highly inaccurate age estimates. For instance, a scatter in age estimates may indicate that erosion and sedimentation processes were complex (Rittenour, 2008). The method has been widely used, and the popularity among Quaternary researchers has increased much recently partly because of the capability to estimate from decades and up to hundreds of millennia (Rhodes, 2011; Rittenour, 2018).

3.5.2 Sample Collection and Processing

Sand-containing sediments to be dated were acquired using metal tubes hit into the walls of gravel-pit outcrops. The tube was hammered horizontally into a subject sedimentary layer, then the surrounding of the inserted tube was carefully delved into and the tube pulled out; and lastly both ends of the tube were covered to protect the sediments in the tube from light until laboratory analysis. Analyses of seven (7) collected samples were conducted at the Utah State University Luminescence Laboratory. The sample processing involved opening in a "dark room," under a dim amber safelight setting. Upon opening, the sample on both ends of the tube was discarded, and only the inner mid-section of the sample was meticulously kept for further processing. The procured sample was subjected to 1) sieving, 2) HCl and bleach treatments, 3) heavy mineral separation (at 2.72 g/cm^3), and 4) acid treatments with HCl and HF to separate and isolate a narrow grain-size range (typically 90-150 μm). At the end of the sample preparation, to ensure the purity of the quartz sample, infrared stimulation is used for detecting feldspar, and for removing it afterwards, if necessary.

The luminescence measurements were made on a luminescence detector, and the Single Aliquot Regenerative dose method (SAR) was used for the equivalent dose calculation (Murray and Wintle, 2000; 2003; Wintle and Murray, 2006). Following the SAR protocol, tests for sensitivity correction and brackets the equivalent dose (D_E) the sediment received during the burial condition by irradiating the sample at five different doses (that is, above, at, and below the D_E; a zero dose, and a repeated dose) to check for sensitivity correction and recuperation of the latent luminescence). Then, in accordance with the Central Age Model (CAM), the resulting numbers are fit with a saturating exponential curve (Galbraith and Roberts, 2012). The final OSL age with 2 σ standard error was calculated by dividing the D_E (in grays, gy) by the environmental dose rate (gy/ka) that the sampled sediment has been exposed to before excavation.

3.5.3 Calculation from Dose-Rate

Radiations from the radioisotopes and cosmic rays were calculated as dose-rates. Chemical analysis of the potassium (K), uranium (U), thorium (Th), and Rubidium (Rb) contents was carried out using inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma atomic emission spectrometry (ICP-AES) and in accordance with conversion factors provided in Guerin et al. (2011). To calculate the amounts of cosmic rays contributed to the dose rate, the precise location of the samples originated was to be accounted for, namely, the burial and excavation depth, elevation, and the latitude and longitude in accordance with Prescott and Hutton (1994). Lastly, the water content of the ambient sediment was taken into account for each sample for dose rate calculation (Aitken and Xie, 1990; Aitken, 1998).

3.6 Electrical Resistivity Survey of the Floodplains in Grand Valley

Electrical resistivity tomography (ERT) is a non-invasive geophysical method to image subsurface. The purpose of the technique was to characterize and assess the internal morphology of floodplains in Grand Valley, both ancient and modern, because resistivity contrast in a transect can serve as proxies for composition. In practice, higher resistivity corresponds to coarse grained sediments, i.e. sand and gravel, whereas lower resistivity to groundwater and finer-grained sediments such as shale, and rock fractures and faults (e.g., Lucius et al., 2007; Chambers et al., 2011; 2012; Everett, 2013) Thus, ERT method was used to determine the thickness of the sandy-gravely alluvium that constitute modern and ancient floodplains.

3.6.1 The Principles and Limitations of Electrical Resistivity—the Dipole-Dipole Method

Electrical resistivity is defined as the unique material property that resists the electrical current flow (e.g., Everett, 2013; Reynolds, 2011; Sheriff, 1991; Palacky, 1987). Resistivity (ρ, in ohm-m) is a ratio of voltage measured and current transmitted, and is therefore an intrinsic value of substance under investigation. Resistivity is not to be confused with resistance; resistance (R, in ohms) varies with the amount of electrical current input, thickness and length of the media, among other factors. Because electrical resistivity is intrinsic to the material under consideration, its variation based on composition is exploited for subsurface imaging, namely, a floodplain with unexposed sides.

Geologic materials in floodplains have notably different resistivities, for the benefit of the ERT method; dry sand and gravel typically have resistivity of > 200 ohm-m, and clay, mud, and shale 5 to 50 ohm-m (e.g., Chambers et al., 2011; Reynolds, 2011; Lucius, 2007; Sheriff 1991; Palacky 1987). The stratigraphic materials that pertain to floodplains in Grand Valley are mostly sand, gravels (including clasts of igneous origin), shale, and groundwater. Much of the gravely matrices seen in river terrace outcrops is igneous rocks, which can have resistivity of >1,000 ohm-m (e.g., Reynolds, 2011; Palacky, 1987). The Mancos Shale is known to have < 13 ohm-m in a borehole near the study site (Ball et al., 2010), although the resistivity survey is less likely to be of the same accuracy.

Several caveats are considered for most accurate rendition of the stratigraphy of terraces. Water is conducive to electrical currents, for which groundwater presence is the main culprit for obfuscating the shale-gravel boundaries. When saturated, resistivities for sand and gravel can be < 50 ohm-m. Thus, the regional groundwater level distribution is mapped by interpolation from known well locations (Figure 3.2), which is further taken into consideration in the presentation of the data in Chapter IV.

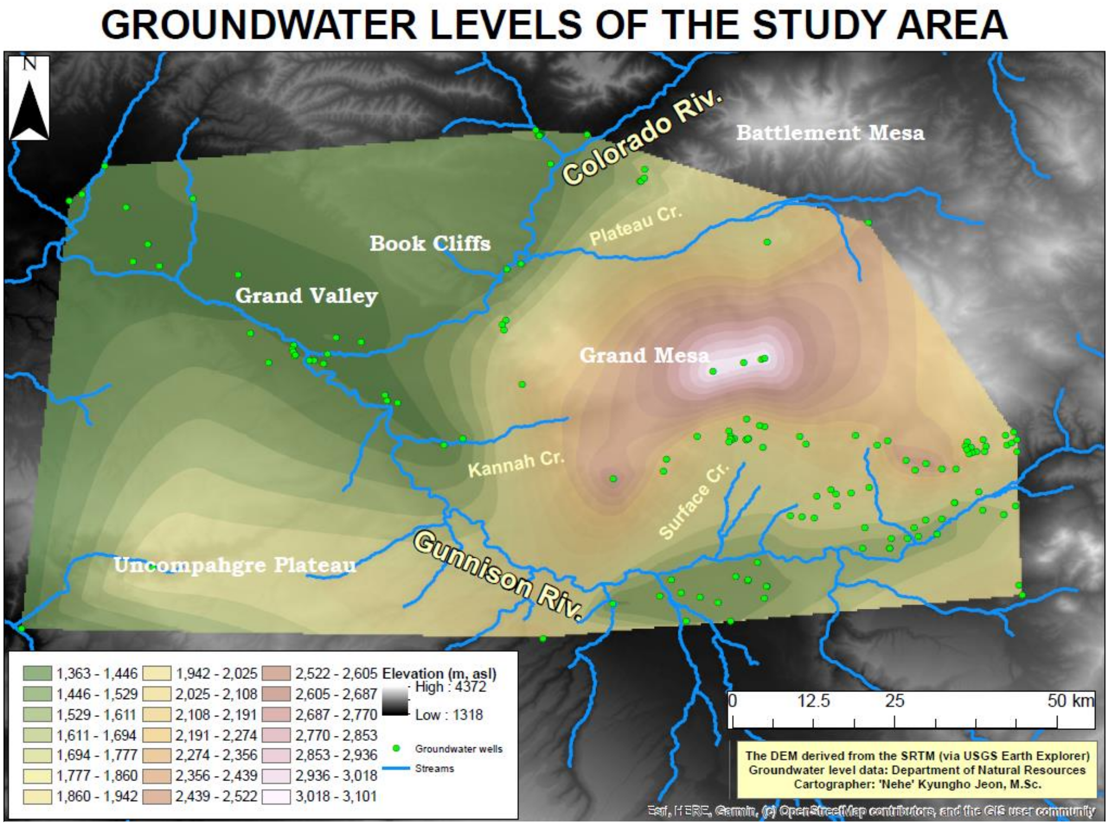


Figure 3.2 Groundwater Levels in the Study Site.

Not only the presence of water, but geological structures such as fractures and faults, and amounts of weathering or chemical alteration may lower resistivities of the material also (e.g. Reynolds, 2011). Because electric current seeks easier paths to travel, other electrical sources or media, such as power lines and metal fences, which have lower resistivities, may yield erroneous results. Potential errors and mischaracterization of floodplains is possible, as any other indirect method. Thus, these physical concerns are addressed in the interpretation of each of the five transects.

Figure 3.3 A Field Setup of a Dipole-Dipole Survey of ERT.

Among various survey arrays available, the most commonly used ‘dipole-dipole’ method was employed for the surveys. For instance, whereas the Schlumberger array is optimal for high resolution for depths and limited laterally, and the Wenner vice versa, the dipole-dipole array merges the capacities of the former two configurations in yielding relatively high resolution laterally and vertically (e.g. Everett, 2013). Nevertheless, for the dipole-dipole array, the more electrodes employed (for lateral extent), the lower the resolution becomes for depth. Also, the resolution is highest on the surface, decreasing with depth.

3.6.2 Equipment and Settings

The SuperSting R8/IP (induced polarity meter) console of Advanced Geosciences, Inc. (AGI) was used for ERT subsurface scanning surveys (Figures 3.3; 3.4). For each a straight horizontal transect, fifty-six (56) electrodes (stainless steel poles) were inserted into the ground with a hammer at the spacing of 1 m. The electrode spacing corresponds to a horizontal distance profile of fifty-five (55) m and a depth of about 10 m (a fifth of the distance). Cables were then attached each electrode, using alligator clips, linking all electrodes and forming a transect. A 12-volt marine battery in the deep cycle mode was used for power.

The collected datasets of apparent resistivity were converted to inverted resistivity (pseudosection) using the numerical inversion feature of AGI EarthImager 2D software on the Panasonic Toughbook in the field. The resultant cross-sections of resistivity were processed further using DiPro for inversion, forward modeling, smoothing, and excising out noises (e.g., Kwon et al., 2002; Kim et al., 2004; Kwon et al., 2004). The final products from the processing are wide-ranging resistivities of subsurface material of cross sections of the fifty-five (55) m distance with up to 10-11 m depth. The range of resistivity values for each of the five transects was set in such a way that makes possible lucid interpretation of composition.

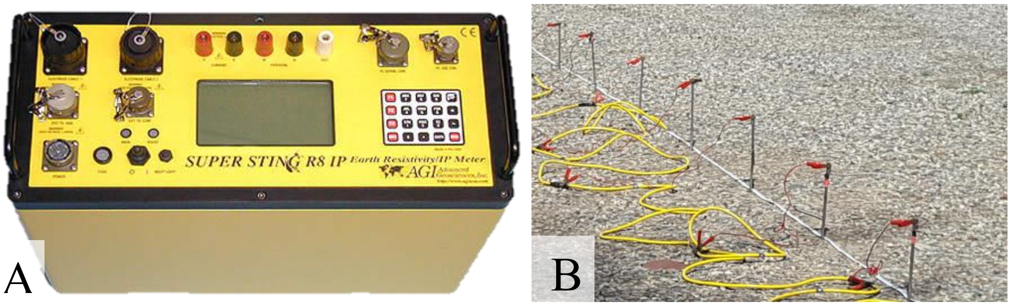


Figure 3.4 A Field Setting of the ERT Equipment. A. AGI SuperSting console. B. The inserted electrodes and yellow cable linking the electrodes with alligator clips. The white measuring tape is set on the transect prior to electrode insertion.

CHAPTER IV

DATA

4.1 River Profiles

Long profiles and cross-sectional profiles of the Colorado and the Gunnison Rivers show particular physiographic features in the area (Figure 4.1). A long profile of 49 km from the upper Colorado River and another of ~ 97 km for the lower Gunnison River were generated from the digital elevation model (DEM, Figure 2.2). A total of fourteen (14) cross section transects were extracted from the DEM, consisting of six (6) Colorado River transects and eight (8) Gunnison River transects.

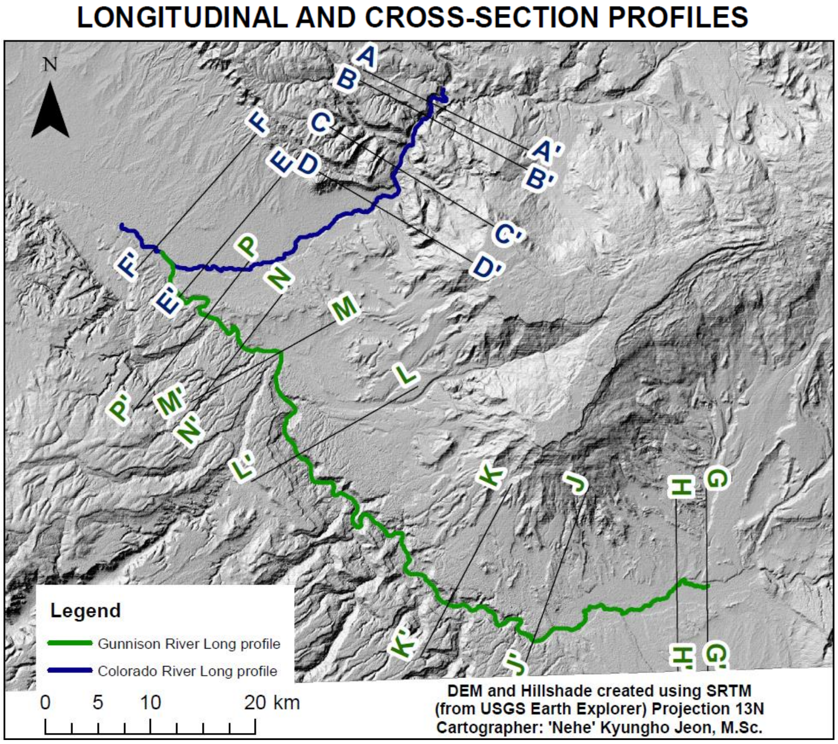


Figure 4.1 Map of the Profiles of the Colorado and the Gunnison Rivers

4.1.1 Long Profiles – the Upper Colorado River

The pertinent sections of the Colorado and Gunnison Rivers are represented in Figures 4.1 and 4.2. Along the 49,000 m-channel, the longitudinal profile of the Colorado River exhibits three major changes (Figure 4.2) in slope, co-occurring with the confluences of tributaries and abrupt widening. The first and third gradient changes along the profile occur at 2,500 m and 41,000 m, which correspond to the confluences with the Plateau Creek and the Gunnison River, respectively. The second gradient change of the three occurs around 12,500 m at the De Beque Canyon mouth, at which the riverbed abruptly steepens and widens as the Colorado River enters Grand Valley. These and other channel trends are noted in the discussion on cross-section transects.

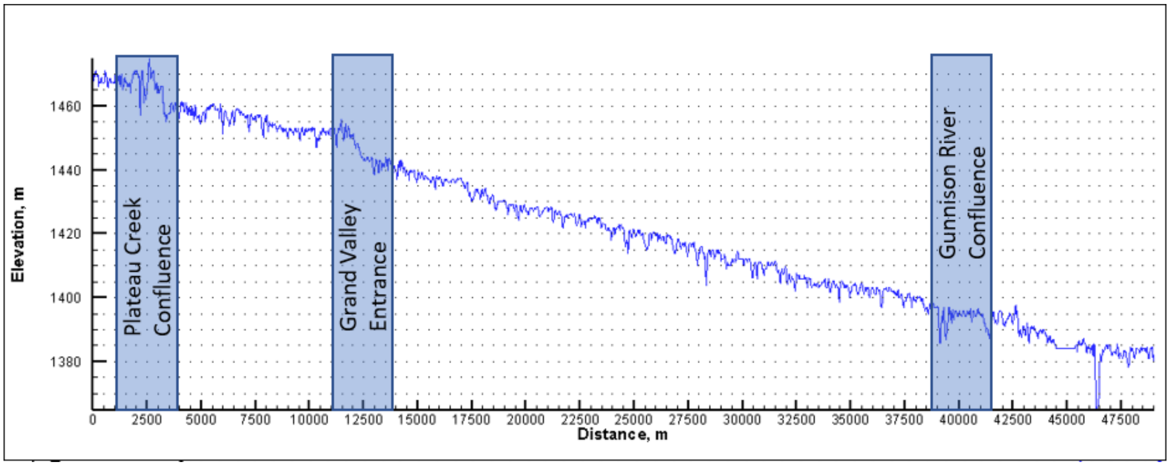


Figure 4.2 The Upper Colorado River Long Profile. It spans from the Plateau Creek confluence to the Gunnison River confluence.

4.1.2 Cross-Sectional Profiles – the Upper Colorado River

The six (6) cross-section profiles of Colorado River were extracted from the highlighted locales of relatively abrupt gradient changes. The six profiles constitute three pairs at the upper, middle, and lower sites, with each pair being 1,500 m, 5,500 m, and 5,600 m apart, respectively. All the profiles were obtained from left bank side to the right, facing upstream. For consistent comparison, the extracted horizontal distance of each profile is set around 18,500 m, and elevation range fixed between 1,350 m and 3,050 m.

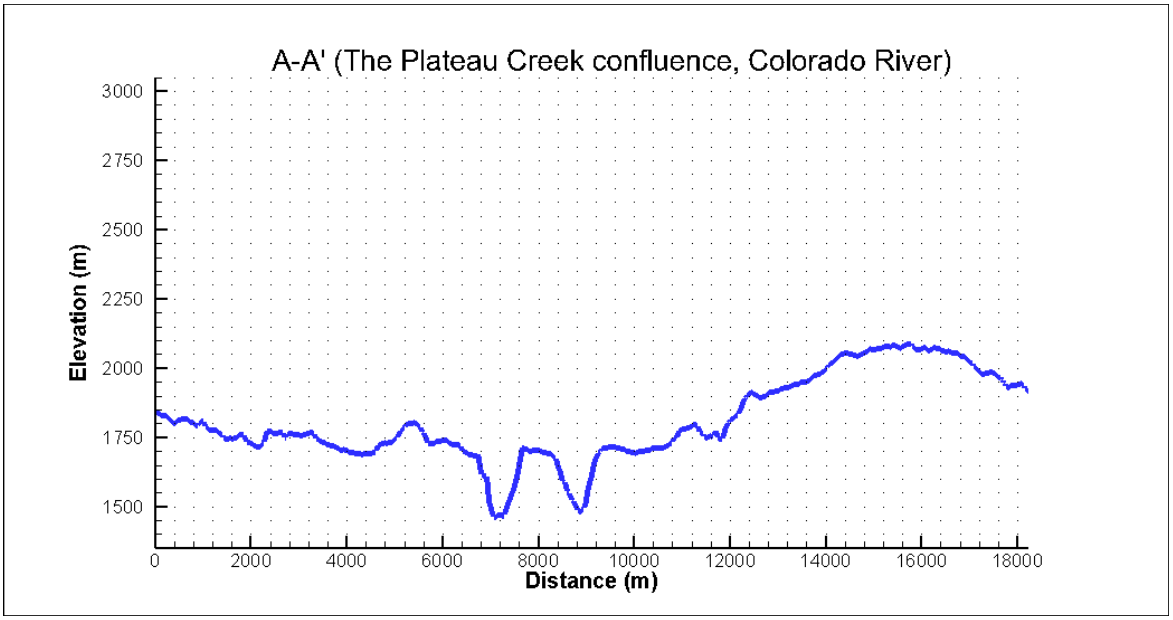


Figure 4.3 The Colorado River Cross-Section up from the Plateau Creek. Note the relatively little variation in elevation throughout except the two valleys of the channels.

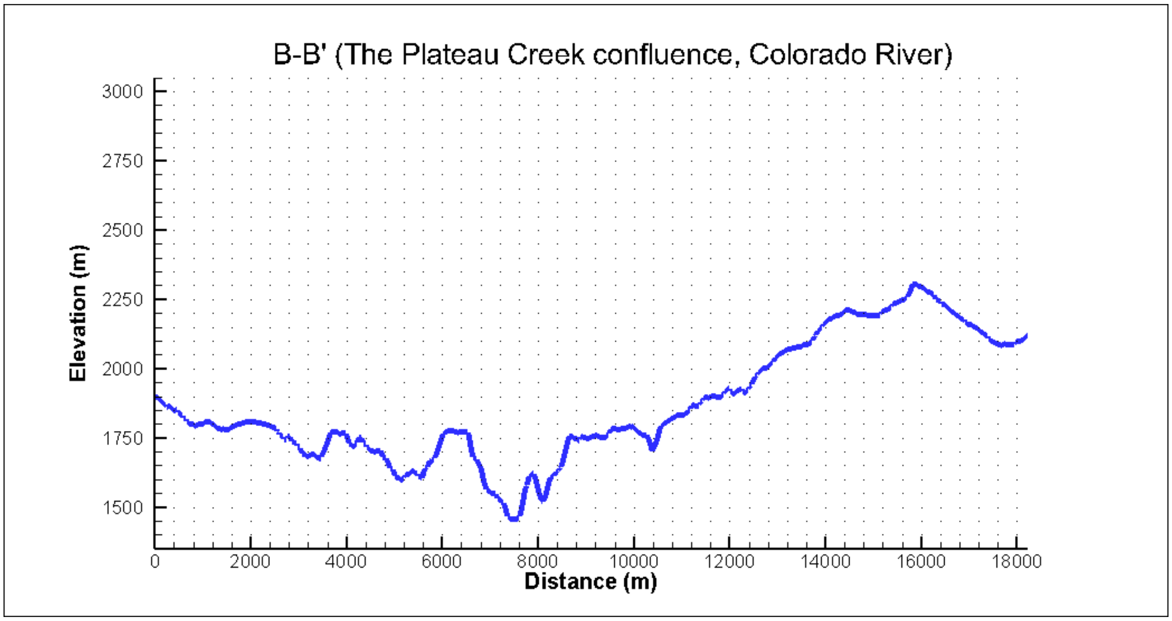


Figure 4.4 The Colorado River Cross-Section down from the Plateau Creek. Notably instead of two channels of comparable size in Fig. 4.3, relatively minor channels are present with the main Colorado River channel near the center.

The upper pair of cross sections was acquired from the confluence of the Colorado River and the Plateau Creek, which is located in the northern flank of Grand Mesa. The upstream profile shows the Colorado River (~7,000 m, horizontal segment) and the Plateau Creek (~9,000 m) channels between the "hinterland" of the Book Cliffs and the foothills of Grand Mesa (Figure 4.3). The topography is relatively gentle, with the relief of about 850 m (rising from 1,450 m to 2,300 m). Likewise, the downstream counterpart (Figure 4.4) shows the Colorado River channel at the lowest location (~ 7,500 m, horizontally; 1450 m, vertically) and the foothills of Grand Mesa (~16,000 m, horizontally; and 2300 m vertically). Although the Plateau Creek is no longer shown here, downstream from the confluence, two additional minor side channels in the area, adjacent to the main Colorado

River and Plateau Creek are present at around 8,300 m and 10,400 m distance locations, and 1,520 m and 1,700 m in elevation, respectively.

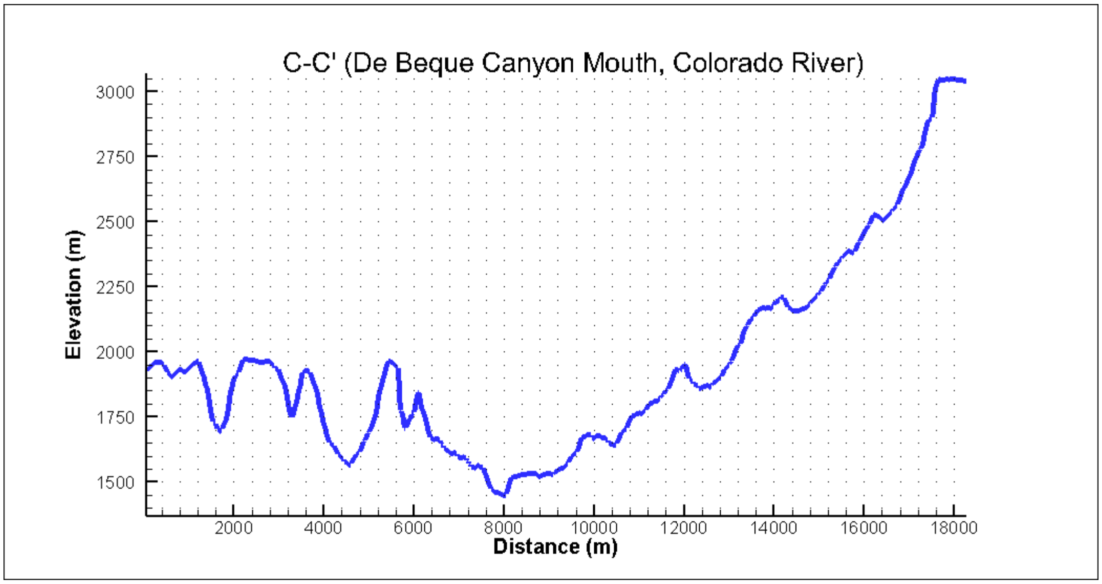


Figure 4.5 The Colorado River Cross-Section up from the De Beque Canyon. Note the highly variant topography.

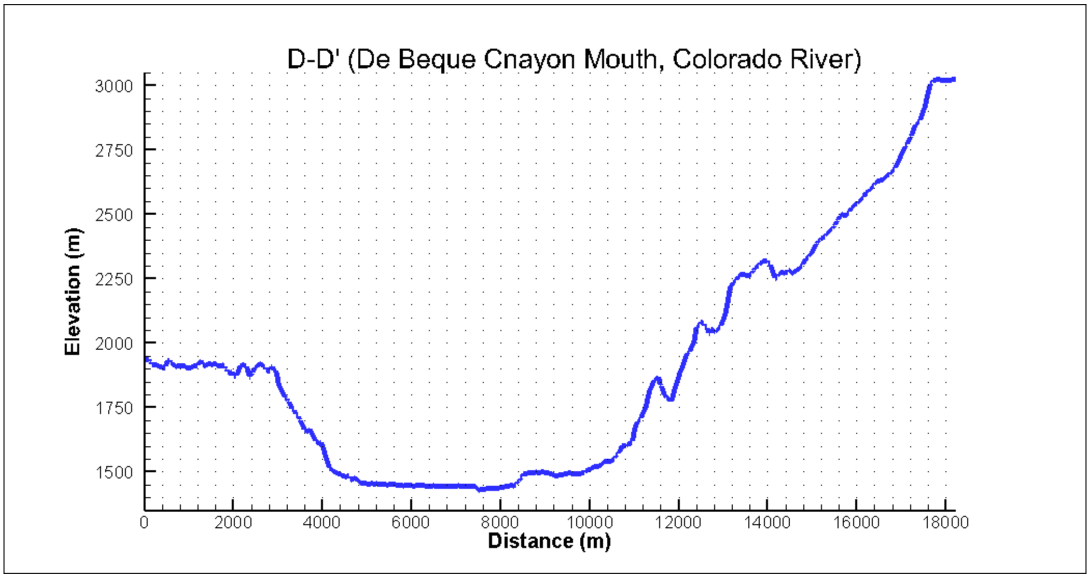


Figure 4.6 The Colorado River Profile down from the De Beque Canyon. It contrasts starkly to Figure 4.5 in the valley shape.

Figures 4.5 and 4.6 are cross-section profiles of the Colorado River immediately upstream and downstream of the threshold from De Beque Canyon and Grand Valley. Figure 2.6 is characterized by 1) highly variant topography from the left to about 6,000 m across, 2) the Colorado River Channel around 8,000 m across, and 3) a rising topography from 9,000 m to 17,500 m distance that culminates at about 3,050 m elevation. The left-hand side of the Colorado River valley is the hinterland of the Book Cliffs dissected heavily relative to the other five (5) cross-sections. Whereas the Colorado River channel marks the lowest point across the profile, the right bank of the valley rises. Although the slope overall has about 15 percent incline, it is relatively variable as smaller valleys and gullies occur around 1,650 m, 1,850 m, and 2,150 m elevation. The zenith is reached above 3,000 m in elevation, marking the highest point of the six profiles and is a northwestern periphery of Grand Mesa.

