SEDIMENTOLOGICAL REINTERPRETATION OF SURFICIAL

UNCONSOLIDATED DEBRIS FLOWS AND STREAM DEPOSITS OF THE

SOUTHERN FLANKS OF GRAND MESA, CO: AN INTEGRATED LIDAR

APPROACH

A Thesis

by

MITCHELL WILLIAM BLAKELEY

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

MASTER OF SCIENCE

Chair of Committee,   John R. Giardino
Co-Chair of Committee,   Michael C. Pope
Committee Member,   Chris Houser
Head of Department,   John R. Giardino

August 2014

Major Subject: Geology

ABSTRACT

The southern slopes of Grand Mesa Colorado consist of glacio-fluvial sediments deposited when the Pleistocene ice cap draping Grand Mesa melted. Debris flows intermixed with braided and meandering stream deposits, were the focus of this study. This study developed a sedimentological description and interpretation of these deposits and tested the capabilities of terrestrial LiDAR (Light Detection and Ranging) for use in sedimentological studies. This research addressed the origin of the deposits south of Grand Mesa and evaluated the significance of terrestrial LiDAR for examination, description and interpretation of sedimentary facies at outcrop scale.

The main outcrop exposed along highway 65 near Cory Grade, Colorado, was studied along with similar outcrops in the area. Field observations aided in calibrating interpretations from LiDAR scans and GigaPan® panoramic images. Facies were distinguished by grain size, depositional fabric, sedimentary structures and stratal geometries. Eight facies, making up three depositional environments were interpreted; Debris flows from the mesa, glacio-fluvial deposits from drainage of melt water, and fluvial deposits from the paleo Gunnison River.

A stratigraphic column of the Cory Grade outcrop shows changes in depositional environments through time. This measured section aided in creation of facies models illustrating changing depositional environments. The first model illustrates the onset of melt sending large volumes of sediment in braided streams and outwash deposits. These

north-south trending deposits are cross-cut by low sinuosity east-west trending abandoned channel and overbank deposits of the paleo Gunnison River.

The second model illustrates that ice cap melt exposed a basalt cap and greater numbers of massive debris flows occurred. The ancestral Gunnison River continued to avulse and abandon channels, and with the increase in water and influx of sediment it migrated south to establish stable channels and banks.

The third model suggests that once the ice cap melted, the lack of sediment from the north restricted river avulsion and small finger mesas were created. Additionally, with the lack of sediment from the mesa, the Gunnison River established a more permanent floodplain, and today flows south of the outcrops.

DEDICATION

This work is dedicated to all my family, friends, colleagues, and professors who were there for me throughout my time as an Aggie. Most of all, my wife Laura, who always helped me to achieve my dreams even when I thought they were out of reach.

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

Page

LIST OF FIGURES

ix

x

LIST OF TABLES

CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Introduction

A series of outcrops along the southern slopes of Grand Mesa, Colorado, that consist of glacio-fluvial sediments. These outcrops were described in general terms in the past (Cole and Sexton 1981, Brunk 2010, Noe and Zawaski 2013) leaving the stratigraphic record of the area incomplete. These braided and meandering stream deposits intermixed with debris flows are the subject for this study. A detailed sedimentological study of the individual beds was undertaken using both traditional fieldwork and state-of-the-art LIDAR technology to better examine, describe and interpret these deposits. The goal of this research was to create a detailed facies model of the deposits south of Grand Mesa, Colorado, and to test the capabilities of terrestrial LIDAR for use in sedimentologcal studies. This research addressed the question: What is the origin of the deposits south of Grand Mesa, Colorado? To answer this question, a more accurate and detailed interpretation was completed to explain the Pleistocene depositional processes and environments of deposition of the Grand Mesa area. Additionally the test of terrestrial LIDAR for use in examination, description and interpretation of sedimentary facies at outcrop scale is significant.

Objectives

The objectives of this study are as follows:

1) Reinterpret the outcrops using a new technique and technology.

2) Produce a detailed description of the facies in the Grand Mesa area.

3) Create a detailed facies model to explain the depositional environments and processes throughout the evolution of the area.