Figure 4.6 shows a profile of Grand Valley at the entrance from the De Beque Canyon Mouth. In stark contrast to the transect immediately upstream, the Colorado River channel no longer exhibits the narrow valley of the De Beque Canyon Mouth ends and abruptly widens about *ten-fold*. Significantly, the width of the valley increases from about 200 m to about 2,000 m across as the Colorado River channel enters Grand Valley within a 6 km along-river distance. A higher ground (~ 1,500 m) believed to be a terrace occurs on the right bank side at about 8,500 m across up to about 10,000 m before it slopes up gently. It then begins to heighten to the top of the northwestern edge of Grand Mesa. This cross-section transection is significant in that it presents the tops of prominent landforms in the study area distinctly: (from left to right) the Book Cliffs, Grand Valley with the Colorado River and a terrace, and Grand Mesa.

As mentioned along with Figure 4.2 above, the long profile is discontinuous at this location with a base level drop. The knickpoint marks an abrupt widening of the Colorado River valley from the De Beque Canyon to Grand Valley and the lithological crossing from Mesaverde Group to the Mancos Shale (although the surface of the Valley is capped with terrace sediments overlying the Mancos Shale; see Section 2.8). Also, significantly, downstream from the De Beque Canyon mouth, only strath terraces occur, whereas in the Plateau Creek valley in the upstream, fill terraces are prevalent. Evidently, interactions between channel processes and lithology are at play at the entrance to Grand Valley. The entrance to the Valley serves as a threshold or a pivot for geomorphic processes in the past and the present. In Chapter V, this dissertation further argues for diluvial processes causing rapid episodic headward erosion up to the De Beque Canyon mouth, and no further upstream from Grand Mesa, because Grand Mesa was the proximal source for nearly the entirety of diluvial flows.

The final pair of Colorado River cross-sections was obtained inside Grand Valley (Figures 4.7 and 4.8). The profiles show an even more deviation in the physiography, from the rugged terrain already presented in the three upper-stream transects to an extremely gently sloped valley.

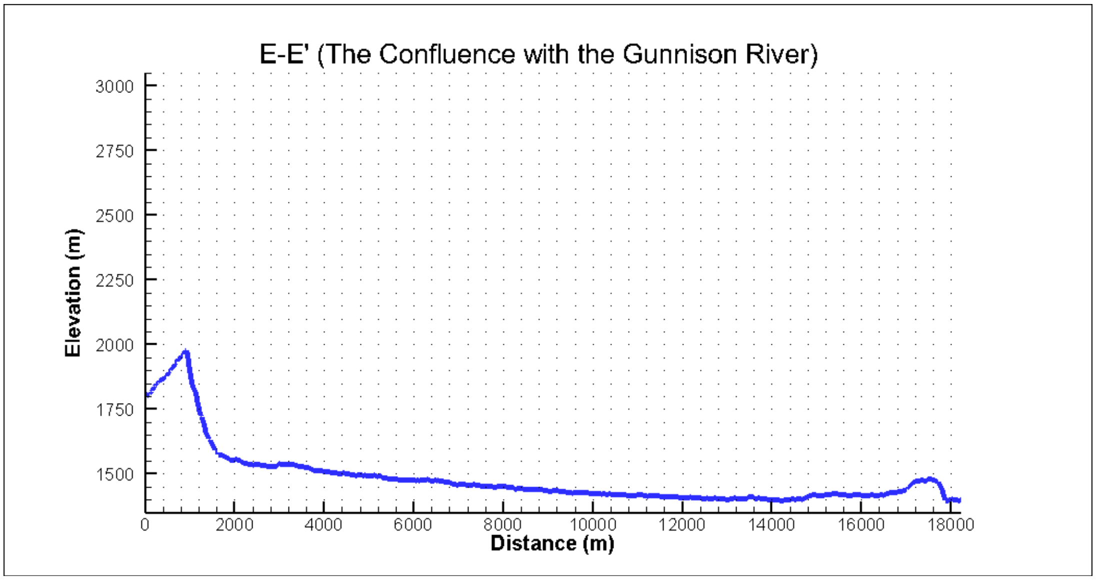


Figure 4.7 The Cross-Section up from the Colorado-Gunnison Confluence. Little variability in topography is shown, except the promontory made by the Book Cliffs on the left side of the valley.

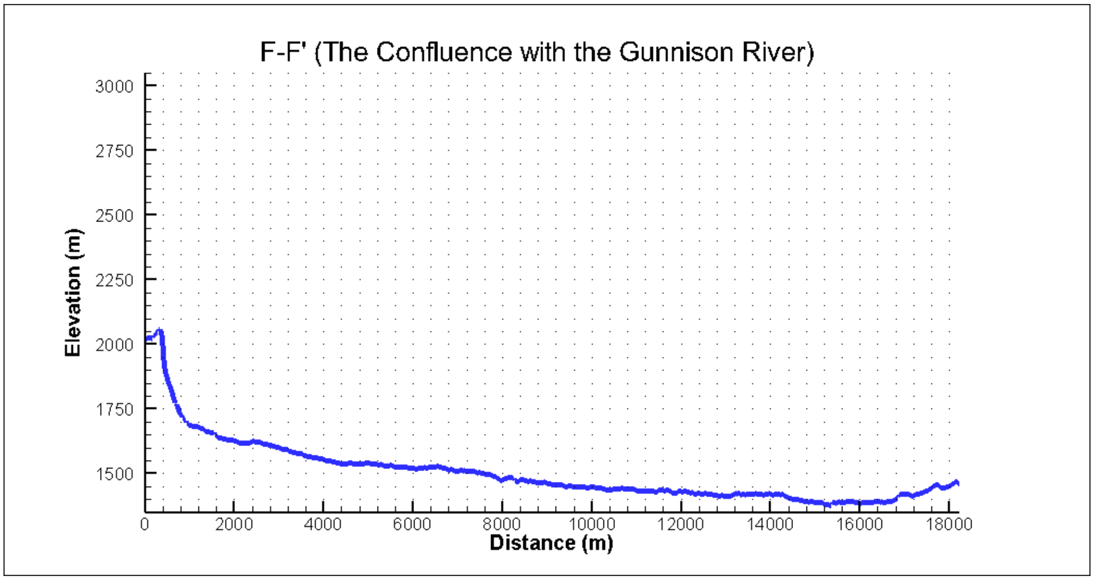


Figure 4.8 The Lowermost Cross-Section of the Colorado River. The profile appears most gentle of all.

The final set contrasts starkly to the penultimate set of cross sections of the Colorado River in the study area (Figures 4.5 and 4.6), acquired immediately upstream from the confluence of the Colorado and the Gunnison Rivers, in the city of Grand Junction. In contrast to Figure 4.6 of near De Beque Canyon mouth, and even starker contrast to the first three profiles, the gentle Grand Valley extends from about 2,000 m to 17,000 m, with a peak of the Book Cliffs shown around 1,000 m across. Over the 15-km distance, the relief difference is only 1,500 m. The Colorado River flows at around 14,100 m distance across, and the Gunnison around 18,200 m, with the terrace appearing like a mound in the profile between 17,000 m and 17,900 m.

Immediately downslope from the Book Cliffs, the steeper portion of Grand Valley is characterized by talus and residual sediments from the retreating Book Cliffs (lateral erosion). Mancos Shale is exposed in patches in these locations. As Figure 2.22 (photo) shows, the Mancos Shale crops out on the right bank of the Colorado River channel. The Gunnison River flows in from the southeast in a narrow canyon in a similar vein as the Colorado River in the De Beque Canyon.

The last profile of the Colorado River (Figure 4.8) was obtained from downstream of the Colorado-Gunnison confluence. The transect appears nearly identical to the previous profile, except the exclusion of the separate Gunnison River channel in the previous transect. However, the lowest point in the cross-section, where the Colorado River flows, is located near 15,200 m, because of the meander subsequent from the confluence. The terrace that divides the two rivers in the previous profile is shown to be undissected. Much alike the previous two profiles, moving away from the Book Cliffs, Grand Valley remains so gentle that the Colorado River channel appears rather subtly in the profile.

4.1.3 Long Profiles – the Lower Gunnison River

The Gunnison River channel section in the study area is lengthier (~97,000 m) than the Colorado River (~ 49,000 m), whereas the longitudinal profile shows subtler fluctuations and slope in comparison (Figure 4.9). The reason for the longer channel span is that the Gunnison River covers more distance as it flows around southern and western flanks of Grand Mesa, whereas the Colorado River spans only the northwestern flanks of it. Three main segments are noted: 1) the Surface Creek confluence section from the upstream end to 5,000 m downstream, 2) the most pronounced local dip near 25,000 m and 30,000 m, and 3) the most slope-varying section between 70,000 m and 78,000 m. The first section around the Surface Creek confluence shows remarkably little variation. The locally pronounced dip is associated with widening floodplain and the directional change of the river course. Finally, the lowermost section with most slope variation will be specially treated with four cross-section transects.

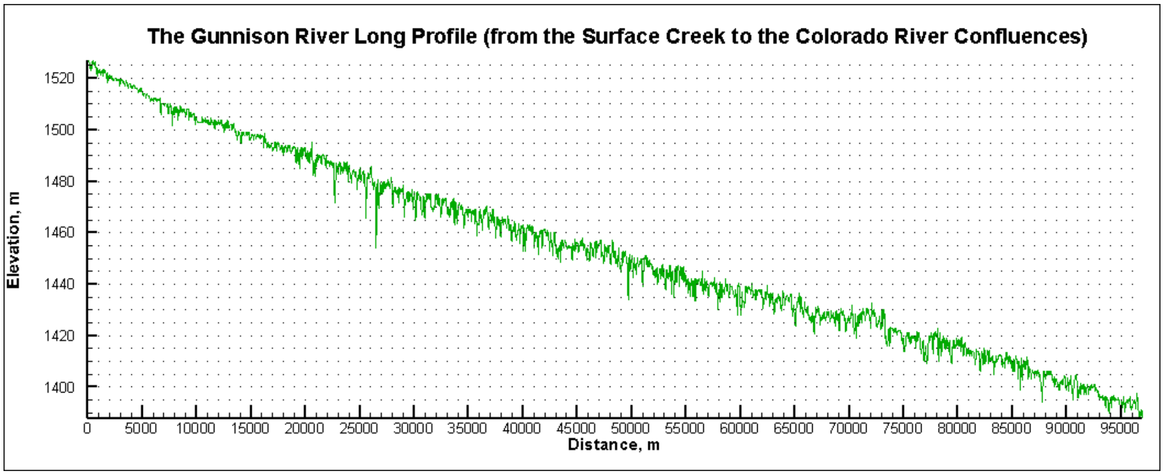


Figure 4.9 The Long Profile of the Gunnison River

4.1.4 Cross-Sectional Profiles – the Lower Gunnison River

The Gunnison River cross section profiles were produced from locations noted from the long profile in the same manner as the Colorado River profiles analysis above, except that there are a total of eight (8) transects instead of six (6): two upper, two middle, and four lower sites, with each pair being about 4,000 m, 1,500 m, 2,000 m, and 5,000 m apart, respectively. Consistent with the Colorado River transects, the transects were acquired from the left bank side to the right, looking upstream. For visual comparison, the horizontal distance all profiles were about 18,500 m with the elevation ranges set between 1,350 m and 3,050 m.

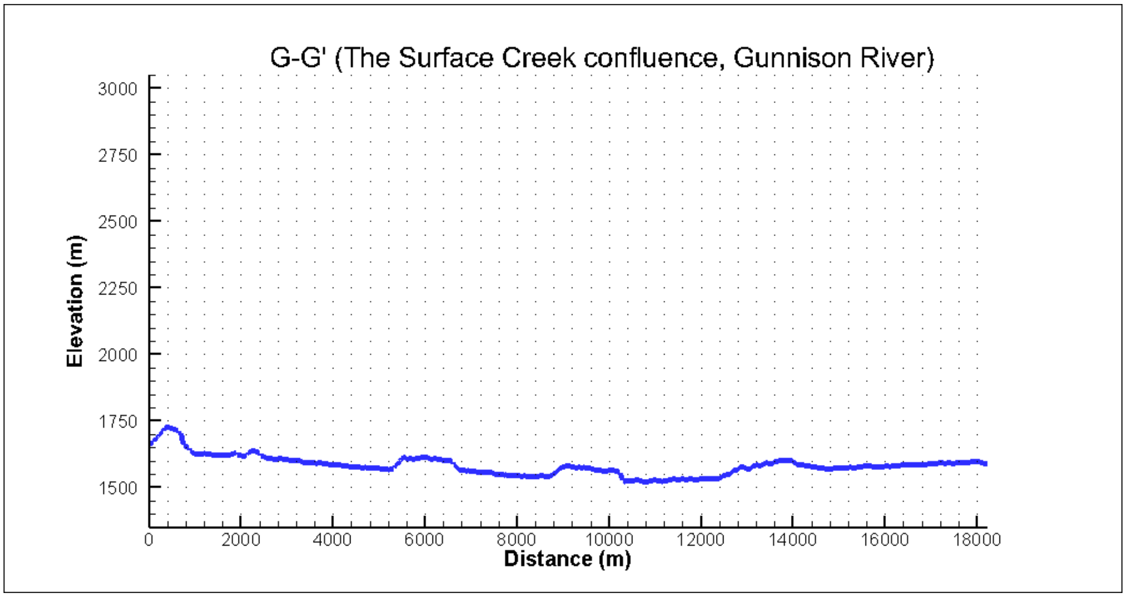


Figure 4.10 The Gunnison River Cross-Section up from the Surface Creek.

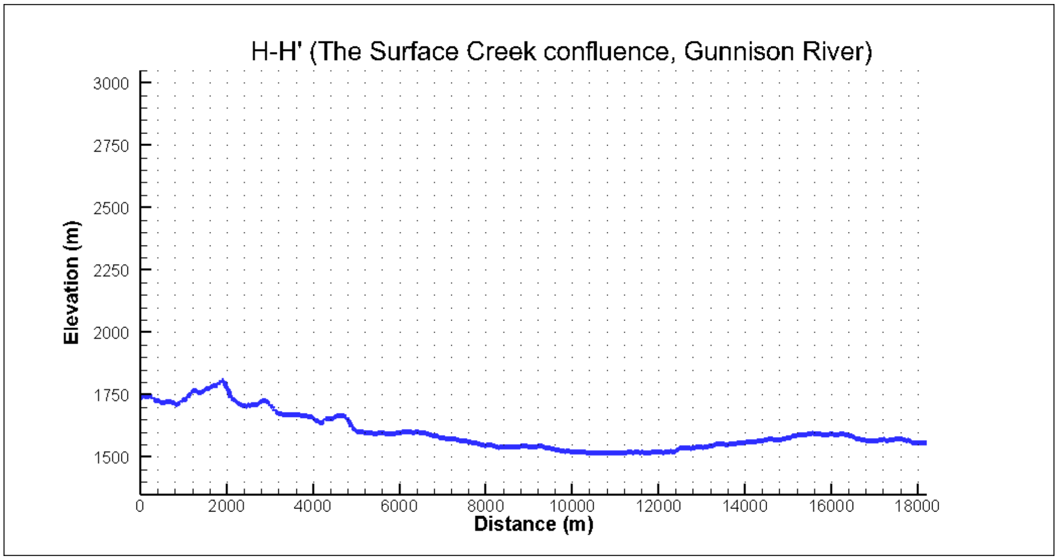


Figure 4.11 The Gunnison River Transect at the Surface Creek Confluence.

The first upper pair of cross-sections was acquired from near the confluence of the Gunnison River and the Surface Creek, located in the southern flank of Grand Mesa. The first cross section profile of the Gunnison River is located upstream from the Surface Creek (Figure 4.10). The Gunnison River channel is located at the lowest elevation 1,520 m (~10,300 m distance) and the Surface Creek channel meandering in and out of the cross section (5,500 m and 9,000 m distance; around 1,550 m and 1,570 m elevations). Relatively gentle but local terraces are protruded as ‘mesas’ adjacent to the stream channels (around 5,500 m – 6,500 m and 9,000 m – 10,500 m), with the relief of about 850 m (rising from 1,450 m to 2,300 m). The cross section downstream from the Surface Creek (Figure 4.11) similarly shows a gentle topography throughout. However, the site lacks any local mesas, although relatively more rugged foothills of Grand Mesa are shown on the left-hand side. As little variation existed in the long profile, there appears to be little difference between the two cross-section profiles, although they are from upstream and downstream from the Surface Creek confluence.

The Gunnison River course changes from generally west-trending to northwest with respect to the peripheries of Grand Mesa. Thus, the mid-stream cross section transects are presented for potential novelties in the cross-channel morphology (Figures 4.12; 4.13). The overall schematic view of the Gunnison River here shows three major breaks in slope, around 2,500 m, 6,500 m, 14,800 m. The first, steepest slope on the left-hand side represents a flank of Grand Mesa. Moving toward the Gunnison River valley between 3,500 m and 6,500 m, a pediment surface. Appears (similar to a mesa, but differentiated by its slope and proximity to Grand Mesa). Further toward the Gunnison River valley, the ground is characterized by rugged topography, albeit more gently sloped overall, compared to the two previous surfaces. Presumably, if the Gunnison River was subject to vast channel migration, then this relatively rugged yet most parallel to the horizontal would have been the channel migration belt. Past the Gunnison River channel valley located around 14,800 m and 15,800 m, the relief rises again slightly.

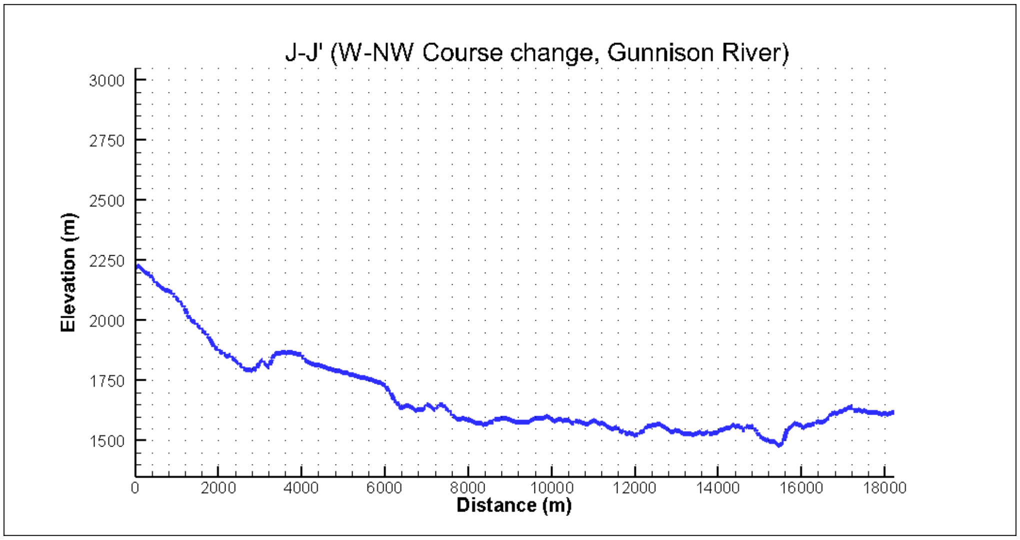


Figure 4.12 The Gunnison River at the Course Direction Change (Upstream).

The overall profile of the downstream counterpart (Figure 4.13) shows three major breaks in slope and similar surface morphology. One notable difference is the “mesa”-like feature from 2,000 m to 5,800 m distance, for its gradual and subtler transition to the lower parts of the cross section transect. Also, the channel belt of the Gunnison River and the canyon of the channel, between 11,500 m and 15,000 m distance, show a starker relief contrast in Figure 4.13 than in Figure 4.12. Finally, across the Gunnison River valley, the topography rises gently forming a dome-like morphology. Together, these two cross-section profiles show that once the channel course direction changes, the channel and its floodplain are more pronounced.

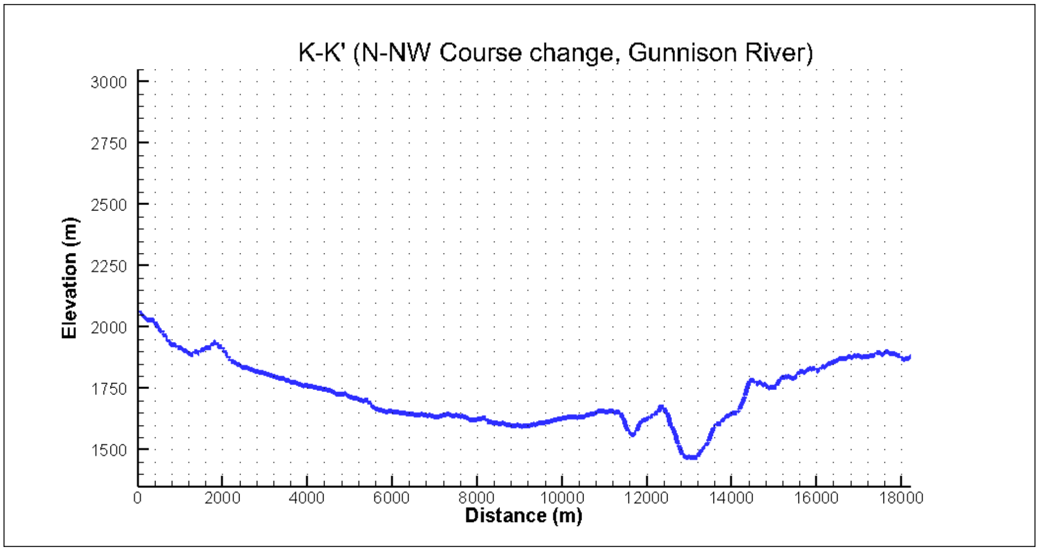


Figure 4.13 The Gunnison River at the Change of Course (Downstream).

The third pair of cross sections along the Gunnison River is located about five km upstream and five km downstream from the confluence with the Kannah Creek, which drains the western flank of Grand Mesa (Figures 4.14 and 4.15).

A juxtaposition of the upstream and downstream counterparts about the Kannah Creek confluence shows a stark difference of the respective channel valley profiles. First, the canyon-like valley of the Gunnison River between 12,500 m and 15,000 m in the upstream (Figure 4.14) is reduced to a its previous size (as in Figure 4.12) at around 8,200 m in Figure 4.17. Second, the Kannah Creek valley spans between 3,000 m and 4,100 m in the upstream (Figure 4.16) before merging with the Gunnison River. Third, the right-hand side of the transect is generally an upward slope that represents the rising limb of the Uncompahgre Plateau. Although generally gaining elevation, it has numerous gullies on the rising slope.

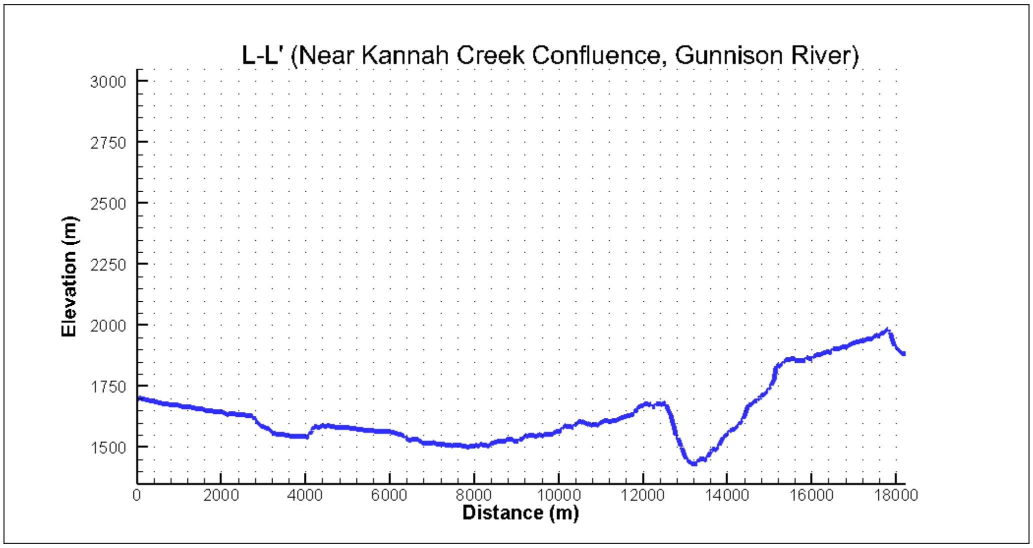


Figure 4.14 The Gunnison River up from Confluence with the Kannah Creek.

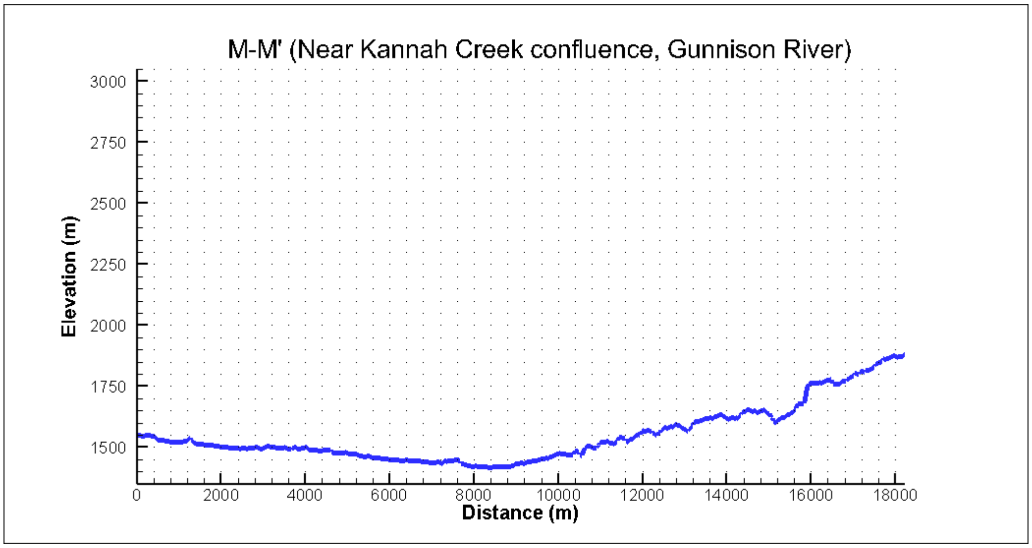


Figure 4.15 The Transect Downstream from the Gunnison-Kannah Confluence.

The final and downmost-stream pair of transects (Figures 4.16 and 4.17) were acquired near the confluence with the Colorado River, with a slight overlap with the final pair of transects from the Colorado River in Figures 4.7 and 4.8.

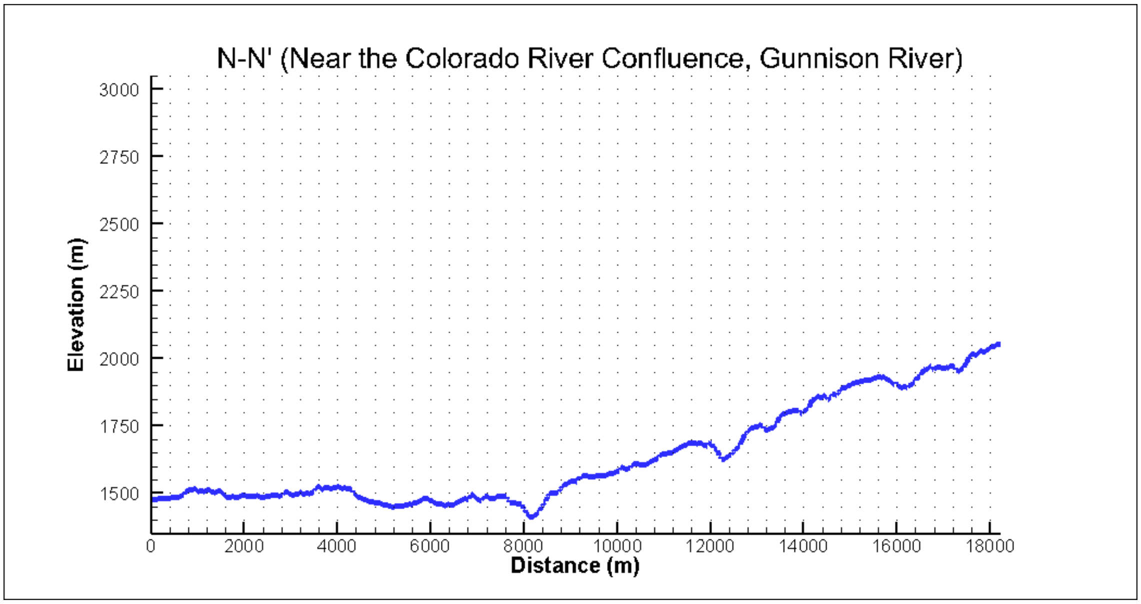


Figure 4.16 The First of the Gunnison River Upstream from the Colorado-confluence.

Contrasting the less pronounced valley of the Gunnison River, downstream from the confluence with the Kannah Creek in Figure 4.15, the Gunnison River channel appears in a more pronounced valley around 8,100 m in Figure 4.16. Pivoting around the Gunnison River valley are the 8-km generally horizontally gentle terrain on the left-hand side and the 10 km-generally rising slope toward the Uncompahgre Plateau with about seven gullies small streams on it.