Hypothosis

Multiple working hypotheses were developed during this study to help guide the research. These hypotheses are:

H_1: The deposits are of glacio-fluvial and fluvial origin associated with the melting of Grand Mesa ice cap and the ancestral Gunnison River.

And the Null Hypothesis is that,

H_0: The deposits are of glacio-fluvial origin as described by Brunk 2010

Additionally the hypothesis is that,

H_1: Terrestrial LIDAR is a useful tool in sedimentological studies and will aid in describing the sedimentary facies of the outcrops in greater detail.

And the Null Hypothesis is that,

H_0: Terrestrial LIDAR is not a useful tool in sedimetological studies and will not aid in description of the outcrops.

Literature Review

This study expands on the work of Brunk (2010). In his study, a preliminary assessment of the depositional environments and geomorphologic changes in the area south of Grand Mesa during the late Pleistocene was performed. Brunk (2010) used grain size analysis, tabulation of sedimentary structures, and photographic logging of outcrop morphology to produce preliminary discussion of sedimentary facies. His work

on the outcrops in the area lays the basis for the sedimentologic and stratigraphic work accomplished in this study.

The facies described in Brunk (2010) outline two major types of deposits: braided stream deposits, and debris flow deposits. Within these deposits there are several facies that provide a better understanding of the overall depositional history during the late Pleistocene. The facies interpreted in the braided stream deposits were recorded as Fl, Str, Sh. These facies codes were modified from Miall (1978). These facies have horizontal laminar bedding indicative of flood plains and transitional zones as well as trough cross bedding and ripple marks indicative of braided streams.

The prevailing fabric in the facies described by Brunk (2010) is orthoconglomerates indicating grain support. The grain size throughout these facies is cobbles to coarse grained sand with some silt in the matrix. This indicates high energy environments of deposition.

The facies interpreted as debris flow deposits were identified as Gm, and Gms. The debris flows consist of orthoconglomerates (Gm) and paraconglomerates (Gms), and are indicative of much higher energy deposits. The large-scale graded bedding and massive bedding in the Gm deposits along with grain sizes ranging from sand to cobble were interpreted as glacial outwash and massive flows (Brunk 2010). The Gms deposits were not sampled because lack of permission from the land owner so the interpretations were solely based on photographic images and field observations. The Gms facies showed similar environment of deposition as the Gm facies, however it is matrix-supported rather than grain-supported was interpreted in to be plasitc debris flows rather

than glacial outwash (Brunk 2010). In facies containing imbricated clasts within the depositional fabric, the direction of imbrication was mapped to help determine the direction of the paleocurrents responsible for their deposition (Brunk 2010).

Idealized stratigraphic relationships of the interpreted facies were created and used in the geomorphological interpretation of the Grand Mesa area during Brunk's (2010) study, however no detailed stratigraphic column of the outcrops was measured showing the true history of depositional events. Other facies were observed during Brunk (2010) preliminary assessment, however because of the scope of that project they were neglected in order to simplify the stratigraphy of the area.

Older literature on the area shows little work on the individual outcrops Overall the studies published address erosional histories during the Quaternary, and landform classifications (Yeend 1965, Cole and Sexton 1981). Very few publications address the individual deposits, they attempt only to qualitatively describe the area. Cole and Sexton (1981) contained a basic description of the deposits in the area however the overall sedimentology was not complete. The major focus of much of the older literature is relative age dating in the area. Lava Creek B ash bed layers in the area indicate the relative age of the deposits in the area (Aslan 2002).

A mapping project was conducted by the Colorado Geologic survey in 2013 by Noe and Zawaski. These outcrops were sub-divided into mappable units and given a very brief description. In the author's notes, the outcrops relevant to this study were described to be of glacio-fluvial origin and contain stratified alluvial fans, debris flows and glacial outwash (Noe and Zawaski 2013). The paper associated with the mapping

4

also suggests that the downstream portions of these outcrops may intermix with ancestral Gunnison River deposits.