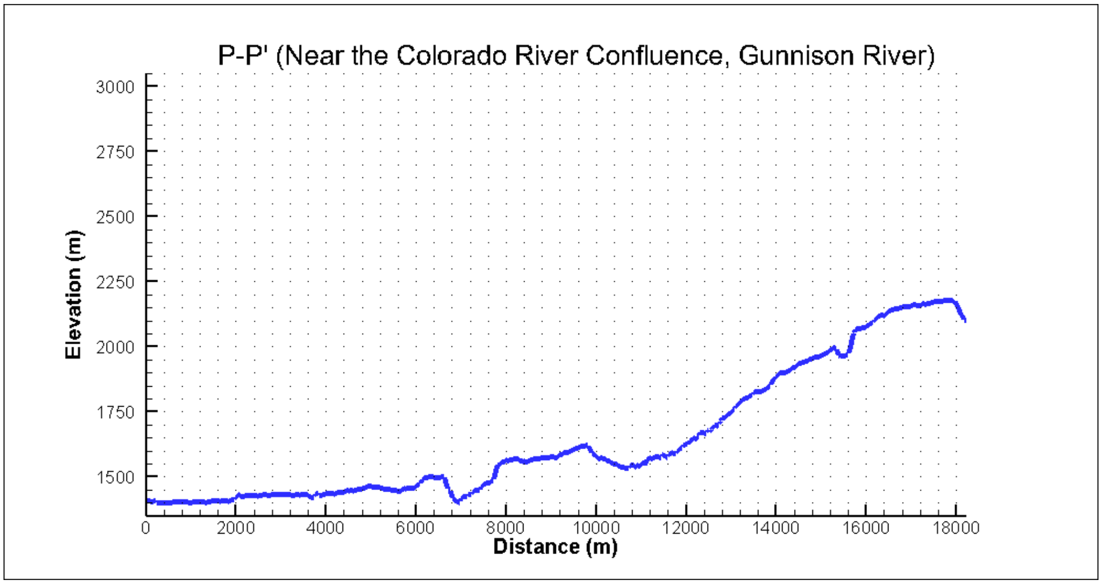


Figure 4.17 The Gunnison River Transect Upstream from Grand Junction.

The final cross section profile of the Gunnison River (Figure 4.17) overlaps with the Colorado River channel on the left-hand side around 2 km. Between 2,000 m and 7,000 m distance, Orchard Mesa, a residential community on a generally flat terrain appears. Beginning from the edge of Orchard mesa, the Gunnison River valley occupies a canyon of about 1 km wide (between 7,000 m and 8,000 m). Except for a 2,000 m wide depression between 10,000 m and 12,000 m distance, represented by a side channel, the rest of the topography in the right-hand side gains elevation to the Uncompahgre Plateau, consistent with the previous five transects (Figures 4.12 through 4.16).

In summary, the survey of longitudinal and cross-sectional profiles of the upper Colorado River and the lower Gunnison River showed highly variant topography in the study site. The Colorado River showed the greatest slope and elevation changes across in the upstream regions because of Grand Mesa and the channel valley are both represented.

The lower Gunnison River was accompanied by the foothills of the Uncompahgre Plateau as well as the southern and western flank of Grand Mesa. Both rivers as constituents of the regional drainage mingle with the convoluted surrounding landscapes, and thus naturally have attracted researchers interested in the complex evolution of the regional geomorphology.

4.2 Reasons for Fieldwork Site Selection

4.2.1 Sedimentology and Geochronology in the Plateau Creek valley

The reason for the strike-dip survey of unconsolidated deposits in the Plateau Creek was for the reconnaissance of the unmapped area of Cole and Sexton (1981) and contribute to the conclusions of the studies by Brunk (2010) and Blakeley (2014) in the northern flank of Grand Mesa. Evidently, the processes of glacial flooding and debris flows had extended down-valley, previously unmapped by Cole and Sexton (1981). Also, essentially, the imbricated basalt clasts in the Plateau Creek valley demonstrate that the valley was as prone to debris flows and deglacial floods as the Surface Creek valley in the southern flank of Grand Mesa.

Five (5) samples of sediments were collected in the a further up-valley of the Plateau Creek valley, including commercial quarries Snyder Pit and Woodring Pit, and an outcrop between the two gravel pits, and two (2) sediment samples acquired in the Surface Creek valley. The sites have only been subject to stratigraphic and relative dating methods (Yeend, 1969; Cole and Sexton, 1981). Fortunately, the numeric dates for the northern flank would complement those in the southern flank, and enhance our understanding of the geomorphic evolution of the side valleys (Noe and Zawaski, 2013; Noe et al., 2015), and furthermore, the development of the floodplains in Grand Valley (Aslan and Hanson, 2009).

4.2.2 ERT Scan of Grand Valley for Indirect Stratigraphy of the Floodplains

The ERT survey sites were selected based on the mapped ages of the floodplains (e.g., Scott et al., 2002; Aslan and Hanson, 2009; Aslan et al., 2019), distance to modern Colorado River channel, and the expected similarities of their internal matrices. Except for the oldest floodplain, the transects of the younger floodplains were set up perpendicularly to the general channel directions of the modern Colorado River so as to imitate cross-sections of paleochannels. Note that the term floodplain in general encompasses the concepts of both 'terrace' and 'modern active floodplain,' although the former refers strictly to ancient floodplains. Accordingly, no equivocation of the terms will be made in this dissertation.

Site 1 is located near the **Mesa County Landfill**, which is the oldest floodplain of all survey sites, as it is located at the highest elevation of all sites. The site arguably belongs to either the ancient counterparts of the Colorado River or the Gunnison River. Most importantly, because the boundary between the Mancos Shale underneath and fluvial gravels above it is well-distinguished in the outcrop, the site is to be the standard to which the rest four survey transects are compared. Site 2 is a modern active floodplain in **Palisade Riverbend Park**. Located inside an active channel belt as a representation of 100-year floodplain (FEMA, 2020), this site is at the opposite end of the spectrum, from ancient to modern floodplain. Site 3 is an **orchard** located on a terrace in Palisade, with an older and smaller terrace immediately adjacent to it (Figures 4.3 and 4.4A). The survey was conducted about two weeks prior to the regional irrigation season, precluding the possibility of significant amount of groundwater present. Site 4, **Palisade High School** was selected as a terrace closest to the modern floodplain of Site 3. The school campus is designated as Flood Zone X, which is outside the 500-year flood zone, the highest flood zone designation (FEMA, 2020). Site 4 is, therefore prominently comparable to Site 3 as it is spatially proximal to it. Lastly, Site 5 was selected near the **confluence** of the Colorado and the Gunnison Rivers in Grand Junction. Site 5 was, akin to Site 4, close to the modern river, Flood Zone X that is rather unlikely to be inundated in modern times as a fluvial terrace.

Groundwater levels for each survey site is of concern for potentially low resistivity values in the matrix which otherwise would be high resistivity. The presence of groundwater in the ERT transects were taken into account in the interpretation of the ERT data, for their low resistivity comparable to that of the Mancos Shale (Figure 4.18).

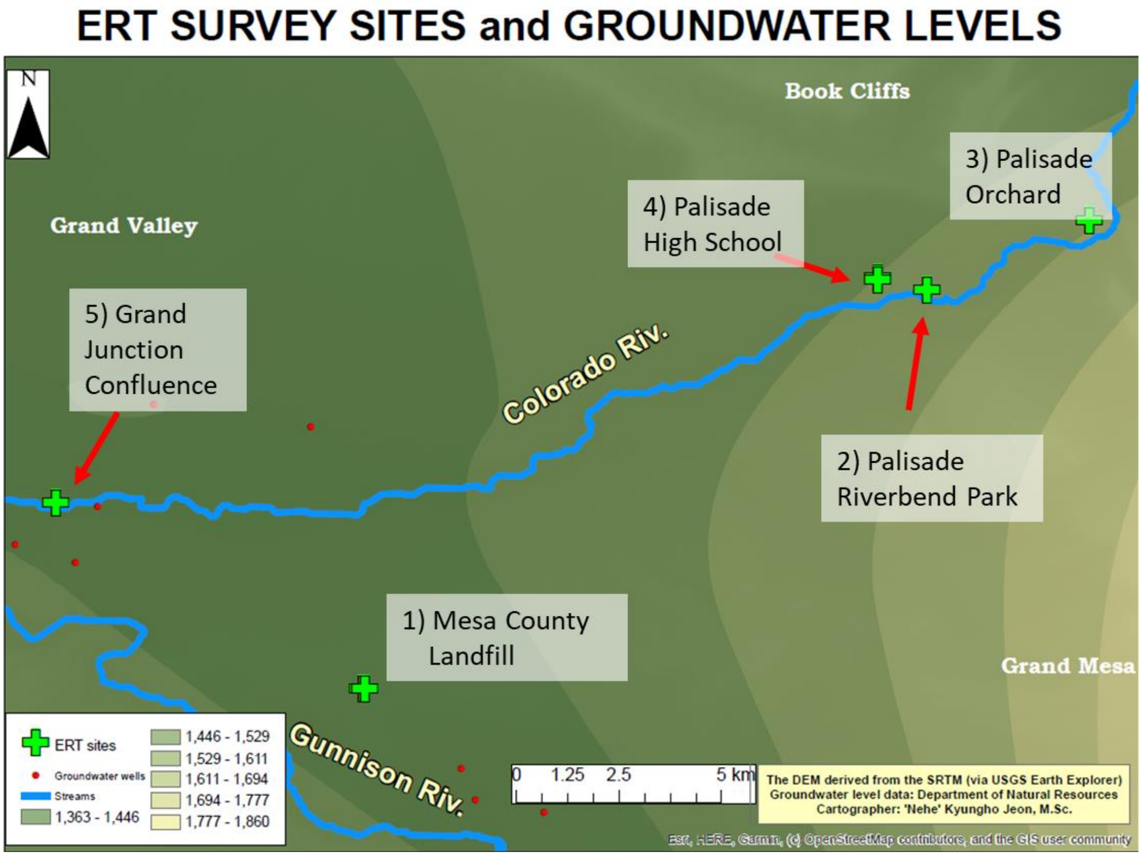


Figure 4.18 The ERT Survey Sites and Groundwater Levels. The latter was interpolated from groundwater well data from Colorado Geological Survey.

4.3 Maps and Photos of the Sampling and Survey Sites

This section of the chapter is devoted to explaining the OSL sampling and ERT survey sites. The OSL sampling sites will be introduced first (Figure 4.19). Note that the samples were acquired from the Plateau Creek valley in the northern flank of Grand Mesa and the Surface Creek valley in the southern flank of Grand Mesa (Figures 4.20 and 4.21).

See the figure captions for the locations of the respective sampling sites in the flanks of Grand Mesa.

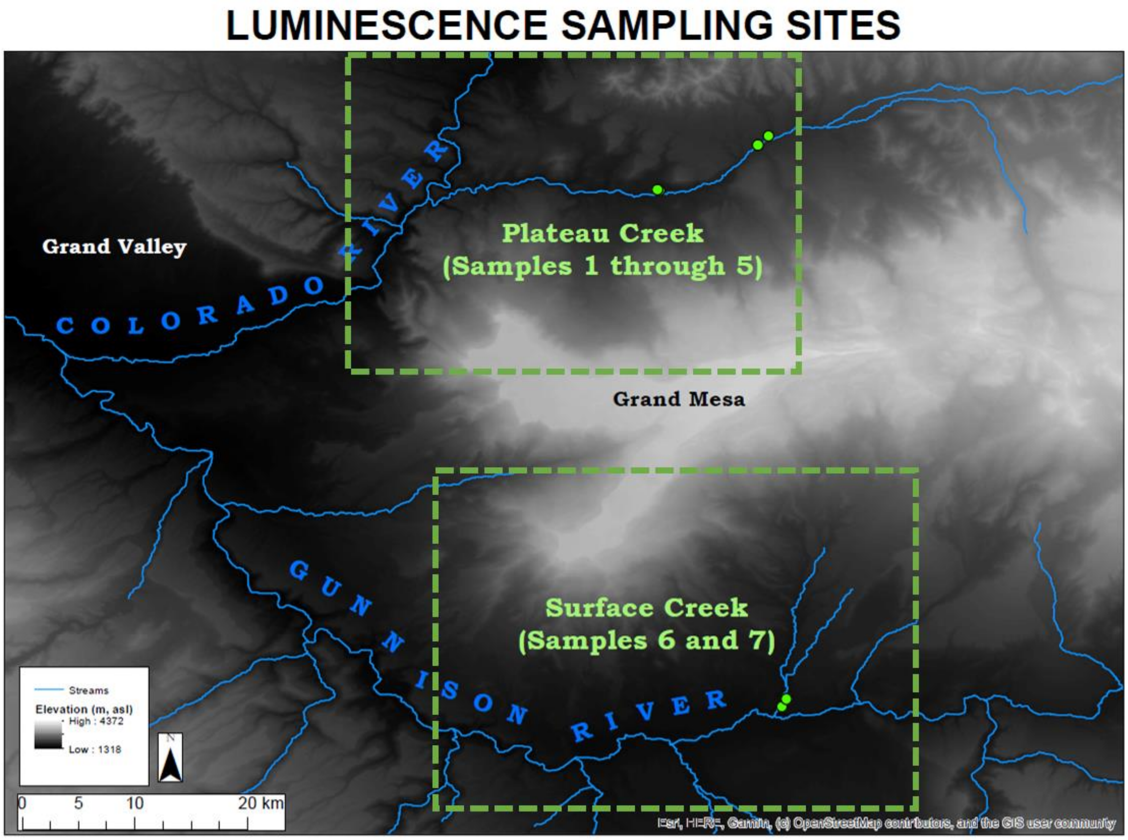


Figure 4.19 The OSL Sampling Sites. Note that the sites were in the northern and southern flanks of Grand Mesa.

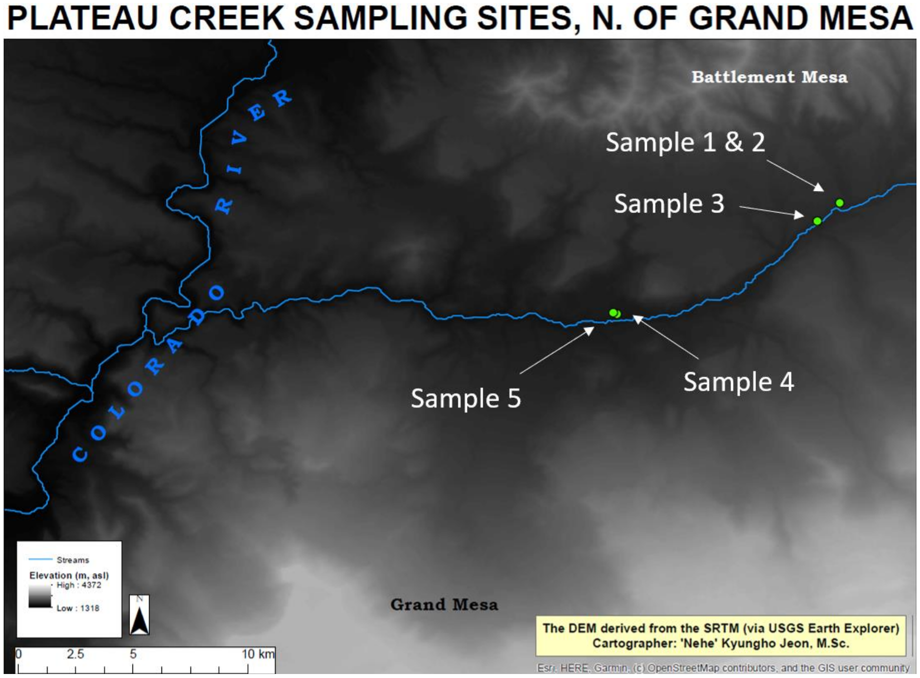


Figure 4.20 Map of the OSL Sampling Sites in the Plateau Creek Valley. The samples were taken at about 20 km and 35 km upstream from the Colorado River.

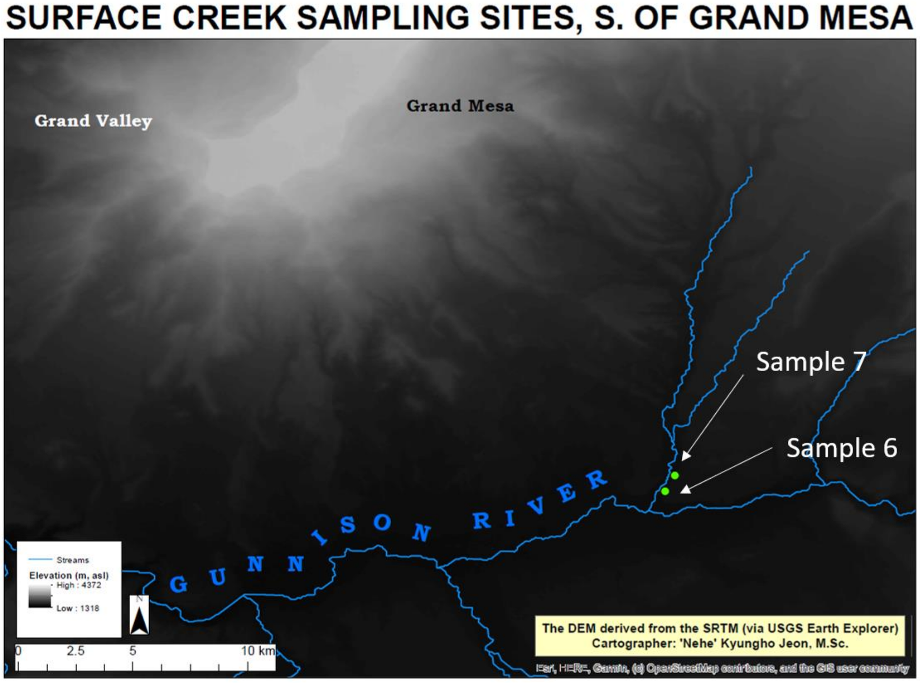


Figure 4.21 The OSL Sampling Sites in the Surface Creek Valley. Only two samples from glacial flood terraces were obtained.

4.3.1 OSL Site 1: Snyder Pit – Samples 1 and 2

The first site for the OSL sample acquisition was in Snyder Pit, the uppermost location in the Plateau Creek Valley (Figure 4.21 and 4.22). Although accessible, the hill was steep and the sample locations in high positions in the Pit.

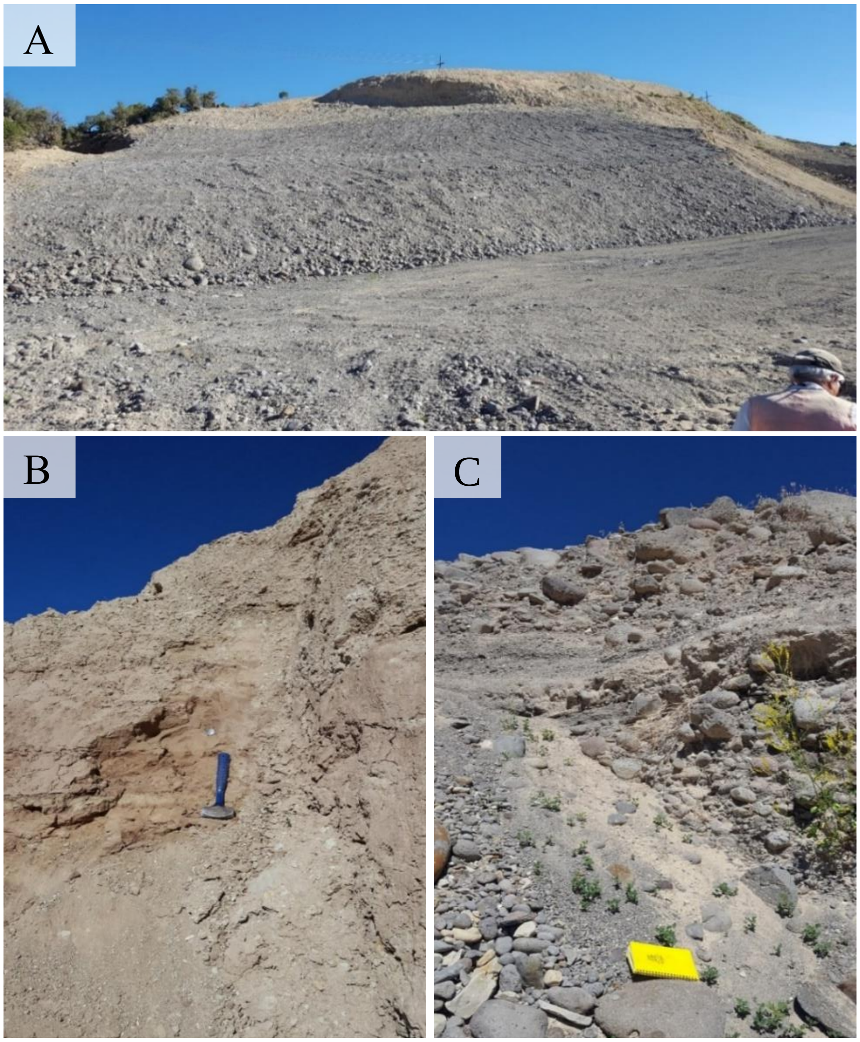


Figure 4.22 OSL Sampling Sites in Snyder Pit. A. Snyder Pit where OSL Samples 1 and 2 (KJ-PC1 and KJ-PC2) were collected. See bottom right for scale provided by R. Cole. B. Sample 1 collected in the loess-like fine grained alluvium. C. A photograph of the surrounding of Sample 2 site.

At the site of Sample 2, cross-bedding was notable (Figure 4.23), indicating a downstream and down-valley flow of the sediments. Unfortunately, the only photo of the sampling tube inserted into the was lost.

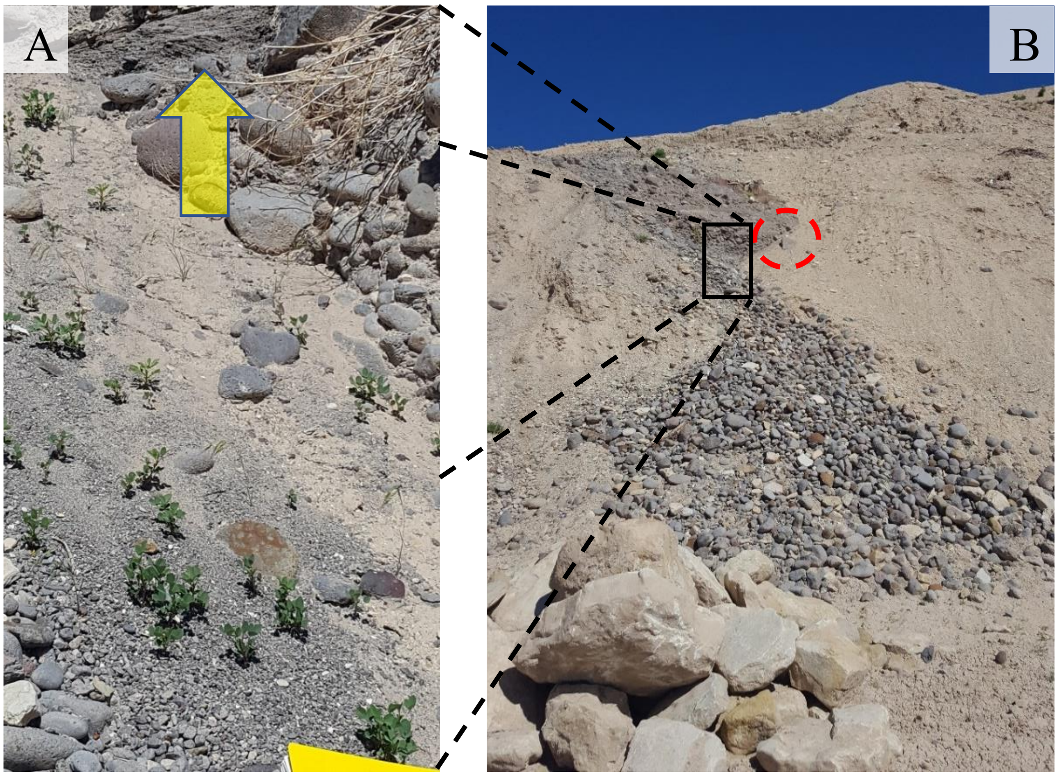


Figure 4.23 The Surrounding of the OSL Sampling Site. A. The immediate surrounding of Sample 2 (KJ-PC2) collection site. There are multiple cross-beds in the vicinity. It is indicated with the yellow arrow. A part of the yellow notebook for scale. From the notebook to the arrow is about 3.5 m. B. The sample site is encircled in red in the light-colored sandy section.

4.3.2 OSL Site 2: Near V Road in Plateau Creek valley – Sample 3

Sample 3 was collected off V Road in the Plateau Creek valley (Figure 4.24). Similar to the site of Samples 1 and 2, there were minor cross-beds that indicated the direction and strength of the sedimentary flows. The sample was obtained in the bed between the gravely beds above and below.

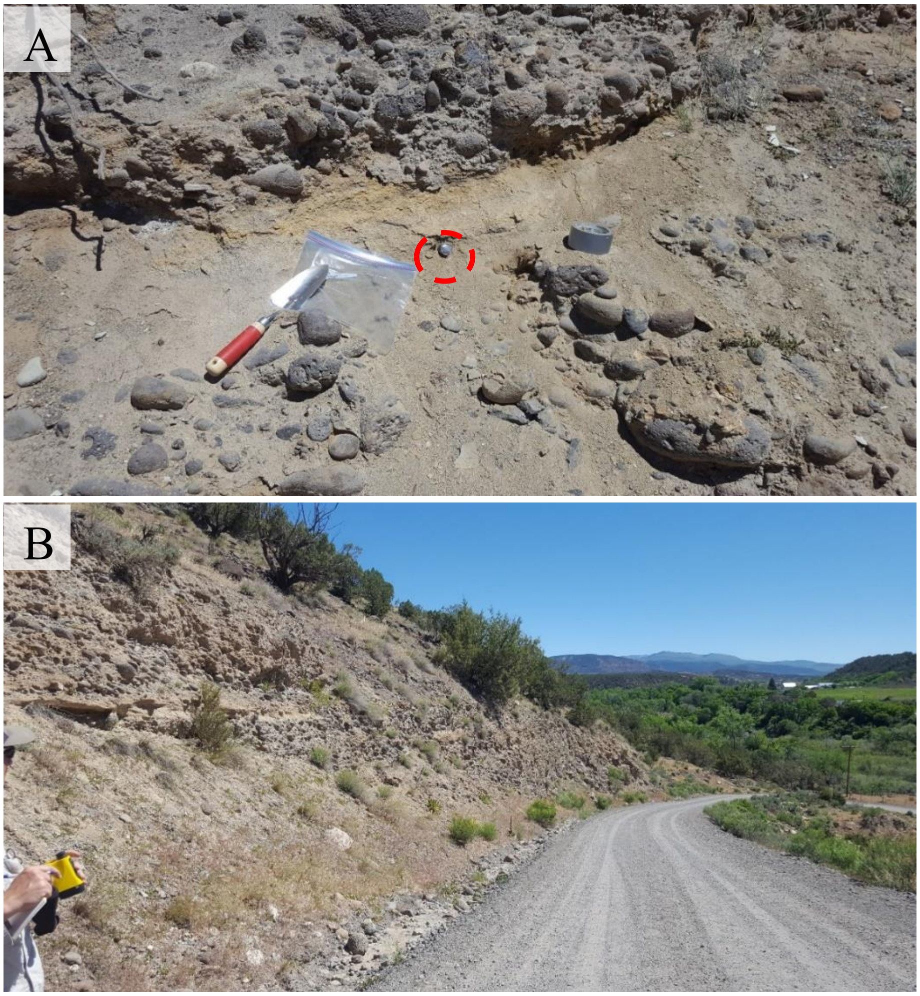


Figure 4.24 Sampling Site for Sample 3. A. Collection site of Sample 3 (KJ-PC3) and B. the road that leads to the outcrop. Texture and the stratigraphy resembled closely to those of Sample 1. Trowel is for scale.

4.3.3 OSL Site 3: Woodring Pit – Samples 4 and 5

Samples 4 and 5 were collected in Woodring Pit, which is located down-valley from Snyder Pit and the V Road outcrop described above. Numerous boulders and poorly sorted deposits are shown in Figure 4.25.