Light Detection And Ranging or LiDAR is a relatively new and accurate tool used to create high resolution 3D images of scanned surfaces. The instrument emits a beam of light (a laser) at a target and then records the reflected and back scattered light from the target. The machine then calculates the distance via two way travel time to the target and assigns an x, y, and z coordinate to the point. The machine additionally records the intensity and RGB values of the return signal for use in later visualization. The scanner preforms this operation millions of times per minute creating a millimeter-scale fine point mesh of coordinates. These coordinates and associated data are then uploaded into a visualization program such as Cyclone® and the resulting 3D image can be used for interpretations in a laboratory setting (Moore 2012).

LiDAR for use in the geosciences is very limited, and a review of the literature shows this. Historically, LiDAR was used extensively in Engineering and geographical applications as an accurate measurment tool. This study examined the capabilities of LiDAR technology in sedimentary studies.

To date, the work done using LiDAR in geosciences is mostly macro scale studies involving either aerial or terrestrial LiDAR derived from a distance great enough to image overall changes in lithology. Studies undertaken by Thurmond (2006) Buckley (2008, 2008, 2010, 2013) and by Jones (2007) show that aerial LIDAR can be used to image structural and depositional pattern changes over large-scale study areas (Buckly et. al. 2008, 2010). Since then, numerous studies were published in the last few years on

the use of terrestrial LIDAR in studies ranging from fault mapping (Rovetan 2009, Kokkalas 2007) to rock composition (Kurz 2009, 2012) and even preliminary work in sedimentology and stratigraphy (Buckley 2010, Bellian 2005, Tomasso 2006, Moore 2012). These studies have shown great potential in the area of LIDAR in the geosciences, however, these studies did not utilize the tool for detailed sedimentologic description and interpretation.

CHAPTER II

STUDY AREA AND GEOLOGIC HISTORY

Study Area

The study area is located on the southern slopes of Grand Mesa, Colorado. The area extends from the flood plain of the modern-day Gunnison River to the foothills and terminal moraines of Grand Mesa the area covers approximately 600 km^2 (~230 mi^2) (Brunk 2010). Grand Mesa is situated in western Colorado to the north of the Gunnison and Northfork River and south of the Colorado River. The elevations in the area varies from lows near the flood plain (~1520 m; ~5,000 ft.) to highs of 2440 to 3050 m (~8,000 to 10,000 ft.) near the slopes and top of the mesa (Yeend, 1965). Access to the study area is provided by Colorado State highway 65 and Colorado State highway 92 (Figure 1). Regionally the geologic record shows Jurassic to Quaternary rocks however the focus of this study is the unconsolidated Quaternary deposits (Figure 2). Individual outcrops studied were Cory Grade, Hotchkiss Grade, Redlands Mesa and Cedar Mesa. The main focus of this study will be on the Cory Grade outcrop because of its large size and complex stratigraphic architecture. The Cory Grade exposure trends approximately north-south and the road cut provides a Western facing view of the deposits. Figure 3 shows the Colorado Geologic Survey map of this area with the study area deposits denoted on the map as Qg3. The names of the outcrops stems from their relative position and surrounding towns and major roads. Their locations were described by Brunk (2010).
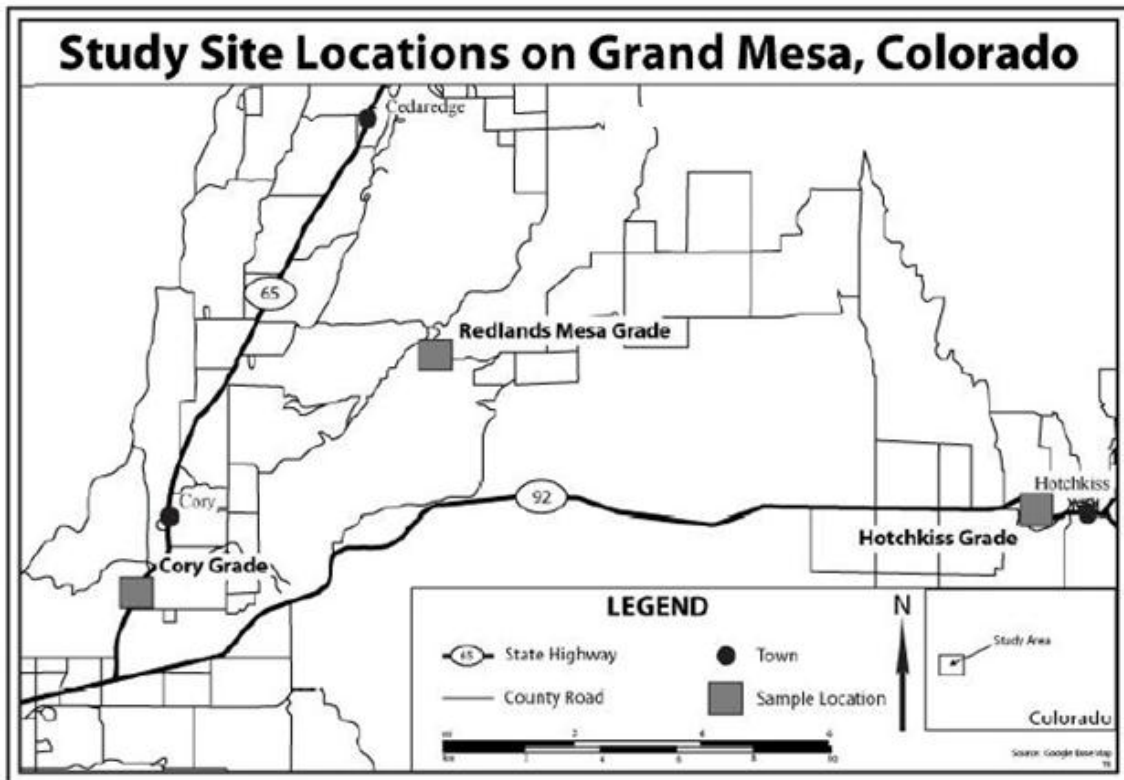
Figure 1. Study site locations along the southern slopes of Grand Mesa. Adapted from Brunk (2010)

Age	Map Unit	Thickness (ft)	Stratigraphic Unit Name		Lithology Column
Quaternary	Qg3	~65	Mixed Glacial		
Upper Cretaceous	Kmu	1,300	Mancos Shale	Upper Part of Mancos Shale	
	Kmss	60-70		Sharon Springs Mbr	
	Kmp	1,250		Prairie Canyon Member	
	Kms	750-800		(Niobrara Fm) Smoky Hill Member	
				Ft Hays Member	
	Kmj	100-120		Montezuma Valley Mbr / Juana Lopez Member	
	Kmb	120-165		Blue Hill Member	
	Kmfb	60		Fairport Member / Bridge Creek Member	
	Kmg	90-140		Hartland Member / Graneros Member	
Lower Cret.	Kdb	160-200		Mowry Shale / Dakota Sandstone / Burro Canyon Formation	
Upper Jurassic	Jm	660-690	Morrison Formation	Brushy Basin Member / Salt Wash Member / Tidwell Mbr	
Middle Jurassic	Jwe	100-150	Wanaka Formation / Entrada Sandstone		
Pre-cambrian	PЄ		Metamorphic and Igneous Rocks		

Explanation:
- Concretion
- Claystone or clayey shale
- Siltstone or silty shale
- Sandy shale
- Calcareous shale
- Chalky shale
- Wavy bedded sandstone
- Cross bedded sandstone
- Conglomeratic sandstone
- Gypsum, sandstone, shale
- Gneiss, schist, amphibolite
- Pegmatite
- Break in section: full thickness not shown
- Mixed Glacial