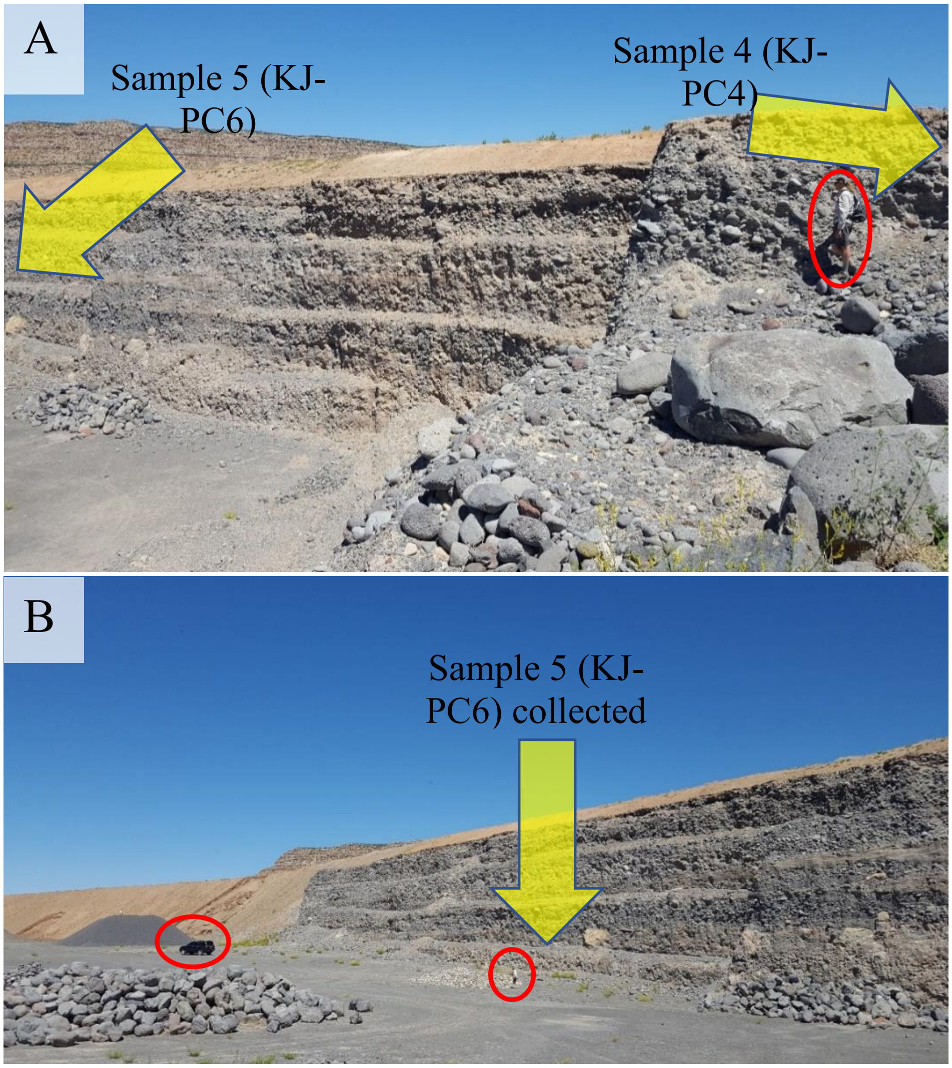


Figure 4.25 Wooding Pit. A. A photograph of Woodring Pit, where Samples 4 and 5, that is, KJ PC4 and PC6 were collected (PC5, undated, is not reported here). B. Sample 5 was collected at the bottom of the outrcop. The standing persons and the parked vehicle are for scale.

A zoom-up view of the sampling sites for Samples 4 and 5 are shown in Figure 4.26. Akin to the two previous sampling sites, the sample beds were between poorly sorted gravely beds above and below them.

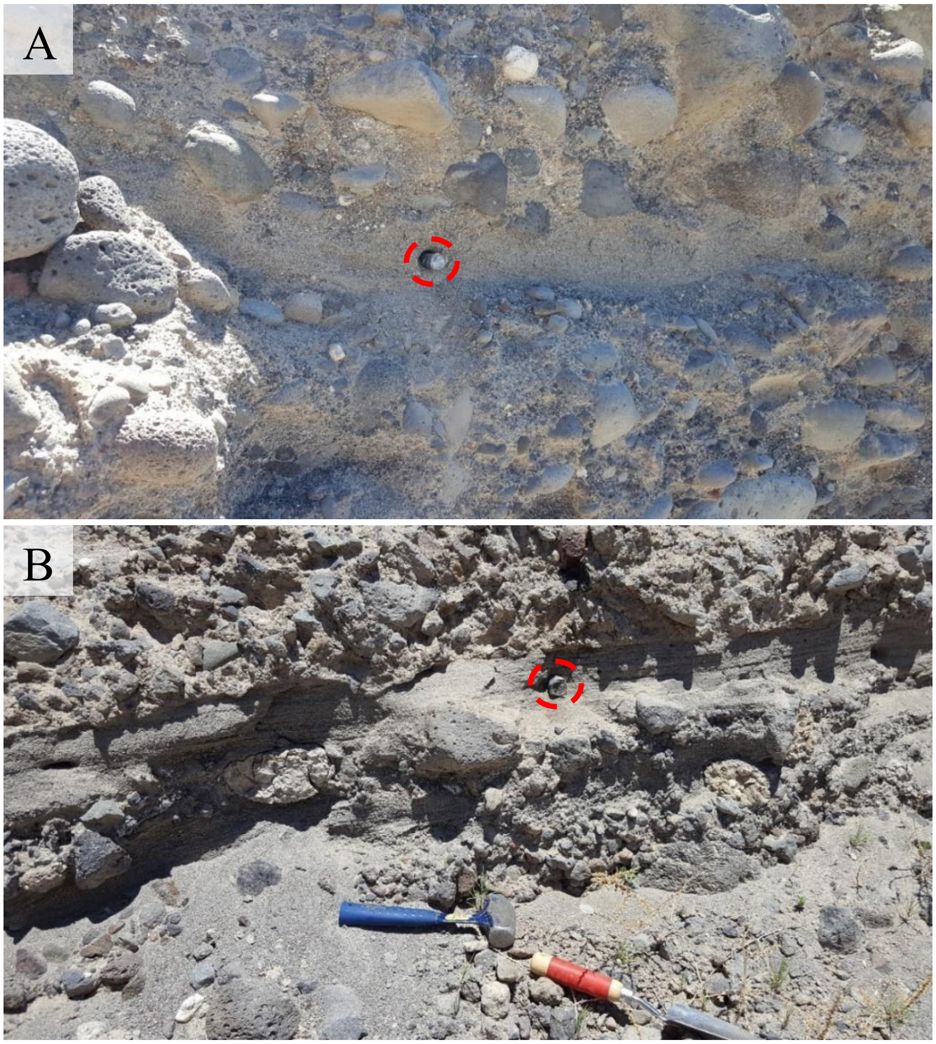


Figure 4.26 Photographs of Sample Collection at Woodring Pit Outcrops. The tubes are denoted by red dashed circles. A. Between poorly sorted layers above and below is where Sample 4 (KJ-PC4) was collected. B. Sample 5 (KJ-PC6) was collected in the finely laminated layer embedded in two poorly sorted beds. Both samples See the previous figure for their respective locations at the Pit.

4.3.4 OSL Site 4: the Surface Creek valley (Cory Grade) – Samples 6 and 7

The final sampling site was in the Surface Creek valley in the southern flank of Grand Mesa. The area has poorly sorted sedimentology, with numerous boulders and gravels as shown in Figure 4.27; the samples were collected in the lower stratigraphic column than that shown in the figure.

Figure 4.27 The Surface Creek Valley (Cory Grade) Sampling Sites. Note the size of the boulder next to the eminent researchers, R. Cole and A. Aslan.

The final two samples (7 and 8) were collected in the Surface Creek valley, in Cory Grade (Figure 4.28). Consistent with the previous sampling sites, laminations and cross-beds were common, although the sediment seemed darker overall because of the basaltic source rocks from Grand Mesa.

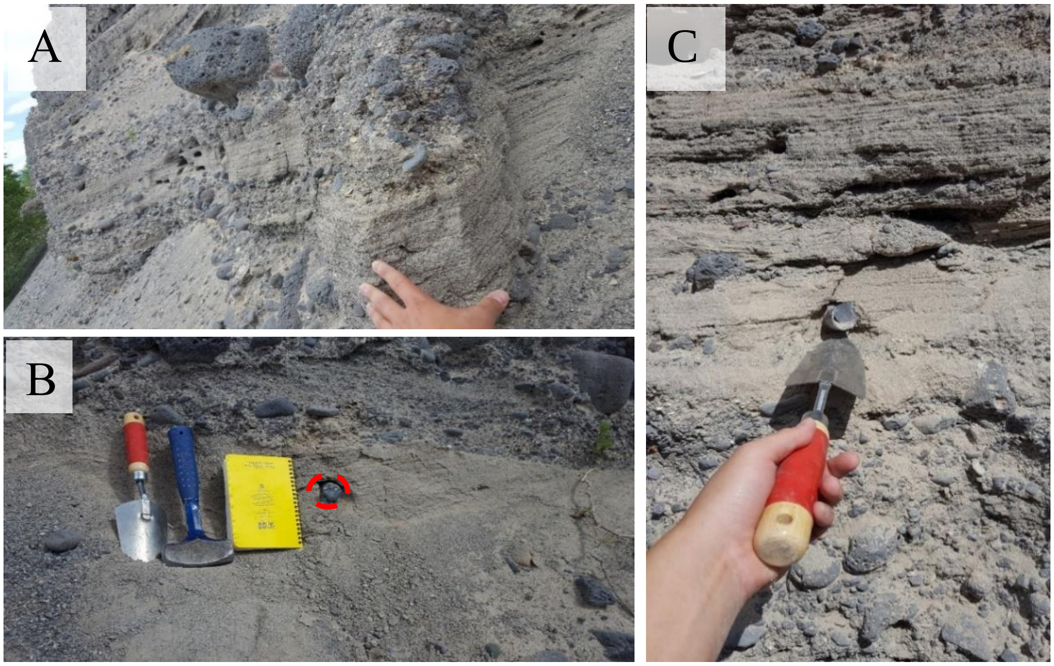


Figure 4.28 Collection Sites for Samples 6 and 7 in Cory Grade. A. The poorly sorted texture is common throughout the stratigraphic column (Brunk, 2010; Blakeley, 2014), although fine lamina and cross-beds are common as well. B. The metal pipe for Sample 7 (KJ-SC8) next to the field tools. C. Sample 6 (KJ-SC7) was collected from a silty bed, well sorted with thin laminations.

4.3.5 ERT Survey Sites in Grand Valley

The ERT survey sites spanned Palisade and Grand Junction. Figure 4.29 shows the oldest and youngest floodplains. The former is located at the highest among the five transects surveyed, whereas the latter at the lowest, adjacent to the modern Colorado River.

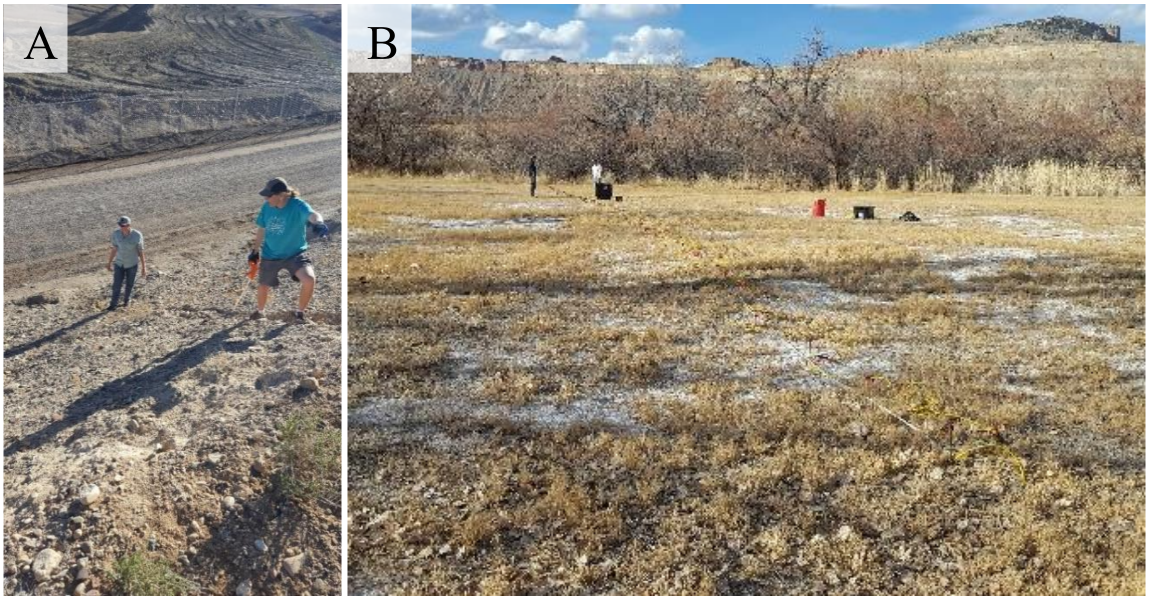


Figure 4.29 The Oldest Floodplain and the Modern Floodplain. These two are the two sites of the age extremes. A. At Site 1 near Mesa County landfill. The thickness of alluvium above the Mancos Shale is being measured by the researchers. The ERT survey photo is missing. B. Site 2 at the Palisade Riverbend Park, a modern, active floodplain.

The rest, the three of the five survey sites are shown in Figure 4.30. The transects were roughly perpendicular to the flow direction of the modern Colorado River channel. As the gentle to no slope indicates, the Palisade High School campus site (Figure 4.30 A) and the Grand Junction (former uranium mill site, Figure 4.30 C) were likely influenced by groundwork for construction. The surface of the Palisade Orchard site (Figure 4.30 B) is slightly angled toward the Book Cliffs shown in the back of the photo. The site would have been re-worked (probably up to the upper 1 m or so) for the agricultural use.

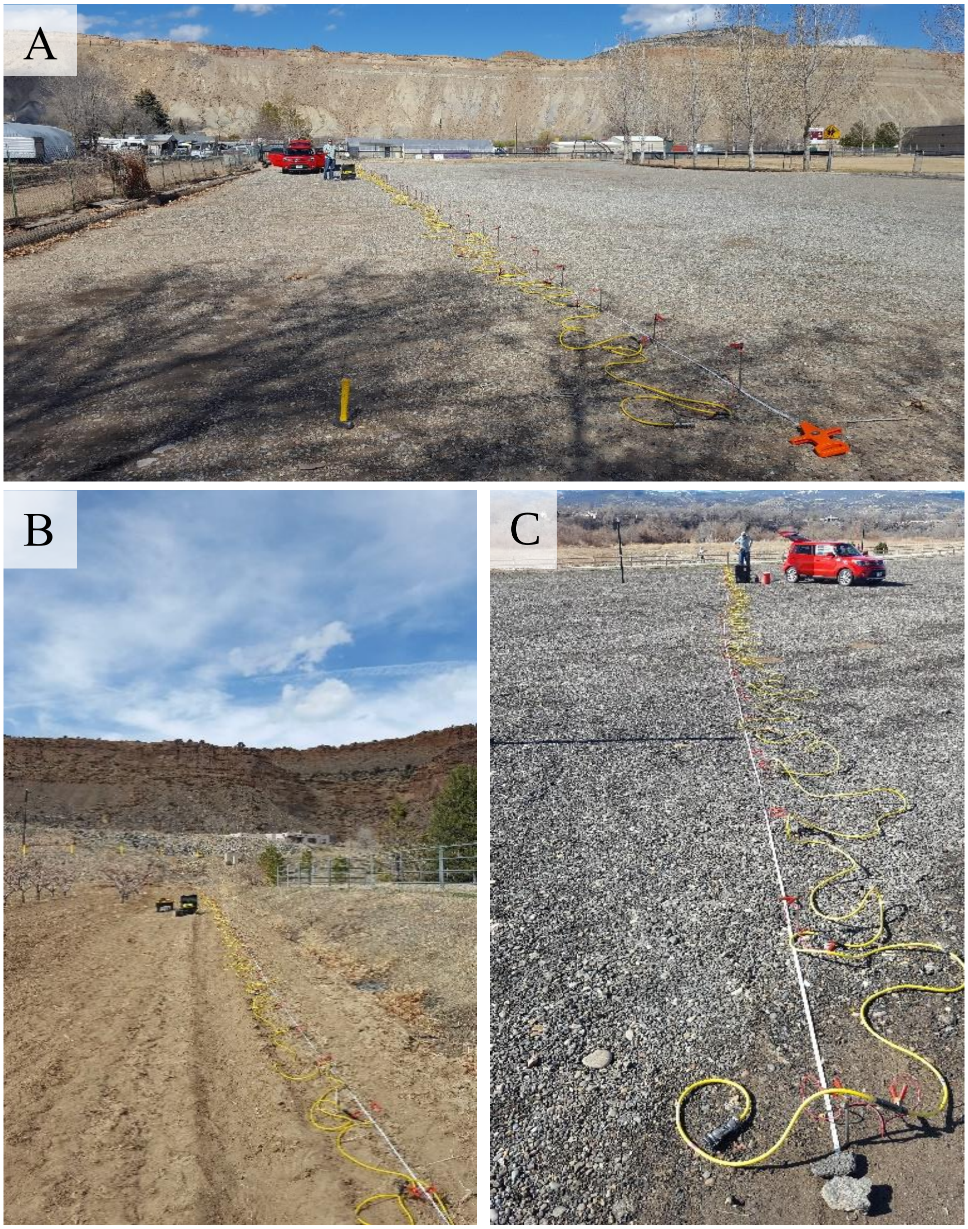


Figure 4.30 Terrace Survey Sites. A. Site 4 on Palisade High School campus. B. Site 3 at a Palisade Orchard, looking north toward the Book Cliffs. C. Site 5 Grand Junction confluence (formerly DoE Uranium Mill).

4.4 Data from Previous and Current Work

4.4.1 Southern Flanks of Grand Mesa by Brunk (2010) and Blakeley (2014)

The most comprehensive surficial mapping in the Grand Mesa area was conducted by Cole and Sexton (1981). Although the map extent includes the study sites of Brunk (2010) and Blakeley (2014) in the southern flank of Grand Mesa, noting the glacial outwash deposits, the map conspicuously excluded the equivalent deposits in the northern flank. The features left unmapped in the northern flank are equivalent to Brunk's (2010) conclusion about the southern flank of Grand Mesa having originated from glacio-fluvial activities. The stratigraphic analysis indicated that the poorly sorted facies consisting primarily of basaltic clasts showed imbrications that were consistent not with the Gunnison River flow directions (ancient or modern), but with flows directed through the Surface Creek that emanated from Grand Mesa. Blakeley (2014) extended the thesis with a slight modification, and delineated the boundary between the deposits from an Ancestral Gunnison River and the Grand Mesa glacio-fluvial, the latter of which comprising the majority of the stratigraphic column.

The data from my new site (Figures 3.1 and 4.31) representative of the northern counterpart of Grand Mesa were as follows. The readings of dipping angles of thirty samples of basalt clasts resulted in a mean dip angle of 29°±11 from the horizontal, with the maximum angle of 53°. The dipping direction was at 125° azimuth on average, parallel to the modern stream flow at the site of measurement. Long-axes were 65% larger than short-axes (mean of 0.81 m and 0.51 m, respectively). Thus, this survey complements Cole and Sexton (1981), which did not report any presence of significant deposits such as these near the confluence of the Plateau Creek with the Colorado River near De Beque Canyon.

Figure 4.31 A Close-Up View of the Basalt Clasts in the Plateau Creek Valley. Essentially this is a zoomed-in section of Figure 3.1.

4.4.2 Published Numerical Ages and the New OSL dates

Although relatively sparse, numeric dates of the region using radiocarbon, OSL, and U-series have been published by others for prominent geomorphic features aged < 1 Ma (Table 4.1). Below is the summary of the ages of alluvial gravels in terraces nearby; arranged in the order of increasing relevance to our new age estimates, reported dates from North Delta, Orchard City, Ridgway (the Uncompahgre River valley), and Grand Junction are highlighted.

Two of the Gunnison River deposits from North Delta were OSL aged 96.7 ka and 2.6 ka (about the time of Aristotle and Buddha; Noe et al., 2015). From Orchard City, alluviums of North Fork River yielded 71 ka, 65 ka, 61 ka, and 58 ka, presumably prior to being captured by the Gunnison River, of which alluvium was 47.8 ka – 42.8 ka (Noe and Zawaski, 2013). The dates of terraces Uncompahgre River valley near Ridgway are at 70 ka–40 ka and 25 ka–20 ka using OSL and post-IR IRSL age estimates (Jarrin et al., 2017). The study site is on the southern edge of Grand Valley. Lastly, inside Grand Valley, four (4) terraces have been dated at 640 ka – 580 ka, 104 ka – 98 ka, 93 ka – 63 ka, and 28 ka – 11 ka.

Grand Junction (Aslan et al., 2019)		**Uncompahgre River valley (Jarrin et al., 2017)**		**North Delta (Noe et al., 2015)**		**Orchard City (Noe and Zawaski, 2013)**	
				Gunnison River Alluvium	2.6 ka		
Qag2	28 ka–1 ka	**Younger Terrace**	25 ka–20 ka				
						Gunnison Alluvium Qag3	48 ka–43 ka
Qag3 (Orchard Mesa)	**93 ka–63 ka**	**Older Terrace**	**70 ka–40 ka**			**North Fork**	**58 ka; 61 ka; 65 ka; 71 ka**
Qag4	104 ka–98 ka			**Gunnison River Alluvium**	97 ka		
Qag9 (U-series)	640 ka–580 ka						

Table 4.1 The Published Dates in the General Order of Age. That is, ordered reverse-stratigraphically, the dates significant to our new OSL dates in Table 4.2 are in red. Decimals to the 10th of a kilo-annum are rounded.

Of the published numeric age estimates, those most pertinent to our new OSL age estimates of the Grand Mesa flank deposits are highlighted in color red in Table 4.1.

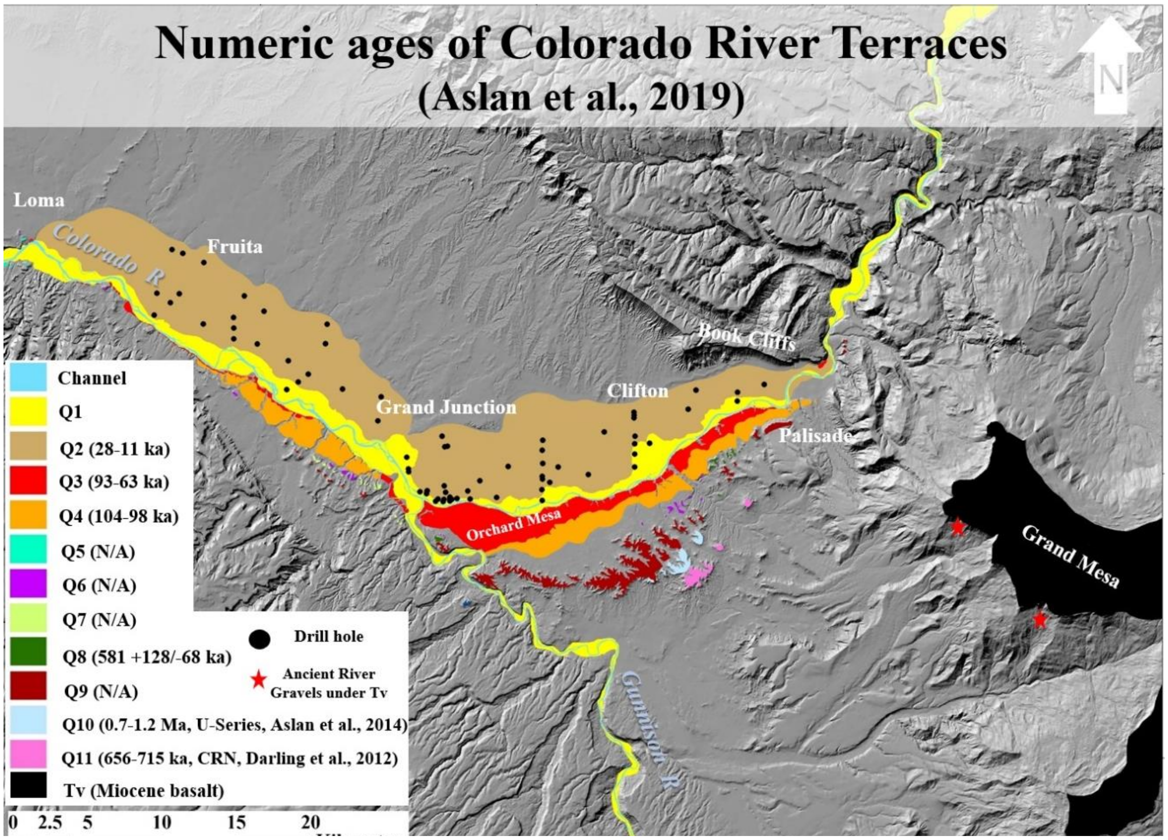


Figure 4.32 The Colorado River Terraces (Adapted from Aslan et al., 2019). Notably the timeframe that concerns the age estimates acquired for this dissertation are Q1 (modern floodplain), Q2, and Q3 for the date comparisons as also highlighted in Table 4.1. However, the diluvial geomorphic scenario in Chapter V will address the possibility of the remaining series of older terrace deposition and incision from Q11 to Q4.

For the distribution of the terraces and their ages in Grand Valley, Figure 4.32 (adapted from Aslan et al., 2019) provides a comprehensive set of numeric dates, mostly of OSL. Geologic maps produced by Colorado Geological Survey starting two decades ago provide some geomorphic insights (e.g., Palisade and Clifton by Carrara, 2000; 2001, respectively; Grand Junction by Scott et al., 2002). The most comprehensive study of the Colorado River terraces in Grand Valley was conducted by Aslan et al. (2019). Common to all these efforts, however, is that they consider timescales spanning beyond 1 Ma, outside the scope of this dissertation. Aslan et al. (2019) covers a total of ten (10) terraces in Grand Valley. With the modern Colorado and Gunnison channels and the respective floodplains being the youngest, six (6) other levels of the strath terraces have age control from OSL, uranium, and cosmogenic radionuclide dating methods that reach back to 1.2 Ma (Figure 4.32); in particular, the ages of Q2 and Q3 are indispensable for the new age estimates reported in this dissertation.

4.4.3 New OSL Age Estimates from Grand Mesa Flanks

Of the seven (7) samples, there appear to be three major groups of ages, where each group arguably representing the same sedimentary event (Table 4.2; Figure 4.32). First are the youngest Samples 1 and 3 (KJ-PC1 and KJ-PC3) aged 58 ka in the Plateau Creek. The second is the lone Sample 4 (KJ-PC4) that is 67 ka and the last set from the Plateau Creek (Sample 2 and 5; or KJ-PC2 and KJ-PC6) aged 85 ka–74 ka. In the southern flank of Grand Mesa, the equivalent deposits of glacial flooding were aged 63 ka–61 ka. These two samples were taken from the sites of Brunk (2010) and Blakeley (2014), and possibly are contemporaneous with the 58 ka or 67 ka events in the northern flank counterparts.

Notably, the entirety of the deposits in the Grand Mesa flanks is consistently within the bounds of the numeric date estimates reported by Noe and Zawaski (2013), Jarrin et al. (2017), and Aslan et al. (2019). The lowest age limit for the youngest terrace is 40 ka in Uncompahgre River valley and the upper limit 93 ka, represented by the Colorado River terrace Orchard Mesa in Grand Junction. The minimum age of deposits is 58 ka and the oldest 85 ka (Table 4.2). Thus, the new estimates of age indicate that the geomorphic events around Grand Mesa commensurate with the geneses of the strath terraces in Grand Valley (Figure 4.33). The historical scenarios, along with detailed analyses of the timing of events along the tributaries and the main channel of the Colorado River, are discussed in Chapter V.

Sample #	Depth (m)	# of aliquots	Dose rate (Gy/ka)	Equivalent Dose ± 2σ (Gy)	**OSL age ± 2σ (ka)**
1 (KJ-PC1)	5	18 (20)	3.18 ± 0.12	187.19 ± 16.52	**58.84 ± 7.01**
2 (KJ-PC2)	29	16 (25)	2.77 ± 0.10	233.87 ± 35.08	**84.58 ± 14.24**
3 (KJ-PC3)	17	17 (31)	3.40 ± 0.13	197.57 ± 30.52	**58.16 ± 10.10**
4 (KJ-PC4)	4.5	15 (22)	3.04 ± 0.11	205.00 ± 26.35	**67.47 ± 10.17**
5 (KJ-PC6)	11.5	16 (38)	2.70 ± 0.12	198.46 ± 15.51	**73.50 ± 9.16**
6 (KJ-SC7)	10.0	19 (34)	3.24 ± 0.12	198.54 ± 26.41	**61.37 ± 9.50**
7 (KJ-SC8)	4.0	16 (28)	3.20 ± 0.12	203.65 ± 38.24	**63.66 ± 12.97**

Table 4.2 The New OSL Age Information for the Grand Mesa Flanks. The lab analysis was conducted at Utah State University Luminescence Lab.

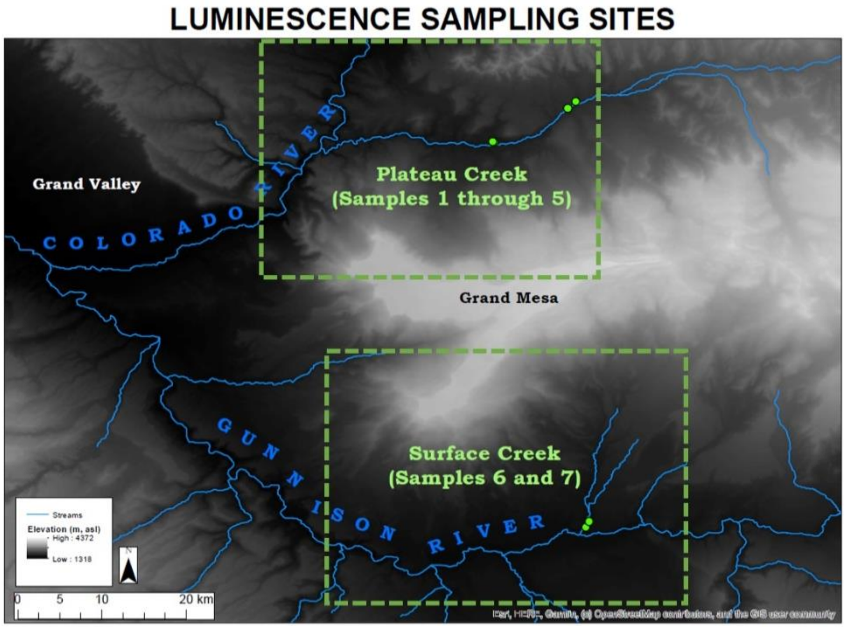


Figure 4.33 The Luminescence Sampling Sites.

4.4.4 Subsurface Imaging of Floodplains (Ancient and Modern) using ERT

Subsurface scanning enables indirect observation of a large spatial extent that direct outcrop observation cannot offer. Although no such geophysical survey has been undertaken previously for the floodplains in Grand Valley, various geophysical methods have been employed for subsurface investigations elsewhere. The ERT method has been widely used in identifying glacial, glaciofluvial, muddy sediments, and groundwater contents based on the spectrum of resistivities of the media (e.g., Smith and Sjogren, 2006; Lucius et al., 2006; Chambers et al., 2011; 2012).

Establishing visually that boundaries of resistivity contrast in the subsurface do exist, and thereby corresponding to the physical stratigraphic boundaries, is essential for the efficacy of the ERT as a subsurface survey method (*sensu* Palacky, 1987; Everett, 2013). Exemplary cross-sections of electrical resistivity scans show clear distinctions between larger, coarser grained sediments of higher resistivities overlying the mud rocks of lower resistivities below (Figure 4.34). As addressed in the latter sections of this Chapter, the terrace and glaciofluvial deposits of high resistivities are similar to the ERT data collected in Grand Valley.

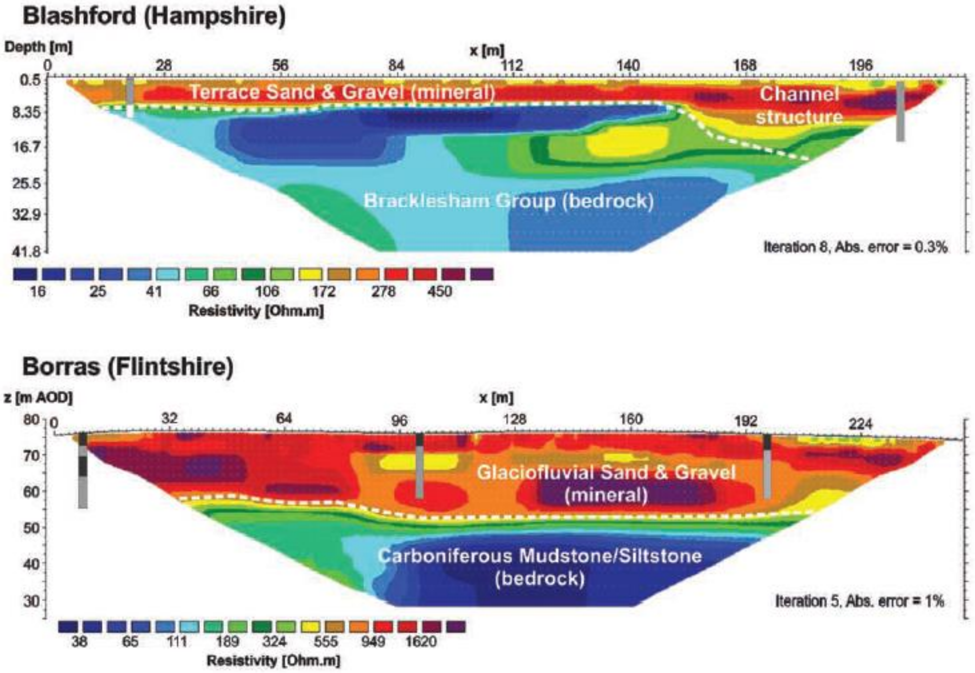


Figure 4.34 Resistivity Contrast between Mud-rocks, Sands, and Gravels. It was adapted from Chambers et al., 2011. Note that the resistivity values (ohm-m) can range from site to site, as little as orders of hundreds to as much as thousands.

In addition to the justification for possible detection of high-low resistivity zones in ERT transects (Figure 4.34), a field corroboration was made at Site 1 (Figure 4.29). The vertical location of Site 1 terrace is the highest among all five (5) transects, with no evidence of tectonics to have changed its relative elevation compared to the rest of the Sites. Thus, it is reasonably assumed to be the oldest terrace of all the survey sites in Grand Valley. Importantly, the higher vertical position relates to least amount of groundwater present in the matrix as well. For these reasons, all other sites were compared to this locale for gravel-shale-groundwater distinction in the respective profiles.

Site 2 was a modern floodplain, and thus the youngest and closest to the modern river channel compared to the rest. As Sites 1 and 2 constitute the two ends of a spectrum of floodplain ages, Sites 3 through 5 ancient floodplains, were compared to Sites 1 and 2.

For all Sites, the accompanied interpretive figures offer delineations of the Mancos Shale, terrace gravels, rain-groundwater, and a brief snapshot interpretation. Particularly, the role of rainwater and groundwater is a major concern for interpretation, and is dealt with in each profile.

As Figure 4.35 shows, once it rains, water would percolate down, as time progresses from A to B through C and D. Because the terrace gravels and clasts are more permeable, water easily descends into depths. Groundwater eventually encounters the stratigraphic boundary between the terrace clasts and the less permeable Mancos Shale, and flows over the Mancos Shale toward the lowest topographic point in the area—typically toward the river channel.

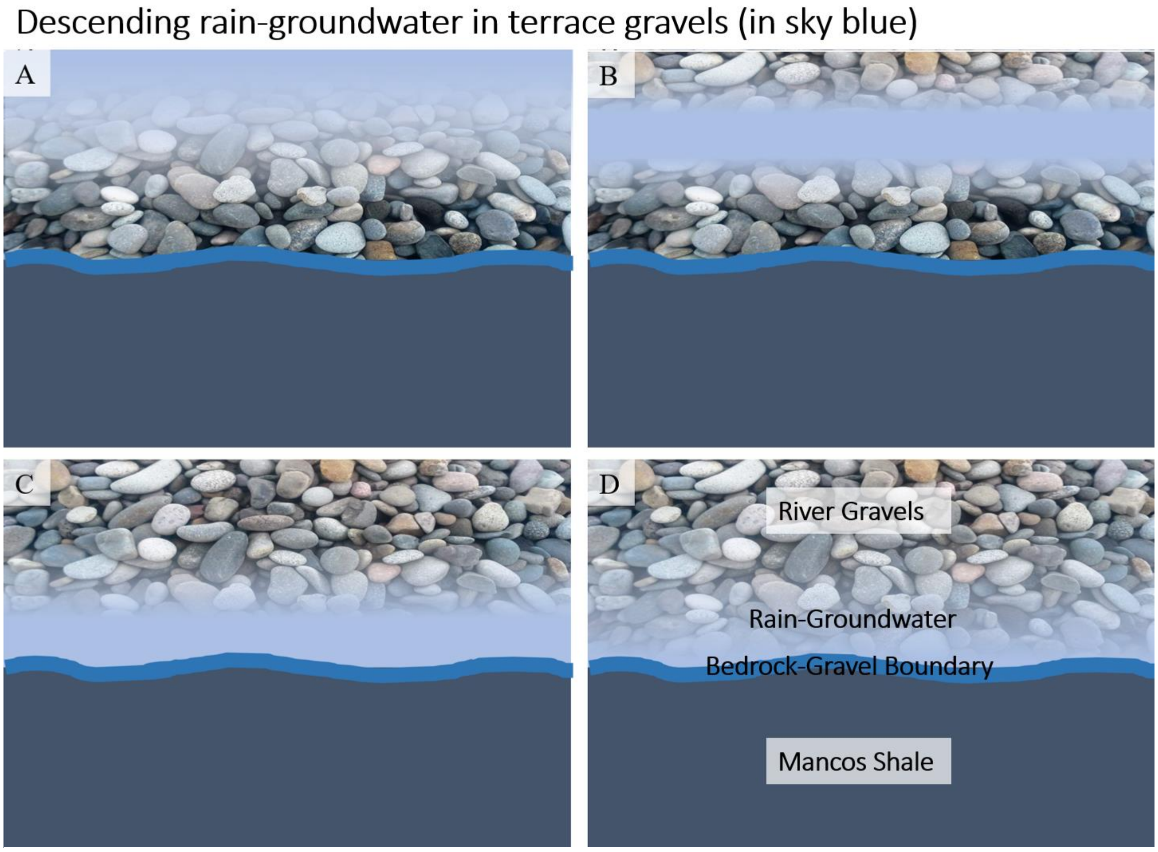


Figure 4.35 An Illustration of Rainwater Descent into the Terraces.

Complemented by the Grand Junction Surficial Geologic Map (Scott et al, 2002), a visual observation with a tape measurer showed that the Mancos Shale appeared at a relatively uniform depth of about 7 to 10-m from the alluvium surface across the profile.

4.4.5 ERT Site 1: Mesa County Landfill (the Standard Transect)

The site at an entrance to the county landfill is located at the highest elevation (1,506 m, above sea level) and thus the oldest floodplain of all sites (Figure 4.36). Most importantly, the site, as an outcrop, enabled a correlation between visual stratigraphic observation and tomographic data of the boundaries between the Mancos Shale and river gravels.

Figure 4.36 An Aerial Image of Site 1. The transect is marked in yellow, distance indicated by the "Ruler" on the left. The elevation of 1506 m from sea level is noted for the starting position of the survey, which makes the site the oldest alluvium site of all five.

The transect is characterized by a stark contrast between higher resistivities in warmer colors red, yellow and green in the upper section, and lower resistivities in colder colors light-blue and blue beneath (Figure 4.37). The section with highest resistivities (> 400 ohm-m), including those appearing as blobs (> 700 ohm-m) are located at 1-5 m depth, whereas the lowest (< 40 ohm-m) in the upper 1 m and below 7-8 m depth, depicted in light-blue and dark blue. The transition between low and high resistivities is more abrupt near the surface and more gradual at depth nearing 7 m.

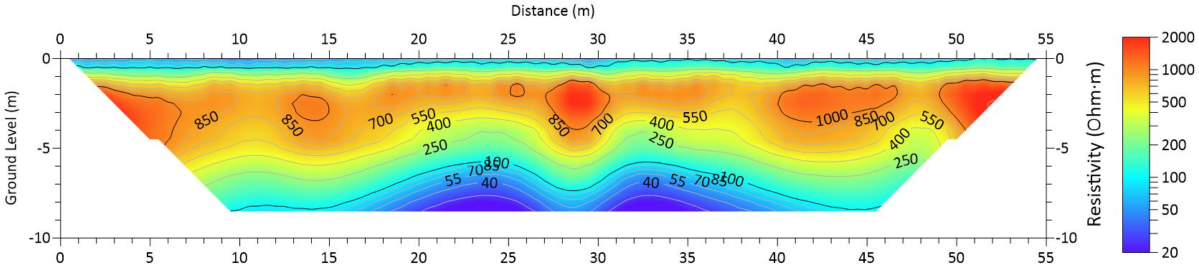


Figure 4.37 Site 1 near Mesa County Landfill.

The depth to the Mancos Shale in the ERT transect data is corroborated by the visual assessment with a measuring tape in the field, which fluctuated between 7 m and 10 m depth across the site (Figure 4.38). Thus, the high resistivity (> 400 ohm-m) correlates to Quaternary alluvium that consists primarily of Colorado River gravels and sand. The zones low resistivity (< 40 ohm-m) highlighted by the blue color correspond to the Mancos Shale. The thin veneer of yellow and green that is present at the 1-m depth was verifiably rainwater from the days preceding the survey that percolated into the alluvium. The more gradual transitional zone from green to light-blue seems to indicate moisture from other rain events that remained at the bottom of the porous and permeable alluvium, or on top of the underlying shale that is relatively impermeable. The Mesa County landfill site profile, thus, establishes that higher resistivities on the order of 40 ohm-m and higher represent alluvium (drier if higher ohm-m) and the lower resistivities (<40 ohm-m) the Mancos Shale.

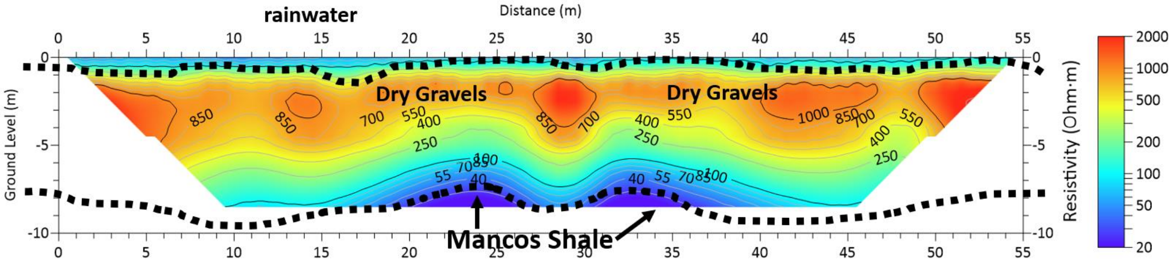


Figure 4. 38 A Stratigraphic Interpretation of Site 1.

4.4.6 ERT Site 2: Palisade Riverbend Park (Modern Floodplain)

Palisade Riverbend Park is the youngest floodplain, and the sole active floodplain site, of all the survey sites (Figure 4.39). As such it is at the opposite end of the age spectrum from Site 1 among the five transects (Figure 4.40). Presumably, the amount of anthropogenic activities is the least at this site along with Site 1.

Figure 4.39 An Oblique View of Site 2. Immediately north from the transect is a canal, which was dry during the survey.

A major contrast to Site 1 and others is with the matrix that is most wide ranging in the ohm-m reading from one- to three-digits. High resistivity values (> 100 ohm-m) are concentrated as blobs around 1) 4 m and 13 m; 2) 14 m and 22m; 3) 25 m and 33 m; 4) 33m to 38 m; and 5) 40 m and 52 m, with varying vertical extents. These high values are underlain and overlain by regions of low resistivities (< 20 ohm-m); as concentric regions alternate the zones of high resistivity in the depths around 7 or 8 m, a veneer of low resistivity (< 20 ohm-m) covers the profile from 0 m to 40 m across. (The survey transect 0 m side was closer to the modern Colorado River and the 55 m was toward the town of Palisade, despite all other Sites the reverse is the case.) Conspicuously, the contrast between high and low resistivities is more abrupt on top of the centers of high resistivity blobs, and more gradual below them.

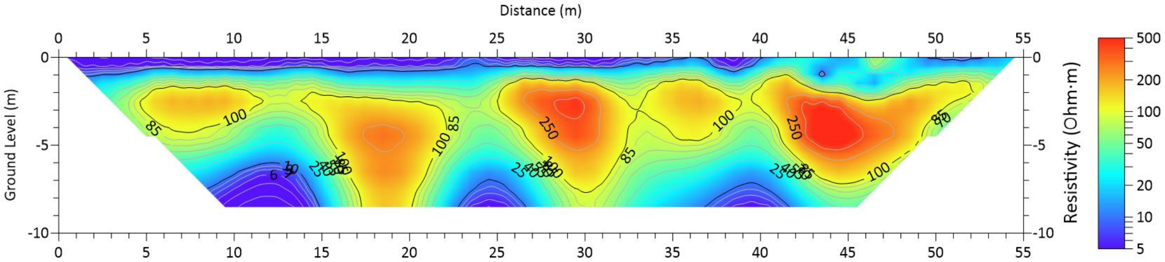


Figure 4.40 Site 2—A Modern Active Floodplain, Palisade Riverbend Park.

Higher resistivity is interpreted as river gravels, based on the insights from the Site 1 ERT data and the field corroboration, and the low resistivity as groundwater on the surface and shale as three blobs at the deepest sections (Figure 4.41). Apparently, the values of high-resistivity (> 100 ohm-m) blobs decrease toward the modern river (~260 m) as groundwater flows according to the hydraulic gradient. However, the concentration of the high resistivity appears to be unusual and contrastive to the gravel layer of Site 1, which is generally continuous, rather than discrete. These zones of high resistivity may be either boulders or aggregates of gravels, and the blobs of low resistivity Mancos Shale. The interpretation of these deposits will support either historical scenarios of diluvial (glacial flooding) or fluvial (gradual fluvial evolution). The historical alternatives will be discussed in Chapter V.

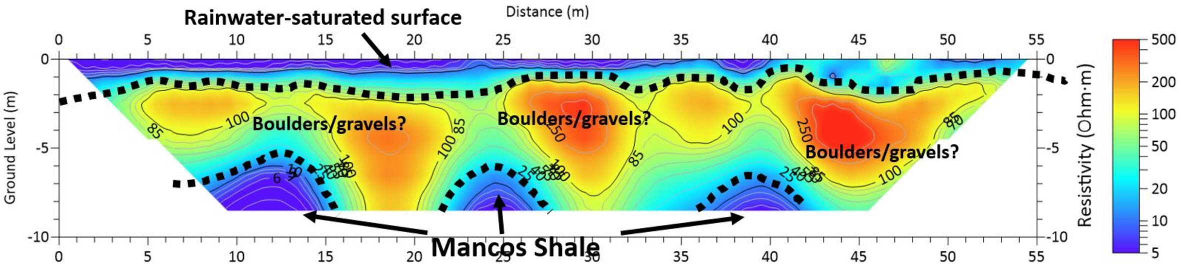


Figure 4.41 An Interpretation of the Modern Floodplain.

4.4.7 ERT Site 3: Palisade Orchard Terrace

The Site 3 is an orchard and a younger "Qt1" Quaternary terrace transect (Carrara, 2000), between an older terrace in the north modern floodplain (not Site 2) in the south next to the Colorado River near the De Beque Canyon mouth (Figure 4.42). The orchard is about 430 m horizontal distance away from the edge of the Colorado River and 150 m from the foothill of the Book Cliffs.

The transect is characterized by mid- and deep sections of high resistivity (> 150 ohm-m) and moderate resistivity values (between 50 and 100 ohm-m) in the upper to mid sections down to 5 m depth (Figure 4.43). The lowest resistivity (< 40 ohm-m) occurs in patches in the upper section and one apparently slab-like section and two small blobs of low resistivity around 39-43 m and 45-50 m across. The site has no zones of < 20 ohm-m, unlike other ERT transects.

Figure 4.42 Site 3—an Orchard in Palisade near the De Beque Canyon. The site is seen obliquely in an aerial photo. Note that immediately northwest is an older terrace and further up, the Book Cliffs that start at the canyon mouth and extends to Utah. Note the Colorado River exiting the De Beque Canyon in the northeast.

Overall, there appears to be no materialistic cause for low resistivity at the site. The Mancos Shale is absent in the transect, although it may be present at a greater depth than the survey transect. Either the terrace is composed of thick alluvium or is compounded by colluvium that originated from the Book Cliffs. Although available geologic map (Carrara, 2000) makes no mention of colluvium in this terrace, the surface is roughly on the trajectory of the talus flow direction of the Book Cliffs < 200 m away, gently angled (2~3°) upslope toward them. As in other transects, the patches of low resistivity on the surface form in the uppermost a 1-m, corresponding to meteorological input from preceding days. However, organic materials are possibly present in the orchard, and thus they also may contribute to the low resistivity near the surface. That no resistivity < 25 ohm-m exists in the transect, the mid-section concentric circles and slabs, and resistivity generally increases with depth indicates that this terrace is located relatively high (> 9 m) in stratigraphy, away from the Mancos Shale that may be present below the depth penetrable by the ERT setup.

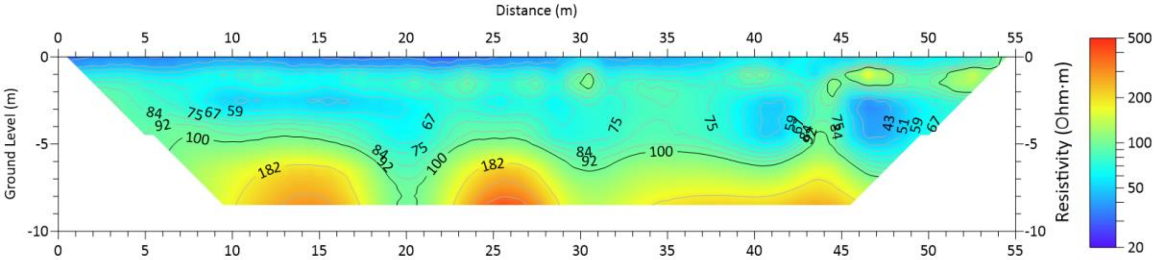


Figure 4.43 Site 3 Orchard in Palisade near the De Beque Canyon.

The unmistakably high-resistivity blobs (> 150 ohm-m) at depths constitute a feature exceptional to this site. The blobs may steer historical interpretation because they could be either 1) boulders transported from the Book Cliffs or 2) boulders transported by glacial flooding from upstream colluvium input, or 3) aggregates of gravels transported by the Colorado River (Figure 4.44).

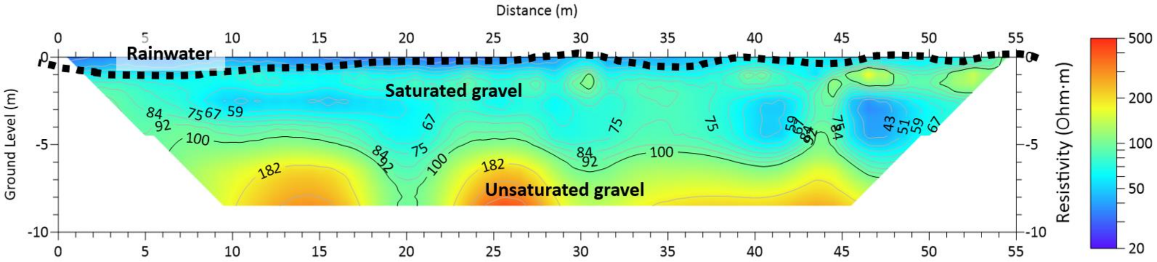


Figure 4.44 Site 4—Palisade Orchard Transect Interpreted.

4.4.8 ERT Site 4: Palisade High School Campus Terrace

Site 4 is inside the campus of Palisade High School, about 0.5 km distance from the modern Colorado River. Although the survey site is flat, as indicated by the adjacent school sports fields, the surface was recognizably engineered horizontally (Figure 4.45).

The mid- to lower- sections consist of high resistivity blobs—the resistivity stands out among the rest of the transects, being beyond the scale and on orders of 1,000-4,000 ohm-m (Figure 4.46). Relatively lower resistivity occurs on the 1-3 m from the surface, and the more prominently low blobs of resistivity occur in spaces unoccupied by the high-resistivity blobs from 7 m to 21 m and from 28 m to 38 m across.

With the possibility of being concrete or colluvium notwithstanding, the high-resistivity blobs are as large as 10 m in diameter (Figure 4.47). The blob in the middle of the transect appears to be dividing the substrate of low resistivity, which may be tops of the Mancos Shale. The horizontal boundaries between the blobs of high- and low-resistivities may be permeable gravel is resting on top of the Mancos Shale that is further beneath the transect.

Figure 4.45 Palisade High School Transect. Note that the presence of sports fields attests to the flatness of the transect.

Assuming that the two blobs of low-resistivity at the bottom section (~7-8 m depth, cf. Site 1) are the shale, higher resistivities (still in light blue) resting on top of these may be groundwater that has accumulated on top of the Mancos Shale. Around sections between 22-23 m, and 37-39 m across, there appears to be a systematic discontinuity of 1.5 m drop on the surface, perhaps indicating a fault in the latter. The former appears to be a minor dip unrelated to tectonics. However, both dips must have been bulldozed over on the surface for the construction of the campus, particularly more permeable material. However, the five zones of high resistivities seem to be notable anomalies. If the five zones of high resistivity in the transect are horizontal construction material, why are they discontinuous and how large a boulder does a school campus ground need for construction? If these are merely aggregate of gravels formed via fluvial processes, how can they appear on the order of 1,000 ohm-m, whereas typical river gravels are on orders of 100 ohm-m? If they are boulders, where did they come from: the Book Cliffs, or somewhere upstream during high stream-power episodes? These questions are addressed in Chapter V.

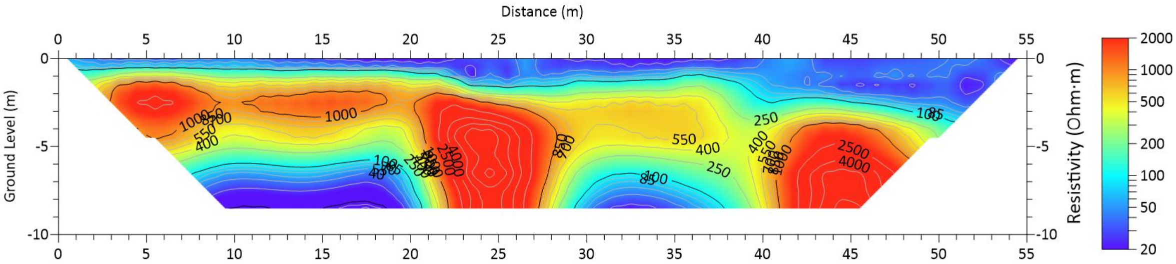


Figure 4.46 The Cross-Section Transect of Palisade High School Campus. Note that the range of high and low resistivities is the widest at this location. The scale was lowered to 2,000 ohm-m to enable more precise delineation of the boundaries.

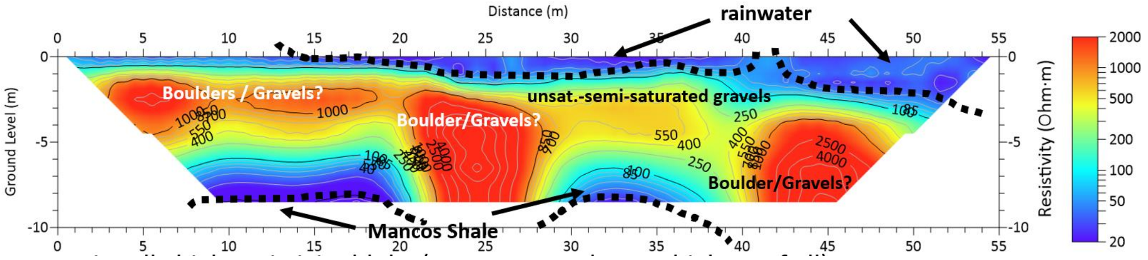


Figure 4.47 Palisade High School Site Interpreted.

4.4.9 ERT Site 5: Grand Junction Confluence Terrace

Site 5 is on an artificial fill on top of a former uranium mill operated by Department of Energy in Grand Junction, just about 1 km upstream from the confluence (Figure 4.48). However, noting that fills in the Grand Junction area are at most 5 m in depth, the transect is legitimate for detecting the Mancos Shale underneath. Knowing that across the river, a 20-m tall riverbank consists visibly of the Mancos Shale, the transect ought to recognize low resistivity signals of the shale generally at its pre-construction condition.

Figure 4.48 Site 5—Former Grand Junction Uranium Mill Site. It is about 5 km upstream from Grand Junction confluence with the Gunnison River. It is an artificial fill, adjacent to the active floodplain.

Figure 4.49 shows the cross section characterized by generally low resistivities throughout (< 50 ohm-m). Relatively higher resistivity forms a nearly parallel bedding of in the upper (in warmer colors) and the lower low-resistivity section (in colder colors). Resistivity is exceptionally low even in the upper 2 m. Between from 4 m to 9 m and from 41 m to 47 m across, there are two vertically elongated zones of high resistivity (ranging from 20 to 50 ohm-m) from 2-m depth and below. Alternately, between them, there are two blob-shaped zones of low resistivity (< 10 ohm-m) at 9-16 m across and 33-40 m across, covered by a ~15 ohm-m zone.

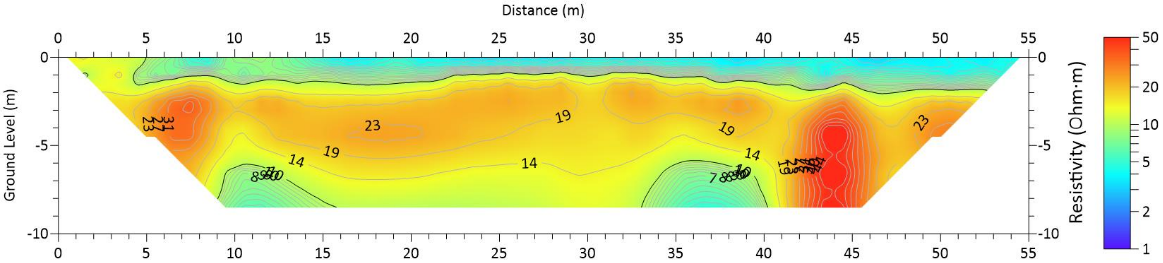


Figure 4.49 Site 5 Transect. It is immediately next to Colorado River channel, so is there much groundwater still retained inside the gravel matrix?

The 1-2 m depth low resistivity zone appears to be a veneer of rainwater akin to seen in the previous Sites (Figures 4.49 and 4.50). Particularly, the artificial fill would have been bulldozed over with coarser material seen on the surface as was likely the case in Palisade High School Site (see Figure 4.47). Apparently, the groundwater is flowing from 0 m end to the 55 m direction, toward the modern Colorado River channel. The zones of the lowest resistivity (< 10 ohm-m) starting around 6 m depth is the impermeable Mancos Shale, and the thickest section buried parts of old building material or foreign gravels with high permeability. The most notably high-resistivity sections that appear as upright beam-like structures might be remnants of the DoE uranium mill building, perhaps concrete. Otherwise, although highly unlikely, the zones of relatively higher-resistivity in the transect may be gravel, or even more unlikely, boulders placed there by strong stream flows.

Overall, the Colorado River gravel is missing at this site, but only artificial materials related to building construction, indicated by relatively higher resistivity, and blobs of the shale in the depths with the lowest resistivity. Even if naturally transported gravels are absent at this site, the morphology of the remaining Mancos Shale fits with the rest of the ERT data.

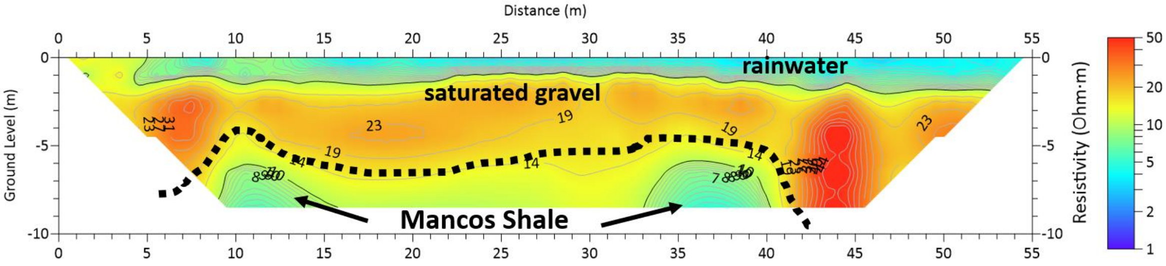


Figure 4.50 An Interpretation of Site 5.

CHAPTER V

ANALYSIS

The introduction of this dissertation has addressed two major research questions for the Grand Valley and Grand Mesa area. One question involved the dearth of age estimates in the area making it difficult to tie geomorphic evolution to the known glacial advances in the general Rocky Mountains regions, although consistent with the Wisconsin age of the rest of the continental North America. The other question pertained to the simplistic hypothesis of the regional geomorphic evolution, which was based solely on fluvial processes, without regard to climate-driven glacial flooding from the Grand Mesa. Both issues are re-visited and revised in light of the new data presented in Chapter IV in the first section of this chapter. In the subsequent section, a new scenario of the regional geomorphic history is offered.

5.1 Grand Mesa Diluvium – OSL Ages

The field observations from the survey of the Plateau Creek valley demonstrate that multiple glacial floods took place much like in the southern flank of Grand Mesa. The imbricated basalt clasts at our study site are nearly identical to the descriptions of the deposits in the up-valley by Yeend (1969, in towns of Mesa and Colbran, CO) and are consistent with the basic conclusions about their counterparts in the southern flank of Grand Mesa (Brunk, 2010; Blakeley, 2014). The prevalent surficial deposits in the Plateau Creek valley along the modern channel are often poorly sorted, rarely angular, prominently boulder to gravel sized basalt clasts that are imbricated in the down-valley direction as the strike-dip measurements showed. This is reminiscent of a variety of glacial flooding settings documented elsewhere, including overtly megaflood examples (e.g., O'Connor, 1993, Russell and Knudsen, 2002; Fay, 2002; Benvenuti and Martini, 2002). ***Therefore, glacial flooding is invoked as a sedimentary and geomorphic process forming the fill-terrace deposits in the northern flank as in the case with the up-valley regions and the southern flank.*** It is in this sedimentary context that the OSL samples were collected.

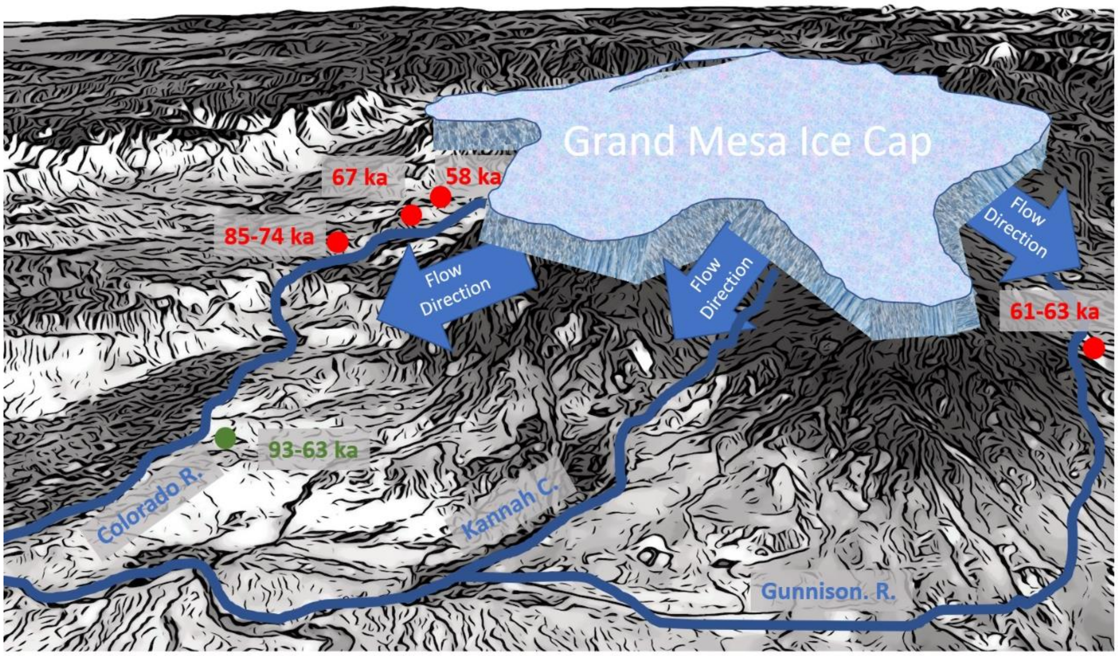


Figure 5.1 A Simplified Illustration of Glacial Flooding from Grand Mesa. Noted in red are new ages reported in the dissertation, whereas denoted in green are the date range reported by Aslan et al. (2019). Drawing courtesy of J. R. Giardino.

The newly reported numeric ages of the deposits in the northern and southern flanks of Grand Mesa showed that deglacial flooding occurred over a wide range of time, 84 ka-58 ka (Figure 5.1). These dates overlap with the OSL ages of the deposits in the southern flank of Grand Mesa (Noe et al., 2015), the moraine deposits in Ridgway, less than 150 km away (Jarrin et al., 2017); and most relevantly, the Orchard Mesa terrace in Grand Junction (Aslan et al., 2019; Aslan and Hanson, 2009). The group of the recently obtained dates, inconsistent with the known glaciations older Bull Lake and younger Pinedale, may be perceived as a puzzling phenomenon in the Rocky Mountains region. Instead of being a puzzle, these new numeric dates as a whole, indicate that there had been glacial advances between Bull Lake and Pinedale, a new interpretation of the climate history of the central-western Colorado. Furthermore, the consistency among the numeric dates established lately allows for a new scenario for the landscape evolution in the Quaternary times. ***In summary, I suggest that multiple glaciations unequivocally occurred in the central-western Colorado region, apart from the widely known Bull Lake and Pinedale glacial times. Accordingly, geomorphic implications of the glacial episodes are so significant as to re-write the account of the landform evolution of Grand Valley. The glacial outburst flooding that generated the fill-terraces must have had major impacts in shaping Grand Valley in the downstream.***

5.2 Estimations on the Glacial Extent and Volume

The glaciers advanced and retreated multiple times during the Pleistocene epoch. The commonly known glaciations in the Grand Mesa area took place around 130 ka (Bull Lake, MIS 6) and 10 ka (Pinedale, MIS 4). As presented in Section 5.1, more glaciations, probably more sizable than the Pinedale must have occurred. Arguably, and most likely, the tills that are commonly presumed to be the Bull Lake-age might actually be from the glaciations proposed in the previous section. This idea is consistent with older studies that suggested that glaciers had occupied the Plateau Creek Valley, because Grand Mesa and

Battlement Mesa would have been physically connected prior to the subsequent erosion history (Figure 5.2).

The conservative estimate of the glacial extents derived from the moraine heights today; the height of the moraine and the lake of the Pinedale age (White, 2018; Chesnutt et al., 2019; White and Palkovic, 2019). The volume of the glaciers was thus 6.28 km^3.

A more realistic estimate of the glacial volume was acquired by following the guidance of Henderson (1923) and Yeend (1969) who suggested that glaciers flowed over the ledges of Grand Mesa based on the presence of lakes (including artificial lakes, which had been natural glacial lakes previously). The estimated volume of the icecap was 10.76 km^3.

The latter estimate is still conservative, judging from the fact that Grand Mesa and Battlement Mesa would have been connected previously and the ledges of Grand Mesa have been and are being eroded today rendering much wider areal extents. Furthermore, the thickness of the ice would have been thicker throughout.

A comparison to other glacial conditions and flooding is instructive. The well-known Missoula ice dam produced megafloods with the melting of the ice volume of 2,184 km^3. (cf. Komatsu et al., 2000; Baker, 2013). Two lesser flooding events that took place earlier in the 21st century Canyon Lake Reservoir failure in Texas (4.71×10^{-1} km^3; Lamb and Fonstad, 2010) and the Taum Sauk Reservoir failure in Missouri (2.45×10^{-3} km^3; Rydlund, 2006; Rogers et al., 2010).

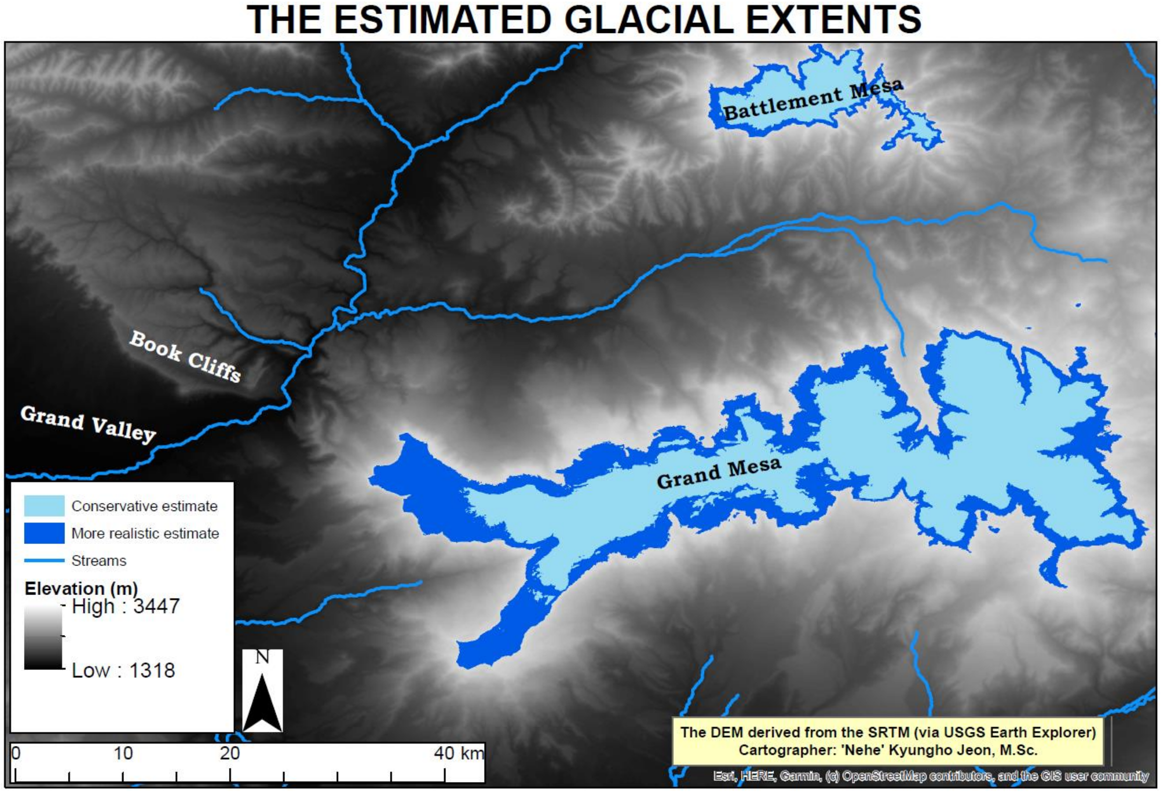


Figure 5.2 Estimates of the Glacial Extents on Grand Mesa. A conservative estimate (light blue) is based on the Pinedale moraines and lakes and the more realistic estimate for Bull Lake or any other pre-Pinedale glaciations.

The estimated glacial volumes on Grand Mesa are orders of magnitude smaller than the Missoula lake that flooded. However, relative to the failures of the Canyon Lake Reservoir and the Taum Sauk Reservoir, the Grand Mesa is more than sufficiently tenable as glacial water storage and subsequent glacial discharge. The volumes of the water released by the two reservoirs were orders of magnitude less than the conservative estimate of the water that had been stored on Grand Mesa as ice. Yet, the geomorphic work that the failure of the two lakes has done on the respective landforms is massive. Hence, the actual amounts of glaciers on Grand Mesa and the subsequent melting would have been greater to have performed the geomorphic work apparent in the Plateau Creek valley.

In summary, melting of the voluminous glaciers from Grand Mesa would have been more than sufficient to have deposited and eroded the fill-terrace deposits exposed in the Plateau Creek valley. Furthermore, the water and sediment from the jökulhlaups would have traveled downstream to the Colorado River confluence and further into Grand Valley.

5.3 Grand Valley Terraces – ERT data

The ERT data showed that each terrace consisted of a thick river gravel bed (~ 5 m) that overlies the Mancos Shale (except at Site 5, where artificial fill overlies the Shale). Visual confirmation of the gravel-Mancos Shale stratigraphy was made in Site 1 and in other gravel pits (Figure 5.3A). Evidently, any lithologic unit (predominantly the Mesaverde Group, preserved in the up-valley region from both Grand Valley and Grand Mesa; see Section 2.8 and Figure 2.6) that used to cap Mancos Shale in Grand Valley had been eroded away and replaced by the Colorado River gravels. Intriguingly, all terraces in Grand Valley, except one at the highest elevation, consist of flat sets of gravels overlying the Mancos Shale (Aslan et al., 2009), as if little channel process was involved in their formation. What processes might have produced these terraces? Are they *fluvial* terraces?

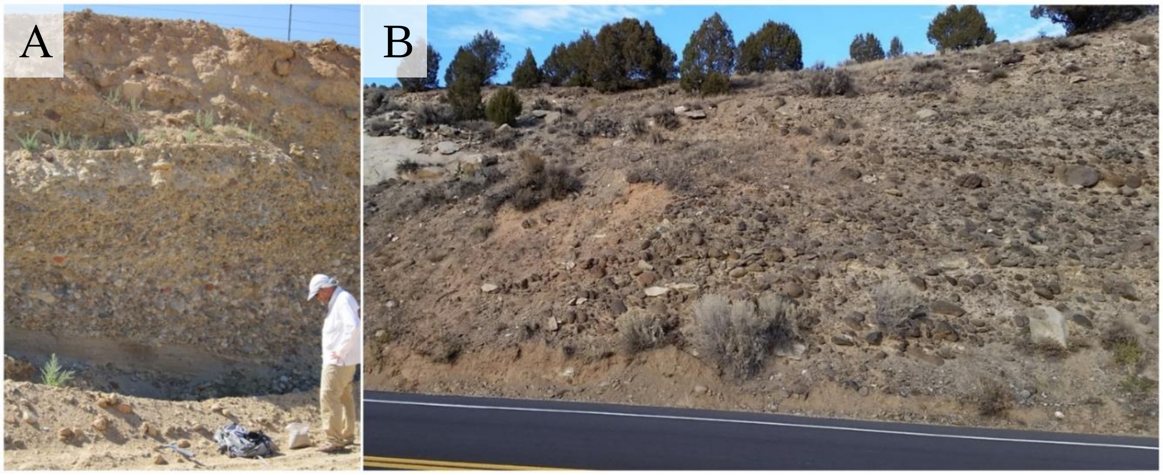


Figure 5.3 Terrace Gravels and Clasts. A: Grand Valley terrace gravels, smaller than their counterparts in the Grand Mesa flank, shown in B. (Photo courtesy of A. Aslan.) B. Larger clasts (ranging from cobble to boulders) in Grand Mesa flank (Photo by K. Jeon).

Despite the lack of identifiable paleochannels and the mechanism for alluviation of clasts in the terraces, earlier workers relegated the genesis of the terraces solely to fluvial processes (e.g. Sinnock 1978; 1981a; 1981b; Aslan et al., 2019). However, examining field evidence (Figure 5.3 A, B, and our ERT data) critical questions can be raised: 1) Could the ancient and modern Colorado River have had an enough competence to transport as bedload clasts of such sizes, or have the capacity to transport the volume of clasts? 2) If seasonal flooding is invoked, then could floods have lasted sufficiently long to have alluviated several meters of sediments without obvious discontinuities in stratigraphy? To address these questions, the Grand Valley examples are compared to diluvial deposits below.

The thick deposits of clasts in the Grand Mesa flanks and the Grand Valley terraces are so comparable in sizes, sorting, and imbrication as to invoke similar processes for their origin (Figure 5.3). That the sizes range from boulders, cobbles, and gravels, leads one to think that the deposits from two locales appear to be in a continuum of an event, that is, proximal and distal deposits eroded from Grand Mesa. Modern analogues of gravel deposits further elucidate the observations.

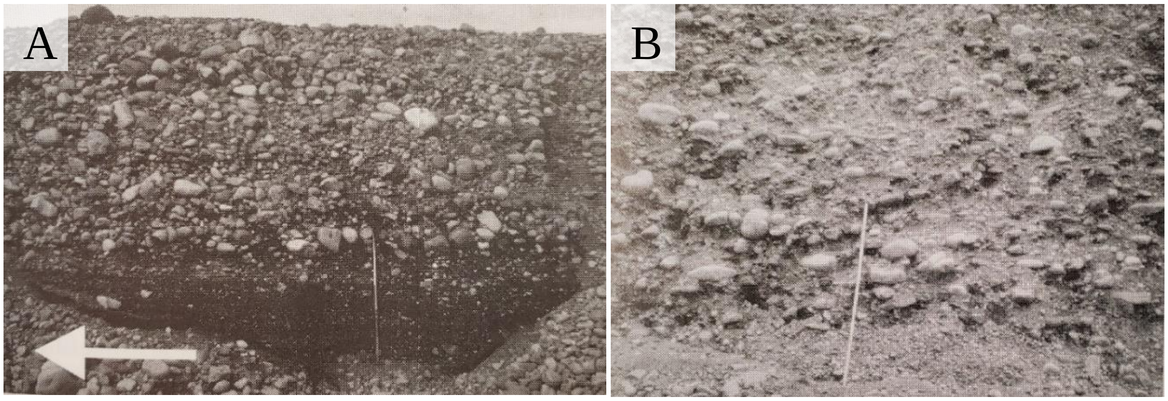


Figure 5.4 Glacial Outburst Flooding Deposits in Iceland. A. A waning stage deposit of glacial outburst flooding. Sorting is poorer than Grand Valley's, but these boulders show imbrication and cluster, similarly observed in the ERT transects. (Photos adapted from Russell and Knudsen, 2002). B. Imbrication of cobbles (the 1 m-rod for scale) Benvenuti and Martini (2002). Aggregates of cobbles are reminiscent of the Grand Mesa flank deposits and the ERT subsurface scans of Grand Valley.

Iceland is climatically isolated and still is a host of voluminous glaciers. With much climate change and volcanic activities ongoing, the country is prone to jokulhlaups that alter landforms dramatically in observable timespans. Figure 5.4 shows two diluvial deposits, both of which are poorly sorted and imbricated to appreciate the fluid energy involved in sedimentation. One difference between the two is that Figure 5.4A is a product of waning stage of flooding that aggraded continuously (as argued for the Grand Valley terraces), and that 5.4B is a result of hyper-concentrated flow, a continuum between debris flow and glacial flooding (similar to the deposits of the Grand Mesa flanks, especially the south).

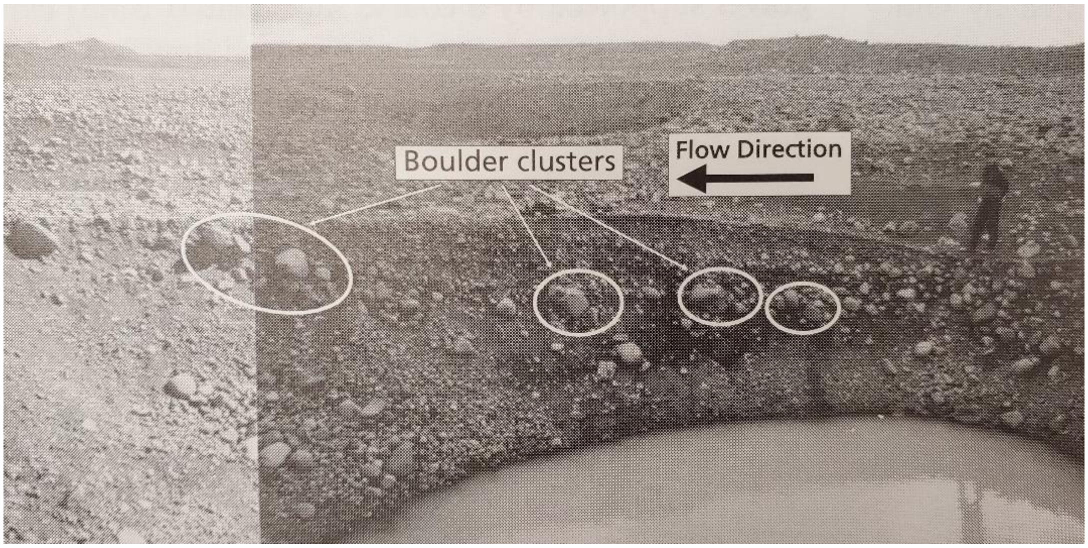


Figure 5.5 Imbricated and Clustered Boulders from Icelandic flooding. It was adapted from Fay (2002). Note the person on the right for scale.

More closely related to the ERT data that showed distinct zones of high and extremely high resistivities (> 100 ohm-m in every site; and even > 1,000 ohm-m in Sites 1 and 4), another field example from Icelandic glacial outburst deposit shows clusters of boulders trailing along the surrounding imbricated clasts (Figure 5.4). As indicated in Chapter IV, the blobs of high resistivity values are most likely to be aggregates of gravels, cobbles, or even boulders. The zones of distinctly high resistivity shown in Sites 1 and 4 (> 1,000 ohm-m) are arguably boulders (~ 5 m radius) transported by the same glacial deluges that extended down into Grand Valley. At the very least, the zones of high resistivity are interpreted as aggregated cobbles and gravels. The source of the boulders may disputably be the Book Cliffs, upstream of Grand Valley, or both. Regardless of the provenance, nevertheless, the boulders had to have been moved by water flows that greatly exceed fluvial or seasonal flood discharges, with the Icelandic glacial outbursts considered as modern analogues.

The lack of observable boulders in terrace outcrops in several gravel pits in Grand Valley could raise a concern. Perhaps urbanization is a reason that such boulder clusters have not been common in gravel pits in the Grand Junction and Orchard Mesa areas. Residential developments rendered some outcrop sites inaccessible (see Figure 2.22). However, it is possible that aggregates of boulders can be found in outcrops in the future.

In summary, three main points are made. First, the new age estimates of glaciofluvial deposits are consistent with the burgeoning recognition of glacial episodes between the widely known Bull Lake and Pinedale glacial times in the Rocky Mountains region. Second, the near contemporaneity of glaciofluvial deposits in the Grand Mesa flanks and the terrace deposits in Grand Valley is indicated also by the OSL date results (Figure 5.1). The third point logically follows that the genesis of terraces as indicated by ERT subsurface scans and field observations of gravels, cobbles, and boulders in Grand Valley are tied to the episodic glacial floods from Grand Mesa. Perhaps the majority of underfit channels in alpine settings around the world can be explained in terms of rather catastrophic processes of glacial floods emanating from glaciated mountains, as opposed to mundane river flows.

In conclusion of the examination of the OSL age estimates and the ERT subsurface scans in conjunction with field observations in the study areas, ***I invoke unusually larger amounts of discharges for the formation of the strath terraces in Grand Valley. Large amounts of clasts were also supplied primarily from Grand Mesa and their flanks by glacial floods that episodically inundated the areas during glacial-deglacial episodes that occurred between the Bull Lake and the Pinedale glacial times. Thus, I contend that the terraces are diluvial in origin, rather than fluvial.***

5.4 Terrace Genesis: a Review, its Relevance, and a Reconsideration

Terraces are generally considered abandoned floodplains (e.g., Bucher, 1932; Schumm et al., 1987; Bull, 1990; Wegmann and Pazzaglia, 2002; Pazzaglia, 2013). Fluvial processes are recorded in terraces, some of which reach to nearly 1 Ma (e.g., Pan et al., 2003). Two end members exist, fill and strath terraces. The former is favored in conditions of high sediment input leading to alluviation, whereas the latter is common if erosion is greater than deposition.

Fluvial terrace genesis is widely accepted to be dependent on three factors: 1) tectonics, 2) climate change, or 3) a combination of both components (e.g., Bull, 1990; Lavé and Avouac, 2001; Pazzaglia, 2013). For the former, uplift of a landform often causes a new base level, creates a knickpoint, raises the slope that leads to faster stream flow and thus incision (e.g., Bull, 1991; Pazzaglia and Gardner, 1993; Personius et al., 1993; Blum and Tornqvist, 2000; Demir et al., 2009; Finnegan and Balco, 2013; Yanites et al., 2010). For climate-driven terrace genesis, discharge and sediment load flux in the channel system are the prominent components (e.g., Hancock and Anderson, 2002; Hanson et al., 2006; Tyráček et al., 2004; Bridgland and Westaway, 2008; Fuller et al., 2009).

In the case of Grand Valley and Mesa, climate forcing appears to have been dominant, whereas tectonic influences significantly less so (for the < 100 ka time frame). Strath terrace formation in Grand Valley and elsewhere can be summarized in three stages: 1) beveling, 2) carpeting, and 3) abandoning. Between the second and the third stages, discharge is greatly reduced and the flow regime transitioned from a sheet-flow to an overall channelized flow. In this regard, of accumulated research efforts on understanding climate-driven terrace genesis, three works stand out: Limaye and Lamb (2016); and to a more extent, Larsen and Lamb (2016) and Hansen et al. (2006).

Numeric modeling of river valleys by Limaye and Lamb (2016) showed that downcutting and meandering can generate multiple terraces in thousands of years. One conclusion is that new terraces form during episodes of increasing incision rate, which was more explicitly advocated by Larsen and Lamb (2016). Larsen and Lamb (2016) demonstrated that accelerated valley incision by outburst floods and terraces were one of the resultant features in a coulee in the Channeled Scablands (Figure 5.6). The authors use the terms bar and terrace interchangeably, as the features formed under the well-known megaflooding conditions in eastern Washington State. With the progression of flooding and lowering of the channel bed, floodwaters no longer remained at the height of the previous channel, thereby deserting terraces aside and continue to incise. This exemplifies a rapid abandonment of a former channel level during large flooding.

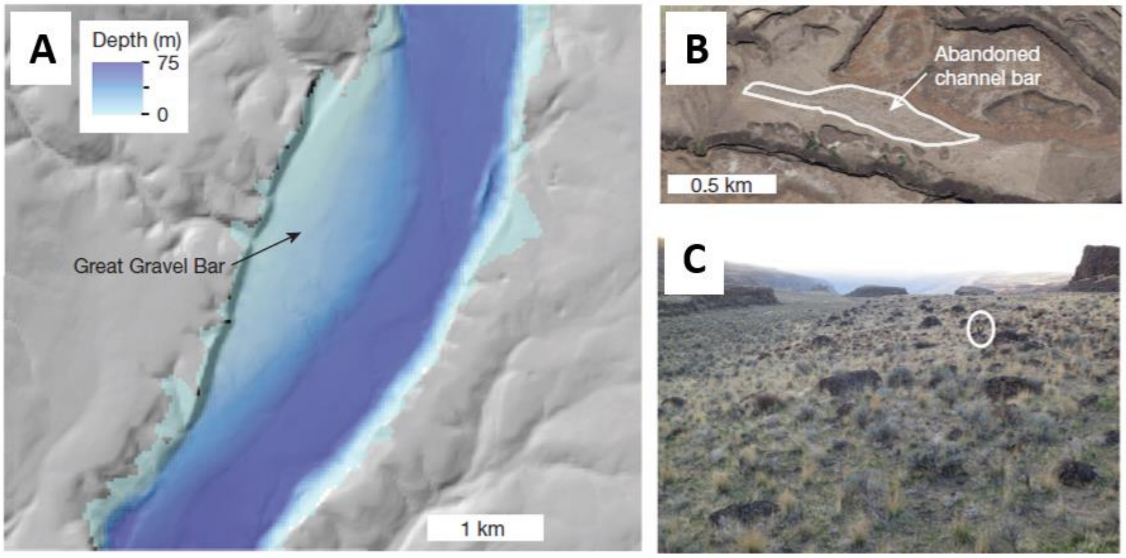


Figure 5.6 The Moses Coulee in the Channeled Scablands. It is the study site of Larsen and Lamb's (2016), and the figure was adapted from the cited work. A. The Great Gravel Bar on a water depth map with a simulated flood discharge. B. the map view of an abandoned channel boulder bar. C. a field photo of b. Unlike the surface of Orchard Mesa, this younger terrace is littered with many clasts, with a median size of 0.15 m.

Hanson et al. (2006) highlights the necessity of heightened stream power during glacial times to account for terrace genesis, and thus most significant for this dissertation. In the Laramie Range of Wyoming, five terrace levels were found to have originated from episodic, high discharge flooding. The site is comparable to this study in at least three aspects: 1) that the subject was in the Rocky Mountains setting; 2) that the ages of terraces (59 ka, 39 ka, 26 ka, 22 ka, 18 ka) roughly overlap with those in Grand Valley and Grand Mesa by post-dating Bull Lake glaciation, and 3) that unusually high discharges are invoked, though the authors do not equate them to glacial flooding *per se*.

As Larsen and Lamb (2016) investigated the genesis of strath terraces in the well-known Channeled Scablands megaflood context and Hanson et al. (2006) advocated that

Pleistocene flooding episodically incised into floodplains resulting in terrace genesis, the context is set for a diluvial interpretation for the evolution of Grand Valley.

5.5 What it Means: a Post-Bull Lake Glacial Flooding Scenario

The analyses of age and subsurface image data showed the possibility that glacial outburst floods from Grand Mesa had extended down to Grand Valley. In support of the analyses, terraces in the Channeled Scablands, Washington and those in Laramie, Wyoming were cited in the previous section as results of megaflooding and heightened discharges during the Pleistocene. Now, a diluvial hypothesis for the evolution of Grand Valley is offered here as a replacement for predominantly fluvial explanation.

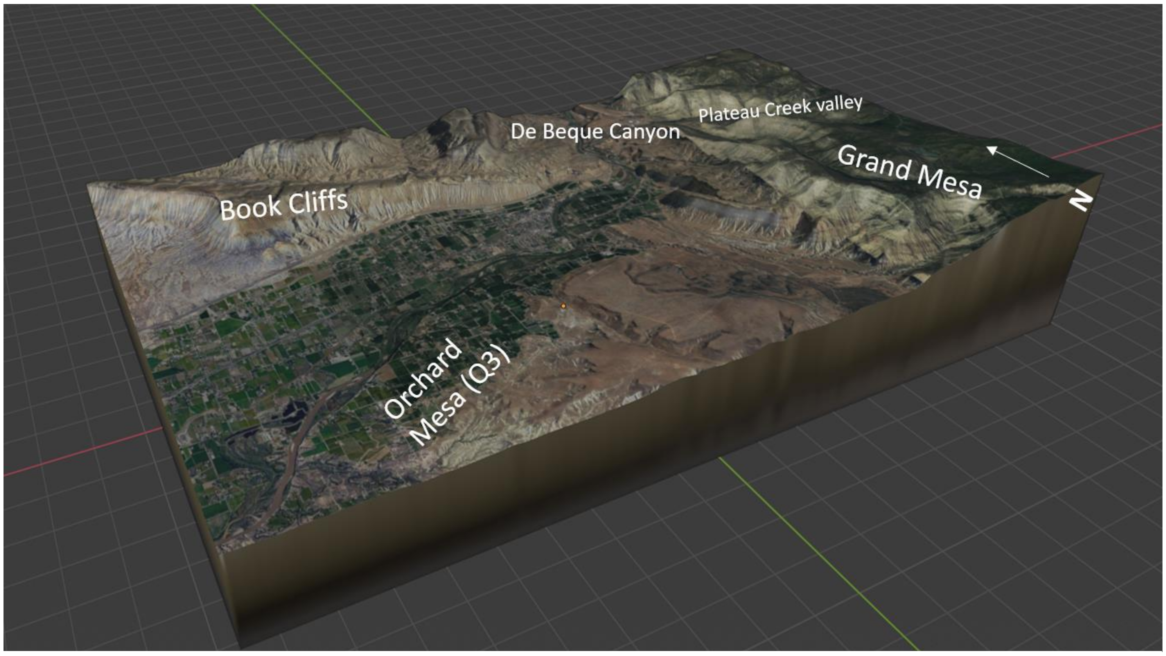


Figure 5.7 3D-Block Diagram Representing the Study Area.

In comparison to Sinnock (1981b), which covered the time frame of about 0.5 Ma between pre-uplift of Uncompahgre Plateau to Holocene, this new scenario spans from about 100 ka to today, since the formation of the most prominent terrace in the area, Orchard Mesa. The term for timing of each step highlights the sequential landform-shaping phases.

A series of block diagrams generated with the freeware Blender with a GIS package are presented. Figure 5.6 is a snapshot of the area from a day in Anthropocene. The subsequent block diagrams are presented in chronological order (Figures 5.8 – 5.12), and the conventional scenario that attribute solely to fluvial processes are rebutted when necessary.

5.5.1 Stage 1: After Tectonics

The ancient Colorado and Gunnison Rivers set in their course since the uplift of Uncompahgre Plateau (Sinnock, 1981b) outside the southwestern corner of Figure 5.8. The Colorado River enters Grand Valley at or higher than the elevation marked by Mesaverde Group that consisted the valley wall in place of the Book Cliffs. Entering the Bull Lake glacial times, Grand Mesa becomes occupied with an icecap.

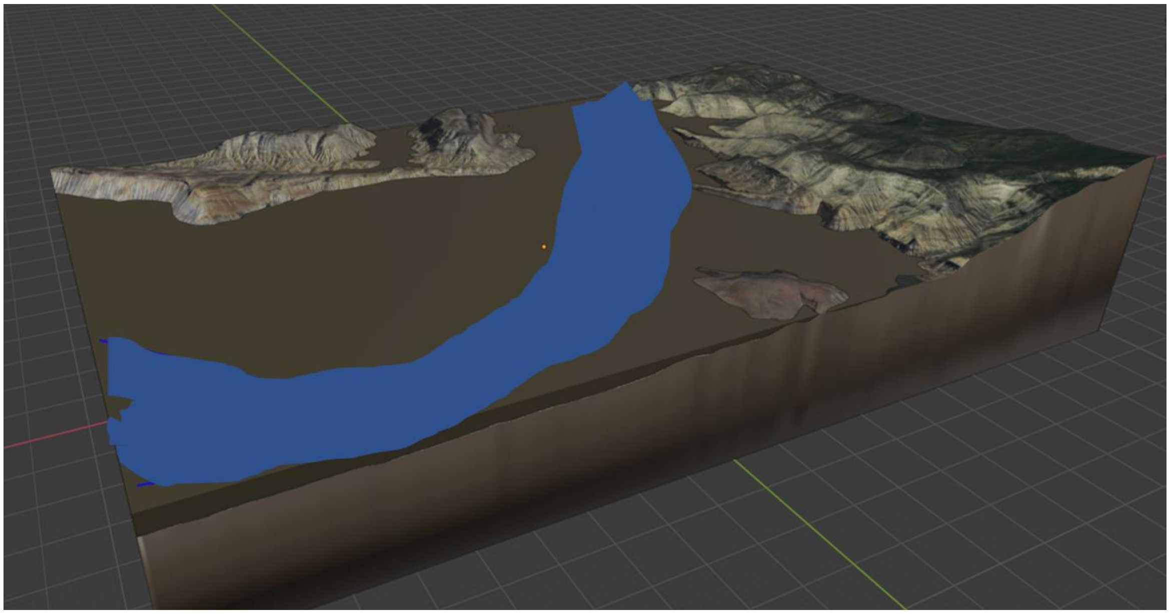


Figure 5.8 Stage 1: After Tectonics. The brown substrate represents the Mesaverde Group, and the blue, the hypothetical, general flood discharge.

5.5.2 Stage 2: Valley Widening (from End of Bull Lake glaciation to 64 ka)

By some dam-breaching process in the peripheries of Grand Mesa, glacial meltwater flooding incises and erodes headward in the flanks of Grand Mesa (Figure 5.9); upon exiting Plateau Creek valley and De Beque Canyon, water starts spreading and forming a sheet-like veneer, eroding into the remnants of Mesaverde Group. Contrary to Sinnock (1981b), Grand Valley was much narrower, and the older De Beque Canyon mouth perhaps extended down to Grand Junction at this time. In the south flank of Grand Mesa, glacial meltwaters create fan-like deposits and continue to flow downstream to the confluence with the Colorado River. At the confluence, with the discharge of the Gunnison River added to it, the Colorado River cuts down below remaining Mesaverde Group and into the Mancos Shale. Subsequently rapid headward erosion takes place upstream toward

Palisade. Much of the erosion-resistant Book Cliff material is removed as well at this time. The floodwaters laterally consume away the walls of the Book Cliffs, and thereby continuously widening Grand Valley.

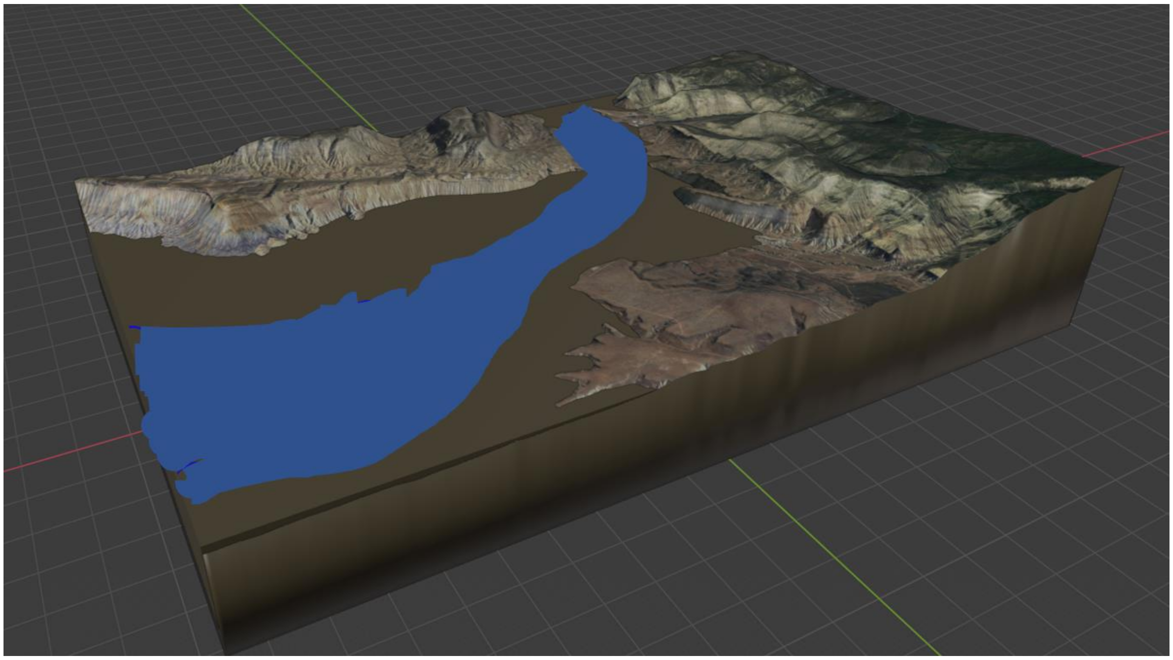


Figure 5.9 Stage 2: Initial Valley Widening

5.5.3 Stage 3: Carpeting Phase (beveling and sedimentation)

This stage overlaps with, but outlasts, Stage 2. With continued headward erosion (beveling), the De Beque Canyon mouth retreats to modern day Clifton and Palisade, sedimentation occurs simultaneously, forming older terraces at higher elevations, southernmost sections of the area (for which age controls are generally lacking; Aslan et al., 2019). Flooding continues as sheets in the downstream, further widening Grand Valley by eroding away the Book Cliffs to the north (Figure 5.10). This stage may be represented by the pulses of deglacial flooding aged 85 ka, 74 ka, and 67 ka from the Grand Mesa flank. Notably, modern day Orchard Mesa level terrace forms during this time (93 ka—63 ka; Aslan et al., 2019). As Montgomery (2004) underscores the significance of substrate erodibility in strath planation, where shale and silt stones or unconsolidated sediments are favorable to beveling, as opposed harder rocks such as granite and basalt. Consistent with it, Stage 3 involved beveling of the Mancos Shale at the initiation of the Orchard Mesa genesis.

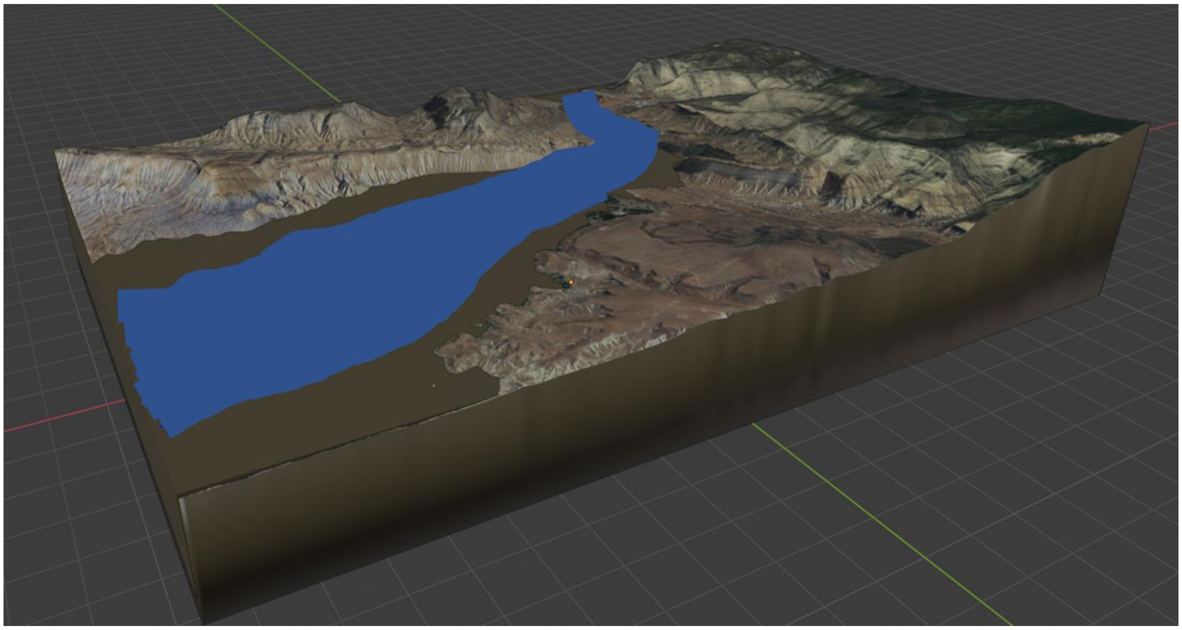


Figure 5. 10 Stage 3: Carpeting phase.

This critical stage may explain why the De Beque Canyon mouth is 1) the lithological pivot from the Mesaverde Group to the Mancos Shale (Figure 2.6) and 2) the pivot for terrace types from fill- to strath terraces. Because glacial meltwaters originated from Grand Mesa close by, the De Beque Canyon is locked between Grand Mesa and Valley. With a base level fall, the Valley opens up downstream from the Plateau Creek but upstream from the endpoint of the Book Cliffs (Figures 4.5 and 4.6). With fluvial erosion alone, the erosion-resistant Mesaverde Group might not have been eroded headward up to the De Beque Canyon mouth, but is still eroding headward completely inside the Grand Valley on top of the Mesaverde Group.

No fill terrace exists downstream from Grand Valley, but only strath terraces. It may be because Grand Mesa was the source of sediments and meltwaters that were used to bevel the Mesaverde Group in Grand Valley down to the Mancos Shale. The solely fluvial explanation for the terrace genesis can merely be descriptive, not prescriptive, of the occurrences of fill terraces and strath terraces. Rapid and extensive beveling is required to erode both the Book Cliffs and the substrate Mesaverde Group. This new diluvial scenario better explains it.

5.5.4 Stage 4: Orchard Mesa Incision

Another major sets of pulsed deglacial flooding around 61 ka and 58 ka take place (Figure 5.12). Initially with a significantly lower discharge, the rising flood allows for channelized incision that isolates Orchard Mesa as a long island or a bar (*sensu* Larsen and Lamb, 2016). It is followed by increased discharge that would re-introduce sheet-flooding. Because the highly erodible Mancos Shale in Grand Valley dips to the north, flooding continues to “carpet” the floor of Grand Valley with gravels, cobbles, and boulders (as seen in the ERT transects and in the analogues shown in Icelandic jokulhlaup deposits discussed earlier in this chapter). The two levels of terraces “Qt2” and “Qt1” near the modern-day mouth of De Beque Canyon form during this time (as shown in Carrara, 2002). Interestingly, only a small patchy area of “Qt2” (contemporaneous with the Orchard Mesa terrace) remains today as hills (with a building in front of the Book Cliffs in Figure 11A), presumably because the rest of it erodes away by subsequent diluvial episodes in Stage 5. Had only fluvial processes of lower stream power been in action, not only should the terrace (Qt2) exist further upstream from the De Beque Canyon, but also a larger amount of Qt2 should remain for less comprehensive erosion by fluvial processes in the Palisade and Clifton areas.

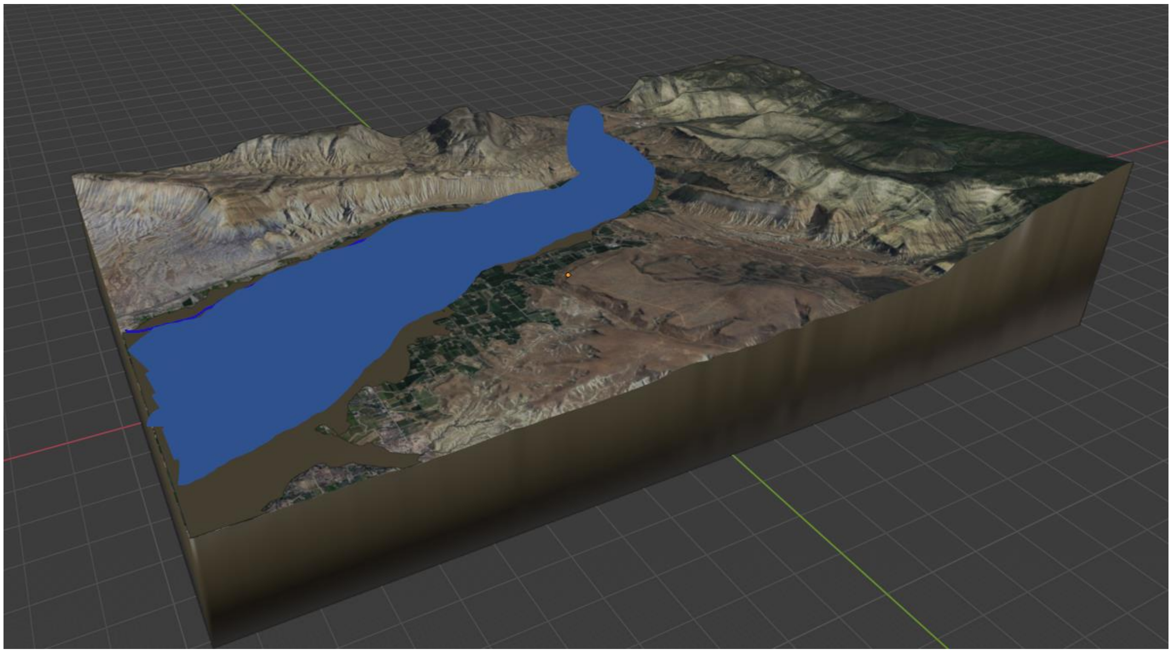


Figure 5.11 Stage 4: Orchard Mesa Incision and Abandonment. At this stage northern terrace is beveled and carpeted.

5.5.5 Stage 5: Pre- and Post-Pinedale Diluviations and Transition to Fluvial

The absence of numeric dates for these times forces one to only imagine that there had been further diluvial episodes immediately before and after the Pinedale glacial advances. Similar to the episodic flooding between 93 ka and 58 ka, a few millennia or centuries prior to and after the Pinedale glaciations, discharges of glacial flooding in relatively lesser magnitudes take place (Figure 5.11). In response, the De Beque Canyon mouth retreats to modern day Palisade, and the Book Cliffs erode away further to the north to where they are today.

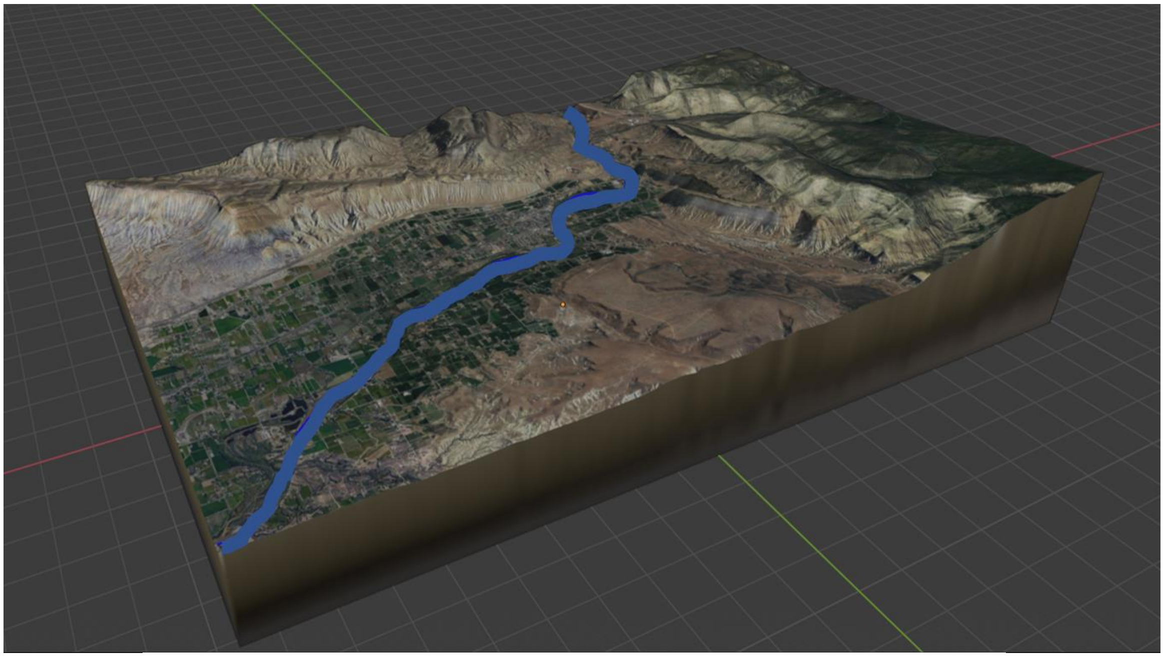


Figure 5.12 Stage 5: Post-Pinedale Glaciation Channel Migration.

The latter glacial floods, with their substantially decreased amount of discharges, drive the channel migration generally south, partly because of the slopes that sediments from the Book Cliffs form. The Colorado River channel encroaches to the peripheries of Orchard Mesa, where channelized flow had set the course in Stage 4. Before fluvial processes take over the area, the modern Colorado River is further incised with glacial flooding along with aggregates of gravels, cobbles, and boulders are emplaced on top of the Mancos Shale in modern day Colorado River floodplain (ERT survey Site 2).

5.6 An Anthropocene Micro-Analogy?

The above scenario received inspiration from an ordinary observational setting in the Anthropocene. Rains, storm events, and the like are conducive to forming ephemeral streams by swelling water flows in a given area (Figure 5.13). When water is sufficiently collected on a dry surface, it flows in sheets, much like the Carpeting Stage (Stage 3 of the Orchard Mesa formation). The waterflow can move the overall surface sediments, particularly, sediments with relatively smaller grain sizes. Then, as water is collected to the lowest topographic area, it becomes channelized and starts to erode into the generally flat ground surface—analogous to Orchard Mesa incision Stage 4. The entire landform change would take place within tens of minutes or an hour at the most, given that collected rain in channels or sheets, the swelled channel starts to erode the bed and leave straths on top of "floodplains." The resultant landform is a flight of terraces.

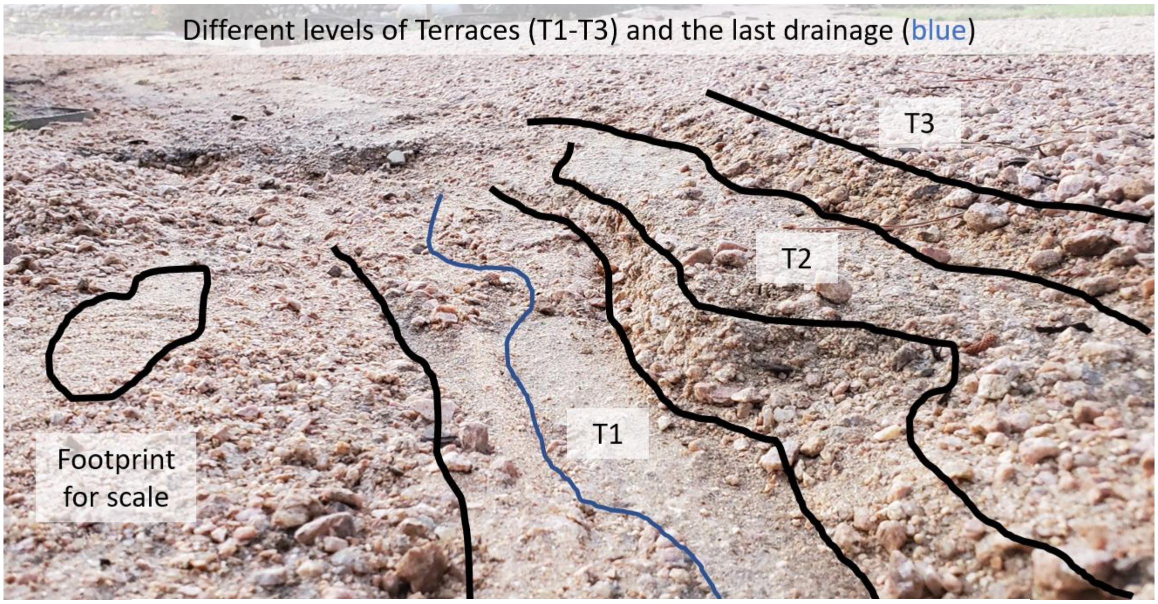


Figure 5.13 Rapid Micro-Terrace Formation during One Rain Event.

This dissertation is an attempt to ascribe a series of rapid geomorphic episodes to account for a late Cenozoic geomorphic evolution. An ordinary meteoric phenomenon observed in modern human surroundings—of a few minutes of rain event—can serve as a remarkably simple illustration for a surface morphology created by successive catastrophic glacial flooding in an alpine setting. The only differences between the evolution of Grand Valley and the local gravel trail (Figure 5.13) are scales, the timing and the duration of flow, and the presence of a perennial river channel.

5.7 Summary and the Bigger Picture

In summary, the evolution of Grand Valley in accordance with glacial flooding from Grand Mesa is feasible from geochronological vantage point and the depositional conditions of terraces analogous to modern glacial outburst floods in other places.

Although the lack of age control and the little appreciation for glacial flooding had prevented researchers from recognizing the necessity of deglacial flooding in the landform evolution of the Grand Valley area. Earlier in this analysis chapter, new numeric age control of the Grand Mesa flanks and the Grand Valley terraces were addressed. The independently reported dates point clearly to glacial advances that took place between the only established glacial times, Bull Lake and Pinedale. Then, using the ERT subsurface scan results and modern analogues of glacial floods, I tied the genesis of Grand Valley terraces to climatic and sedimentary events that occurred around the same time in the Grand Mesa peripheries.

If the Cenozoic geomorphic history of the Grand Valley-Mesa system can be attributed to diluvial episodes, what are the implications for the rest of the world? Two major implications are suggested. First, most terraces in the world thought to be fluvial in origin ought to be re-examined to incorporate diluvial processes in their genesis, given that staircases of terraces are a worldwide phenomenon (Bridgland and Westaway, 2017). Grand Valley has, arguably, over five (5) different levels of terraces scattered throughout (as many as eleven, in fact). Almost all river valleys involving megaflooding in the past and glacial outbursts in modern times accompany terraces, which had been former “channel bed” levels, that has been incised into since. Gleaning from the fact that terraces are associated with valleys around the world that have been deluged by glacial floods and Grand Valley in this dissertation, numerous other underfit river valleys in the world with terraces next to their main channels as well as modern floodplains are landforms originated from episodic glacial flooding.

Second, returning to the vicinity of the study site, the understanding of the geomorphic evolution of the Book Cliffs should be amended. The Book Cliffs span from Grand Valley to Price, Utah. Lateral erosion driven primarily by climate and colluvial processes is deemed the most prominent means of the retreat of the Book Cliffs. However, parts of the Book Cliffs, including the eastern part in Grand Valley may have formed dramatically under catastrophic conditions as advocated in this dissertation. The reason for this consideration is supported by the fact that the vast amount of sediment between the tops of the Uncompahgre Plateau, the Book Cliffs, and Grand Mesa had been removed since the Tertiary times, because the ancient Colorado Riverbed used to be at the Grand Mesa elevation at some point in the Cenozoic period (Aslan et al., 2009; Aslan et al., 2019). Furthermore, headward erosion from eastern Utah to the De Beque Canyon mouth by fluvial processes alone, and without any diluvial assistance, seems absurd.

CHAPTER VI

SUMMARY

6.1 Problem

For nearly five decades, the constructing the geomorphic history of Grand Valley in central western Colorado has been attributed to fluvial and colluvial processes, for the evolution of the valley floor and the valley side (the Book Cliffs). How did Grand Valley evolve? In particular, terrace genesis has been central to understanding the evolution of the Valley in the Cenozoic. However, the understanding lacked numeric age controls in the area, which have only been made available in the past two decades, at the beginning of the century. Did glacial cycles on Grand Mesa play any significant role in the evolutionary history of Grand Valley? How are the glacial floods in the tributaries of the upper Colorado River linked to the evolution of the down-valley strath terraces?

6.2 Objectives and Summary

In this dissertation, two main objectives were achieved: 1) to obtain numerical dating using the OSL method and 2) to image and assess the subsurface of terraces with the ERT.

New age estimates of the area were consistent with recent findings of others, establishing that formerly unknown glaciations took place between the Bull Lake and Pinedale times. The age estimates built on the works of southern flank of Grand Mesa (Brunk, 2010; Blakeley, 2014). The northern flank of Grand Mesa turned out to have been flooded multiple times in Late Cenozoic. The ages of the events in the northern flanks are consistent with the ages of terraces of Grand Valley published by others. As such, the temporal link between Grand Mesa and Grand Valley and the subsurface imaging of multiple terraces convinced me that there had been multiple glacial flooding episodes in the area that eroded down Grand Valley to the Mancos Shale level and cover with diluvium-alluvium above it. This dissertation thereby addressed the geomorphic evolution of Grand Valley, invoking the need for more dramatic processes in the valley, namely episodic catastrophic glacial flooding.

6.3 Contributions

The geomorphic investigation into central western Colorado was divulged in this dissertation. What do the findings mean? Major relevance to the body of knowledge and society are highlighted here.

First, little was known about glacial advances in the Grand Mesa area between the prominent Bull Lake and Pinedale of the Wisconsin times. Demonstrably there had been multiple glaciations in the Grand Mesa area in addition to the San Juan Mountains areas (Jarrin et al., 2017; Johnson et al., 2017) as well as in addition to those two glacial times. Although numeric age estimates for geomorphic events in the region are scarce, enigma is that the existing dates were inconsistent with the major glacial episodes recognized in the Rocky Mountains region. Turning the table, I contend that the few existing dates by other researchers and those reported in this dissertation are clear evidence that there were regional glacial advances that were allegedly out of sync with the Bull Lake and the Pinedale glaciations. Thus, this dissertation contributes to the current state of geomorphic and chronologic understanding by complementing previously undated materials in the central western Colorado. How many undocumented glacial advances have there been in places fewer researchers have investigated and even fewer numeric dates are available?

Another implication is that the conclusion of the dissertation begs to be considered alongside the well-known catastrophic flooding scenarios such as the Missoula floods. Admittedly, the amounts of water Grand Mesa glaciers discharged through multiple episodic flows must be minor in comparison to such “mega-” floods. Nonetheless, with the presence of diluvial evidence in the flanks of Grand Mesa and Grand Valley producing, and subsequently incising into, multiple levels of terraces, the scenario may amount to “kilo-” or “deca-” flooding of Grand Valley as well as numerous other alpine fluvial valleys formerly flooded by jökulhlaups. A student of J H. Bretz and prominent investigator of megafloods, Victor Baker (2013) states that since the recognition of the Missoula flooding in the Channeled Scablands, there have been increasing number of researchers detecting the landforms related to megafloods around the world. This dissertation is arguably consistent with the trend, and I likewise predict that detection of kilo-flooding and deca-flooding around the world will soon ensue.

The evolution of the surrounding landforms will also need to be re-examined, particularly, the Book Cliffs. A rapid co-evolution of the Book Cliffs by sheet-like deluges was alluded to in Chapter V. Previous investigations emphasized (Schmidt, 1989; 1996; 2009; McCaroll, 2019; Glade, 2019) lateral erosion solely through colluvial and hillslope process. The diluvial hypothesis of this dissertation indicates that the floodwaters eroded the walls of the Book Cliffs. The episodic deca- or kilo-flooding would have accelerated the northward lateral erosion of the Book Cliffs in the Grand Valley area. A spatial and quantitative investigation into the erodibility of the walls of the Book Cliffs by diluvial discharge is a feasible next step in accounting for the erosive history of the Book Cliffs.

Lastly, the catastrophist conclusion by itself is another robust reminder for the dangers that natural disasters pose on human lives and infrastructure. Natural disasters often occur when unprepared, unexpectedly, repeatedly, or as a combination of all of them. At the time of this writing, infrequent yet intense geomorphic events are taking place around the world within months' timeframe. For example, in East Asia alone, earthquakes with magnitudes higher than 5.0, floods that overwhelm historic world-class dams, landslides devastating alpine residents took place in spring and summer of year 2020. Although Grand Valley had been unsettled during the proposed catastrophic deglacial floods took place, judging from the landform changes that would have occurred, the diluvial processes had exerted much damage and would have cost numerous human lives. In fact, as alluded to in the ERT sites selection in Chapters III and IV, if FEMA-assessed zones of 100-year and 500-year floods would be inundated, the damage to the infrastructure and properties along the modern Colorado River channel and floodplain would debilitate parks, schools, agricultural lands to mention a few. As such, public awareness of catastrophic ramifications of natural disasters as demonstrated in this dissertation should not only interest the scientific mind alone but also everyone outside the scientific community, especially policymakers, educators, and those in construction businesses.

6.4 Future Research Direction

Although I am convinced that my conclusion on the geomorphic evolution on Grand Valley is sufficient to convince many, were the investigation to continue, it can be enhanced and complemented further as beating the proverbial dead horse. For the numeric dating, the budget was so limited as to analyze just seven (7) samples. The Kannah Creek valley of the western flank of Grand Mesa could be sampled to offer an even more robust picture for geochronology of glacial flooding. For the subsurface survey, certainly more terraces in Grand Valley and those in the northern flank of Grand Mesa could be surveyed.

For instrumentation, moreover, subsurface imaging could be conducted in conjunction with other methods of sedimentology or other geophysical methods, to better establish internal stratigraphy of terraces that do not have accessible outcrops. For example, vibra-coring could easily reveal stratigraphy in support of ERT or other indirect methods, nonetheless anticipating the difficulty of ground penetration because of boulders. For other geophysical methods, ground penetrating radar (GPR), or seismic refraction methods would aid in distinguishing the gravel-shale boundary more clearly with density differences between the units, although the latter was precluded as an option early in the development of this project for difficulty in transportation and manpower it required.

In regards to consolidating the physical feasibility of flooding, estimating hydraulic energy and stream power at various locations along the modern Colorado and Gunnison Rivers would help exclude the fluvial scenario for the evolution of Grand Valley. Along with it, a statistical analysis of the terrace deposits to estimate the stream power necessary to move gravels, cobbles, and boulders would be highly beneficial.

Lastly, a hydraulic modeling would aid visualizing the inundation of Grand Valley by deglacial deluge. Software HEC-RAS, developed by the U.S. Army Corps of Engineers to model flooding, could be pursued to complement this already sufficient dissertation so as to prepare for publication in widely read, top-rank journals.

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APPENDICES

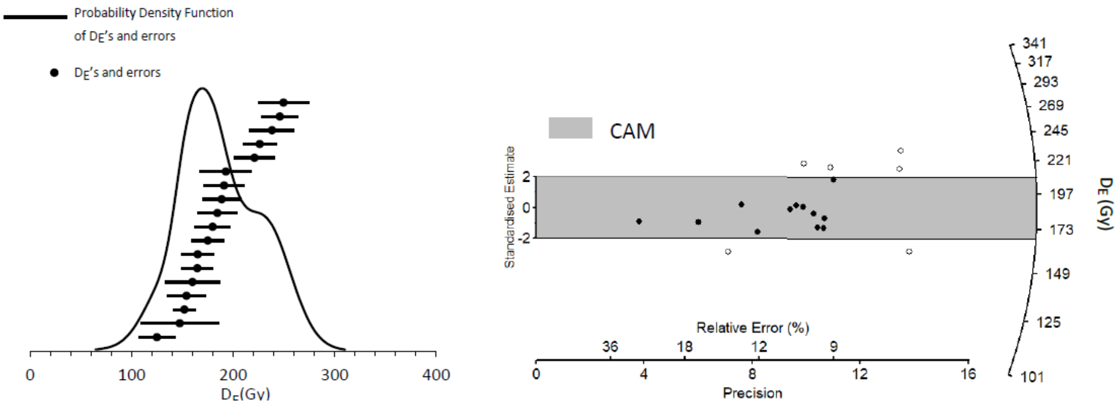
Miscellaneous OSL data

Dose-Rate

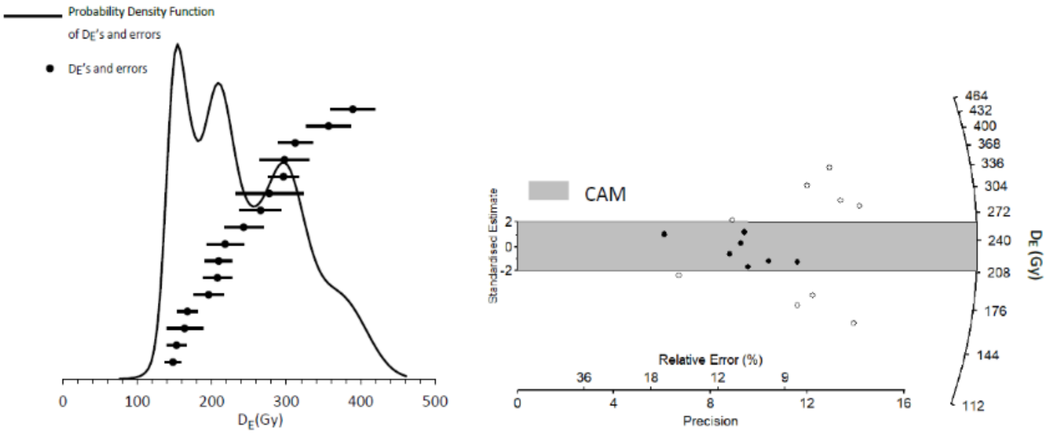
Sample num.	USU num.	In-situ H_2O (%)	Grain size (µm)	K (%)	Rb (ppm)	Th (ppm)	U (ppm)	Cosmic (Gy/ka)
KJ-PC1	USU-2856	6.6	125.212	2.00±0.05	81.4±3.3	8.8±0.8	2.7±0.2	0.16±0.02
KJ-PC2	USU-2857	3.1	63-125	2.17±0.05	57.7±2.3	5.4±0.5	1.2±0.1	0.03±0.003
KJ-PC3	USU-2858	6.1	125-250	2.51±0.06	75.3±3.0	6.2±0.6	2.8±0.2	0.05±0.01
KJ-PC4	USU-2859	1.1	125-250	2.41±0.06	64.6±2.6	5.0±0.4	1.3±0.1	0.16±0.02
KJ-PC6	USU-2861	6.2	125-250	1.90±0.05	42.0±1.7	8.6±0.8	1.4±0.1	0.08±0.01
KJ-SC7	USU-2862	1.1	150-250	2.44±0.06	70.0±2.8	6.8±0.6	1.9±0.1	0.09±0.01
KJ-SC8	USU-2863	0.8	125-250	2.38±0.06	65.2±2.6	7.1±0.6	1.5±0.1	0.17±0.02

Equivalent Dose (D_E) distributions of each sample

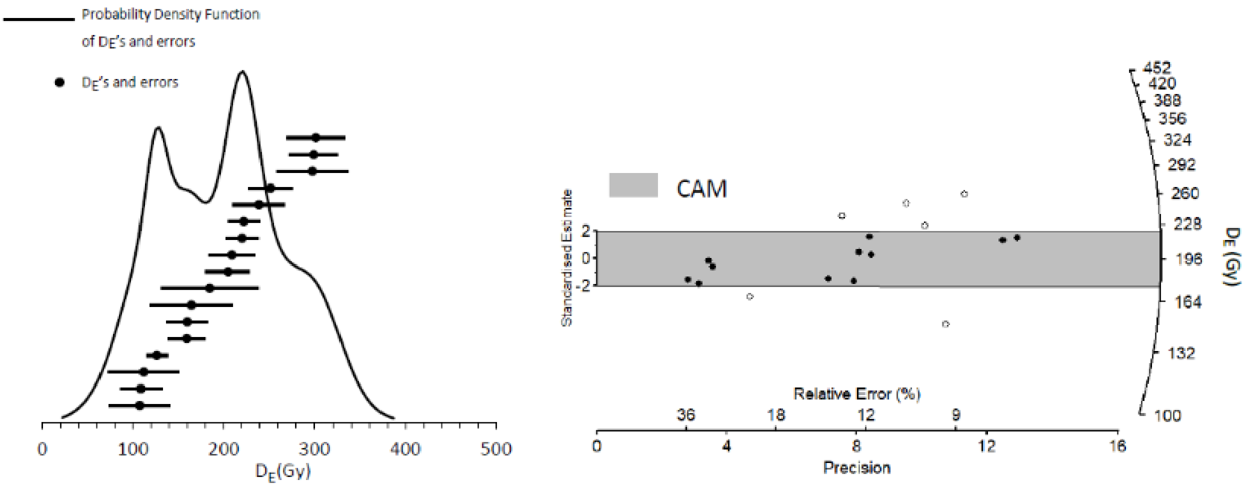
1. KJ-PC1, USU-2856, OD = 15 ± 4 %



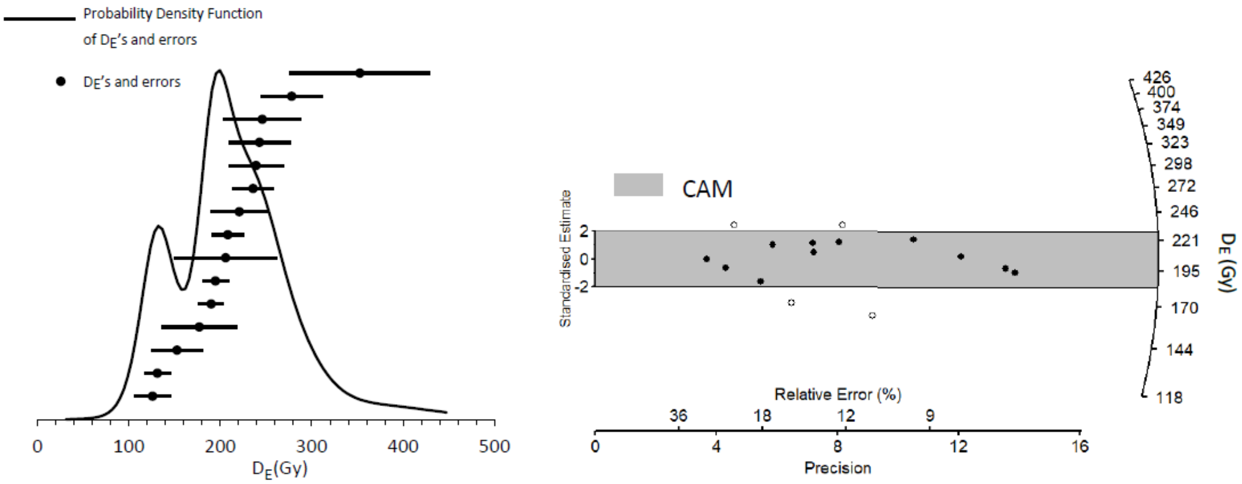
2. KJ-PC2, USU-2857, OD = 28 ± 6 %



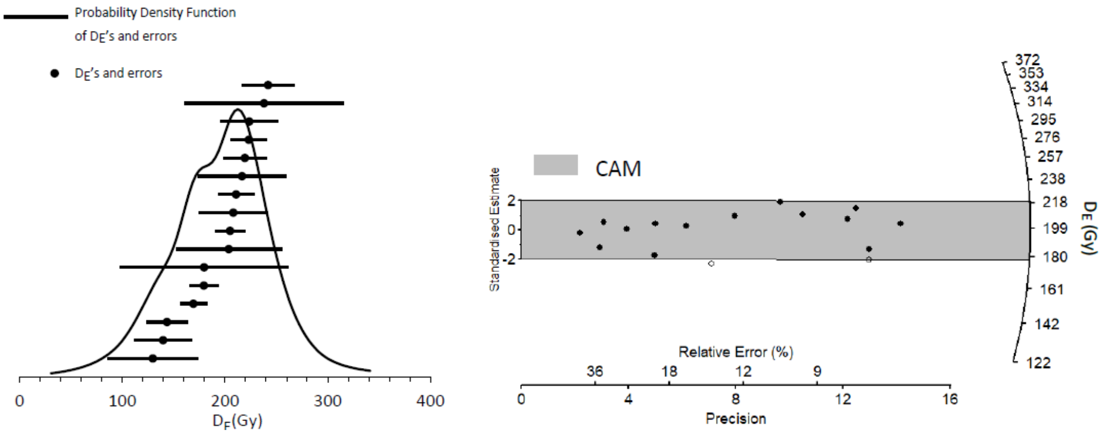
3. KJ-PC3, USU-2858, OD = 28 ± 6 %



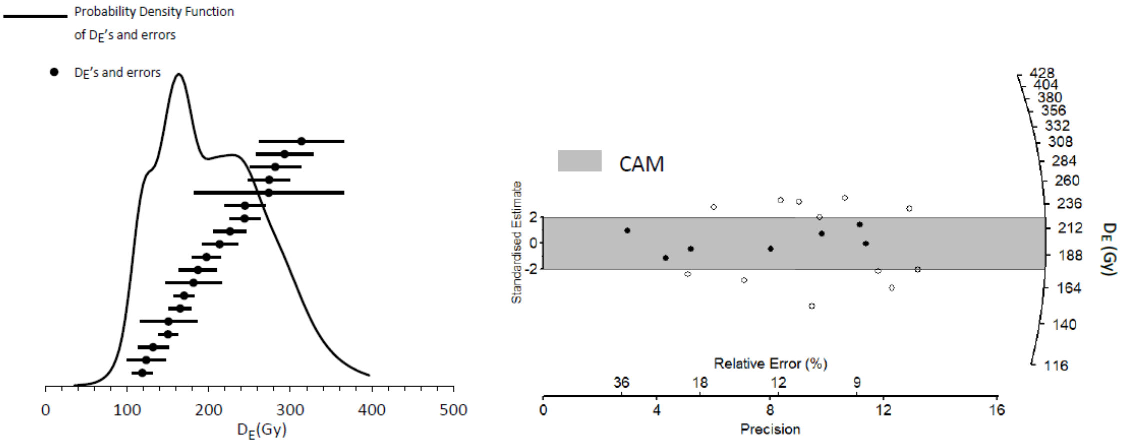
4. KJ-PC4, USU-2859, OD = 20 ± 5 %



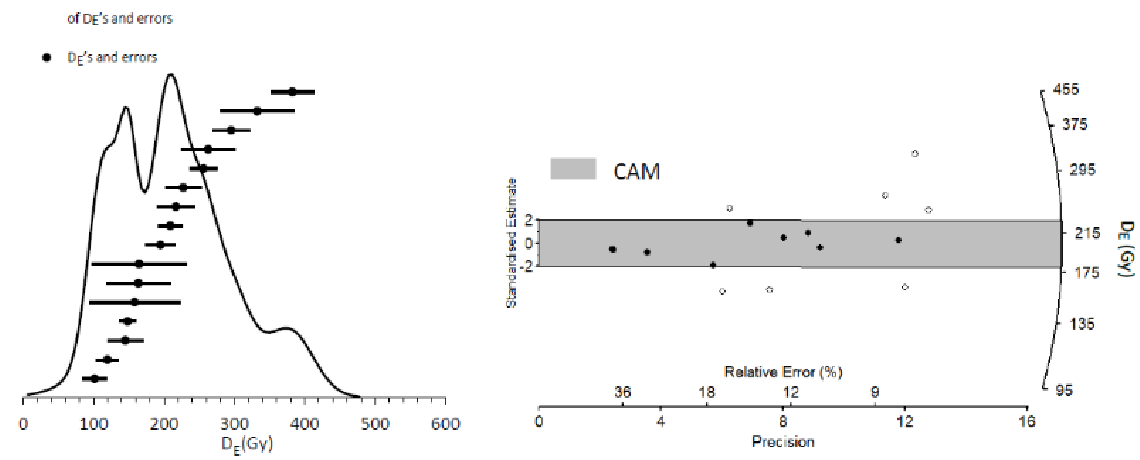
5. KJ-PC6, USU-2861, OD = 9 ± 4 %



6. KJ-SC7, USU-2862, OD = 26 ± 5 %

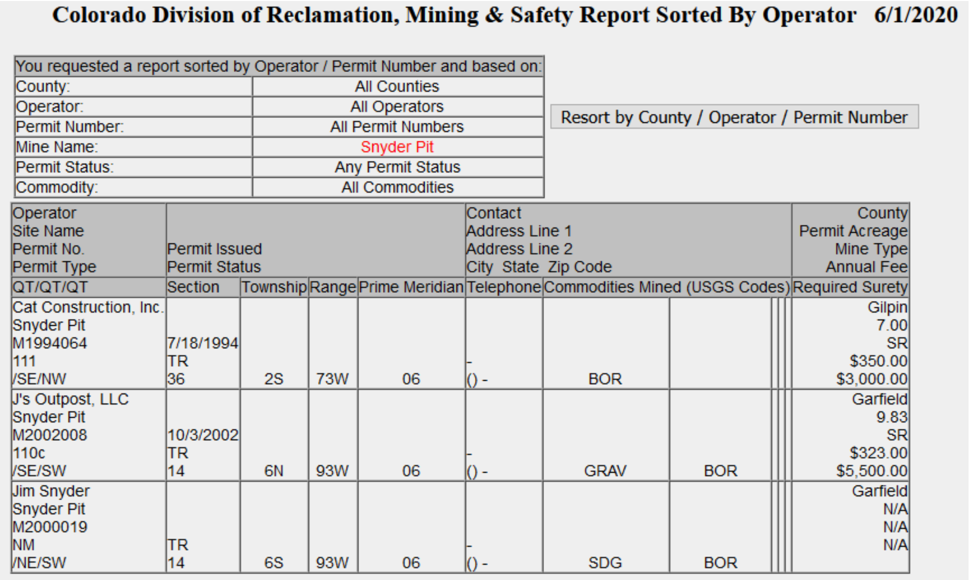


7. KJ-SC8, USU-2863, OD = 34 ± 7 %



OSL Sample Collection Sites

Snyder Pit

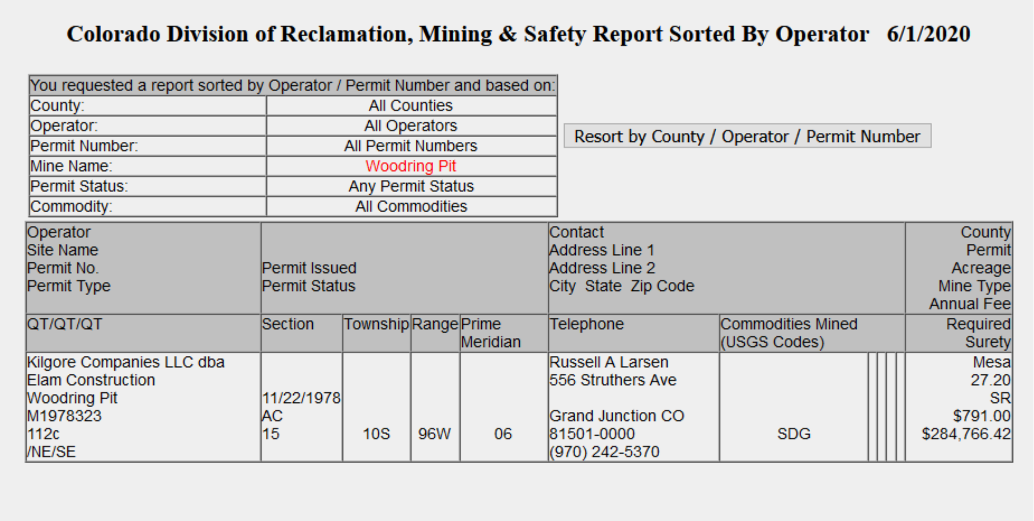


Colorado Division of Reclamation, Mining & Safety Report Sorted By Operator 6/1/2020

You requested a report sorted by Operator / Permit Number and based on:	
County:	All Counties
Operator:	All Operators
Permit Number:	All Permit Numbers
Mine Name:	Snyder Pit
Permit Status:	Any Permit Status
Commodity:	All Commodities

Operator Site Name Permit No. Permit Type	Permit Issued Permit Status				Contact Address Line 1 Address Line 2 City State Zip Code			County Permit Acreage Mine Type Annual Fee
QT/QT/QT	Section	Township	Range	Prime Meridian	Telephone	Commodities Mined (USGS Codes)		Required Surety
Cat Construction, Inc. Snyder Pit M1994064 111 /SE/NW	7/18/1994 TR 36	2S	73W	06	- () -	BOR		Gilpin 7.00 SR $350.00 $3,000.00
J's Outpost, LLC Snyder Pit M2002008 110c /SE/SW	10/3/2002 TR 14	6N	93W	06	- () -	GRAV	BOR	Garfield 9.83 SR $323.00 $5,500.00
Jim Snyder Snyder Pit M2000019 NM /NE/SW	TR 14	6S	93W	06	- () -	SDG	BOR	Garfield N/A N/A N/A

Woodring Pit



Colorado Division of Reclamation, Mining & Safety Report Sorted By Operator 6/1/2020

You requested a report sorted by Operator / Permit Number and based on:	
County:	All Counties
Operator:	All Operators
Permit Number:	All Permit Numbers
Mine Name:	Woodring Pit
Permit Status:	Any Permit Status
Commodity:	All Commodities

Operator Site Name Permit No. Permit Type	Permit Issued Permit Status				Contact Address Line 1 Address Line 2 City State Zip Code		County Permit Acreage Mine Type Annual Fee
QT/QT/QT	Section	Township	Range	Prime Meridian	Telephone	Commodities Mined (USGS Codes)	Required Surety
Kilgore Companies LLC dba Elam Construction Woodring Pit M1978323 112c /NE/SE	11/22/1978 AC 15	10S	96W	06	Russell A Larsen 556 Struthers Ave Grand Junction CO 81501-0000 (970) 242-5370	SDG	Mesa 27.20 SR $791.00 $284,766.42