Figure 2. Stratigraphic column of the bedrock in the Grand Mesa area. Surficial unconsolidated Quaternary deposits unconformably overlie Mancos Shale. Modified from Noe and Zawaski 2013.
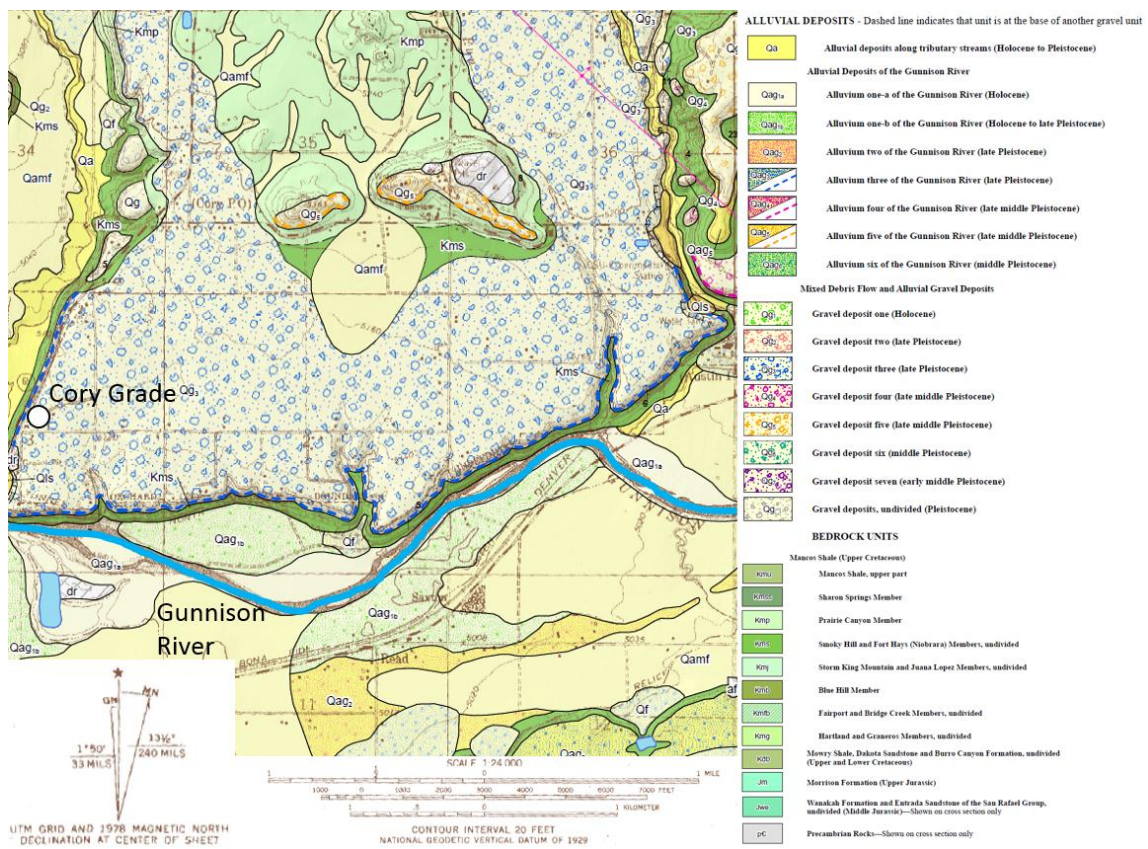
Figure 3. Geologic map of the study area. Modified from Noe and Zawaski (2013)

Geologic History

The basement rock in the Grand Mesa area begins with the Jurassic Morrison Formation. These sands and shales were deposited in the streams and tidal lakes that covered the area. During the Early Cretaceous regional uplift caused erosion of the Morrison Formation and redeposition of the Dakota Sandstone. Shortly after this uplift, a marine transgression swept across Colorado and the sediment type quickly changed from

fluvial to marine. During this time the Mancos Shale was deposited along with the coals and sands of the Mesaverde Formation (Quigley 1965).

At the end of the Cretaceous the Laramide Orogeny uplifted and the shallow sea regressed. The following Tertiary formations were deposited in shallow lacustrine environments and include the interbedded sands, shales, and marles of the Wasatch Formation, the Green River Formation, the Unita Formation and the North Park Formation (Quigley 1965).

Grand Mesa was later capped by several Miocene Basalt flows that covered an extensive portion of the area. The Grand Mesa landform was created during the Pleistocene when the large glacial ice cap on the mesa melted causing large amounts of erosion to occur on and around the basalt capped landform (Henderson 1923, Cole and Sexton 1981). Erosion occurred on this landform for approximately ten million years and produced many alluvial fans, glacial outwash fans, debris flows, landslides, colluvial deposits, piedmonts and moraines (Cole and Sexton 1981). During the Pleistocene several glacial and melting events occurred in the Grand Mesa area. These glaciation events and the subsequent melting events provide the sediment influx and transport capability for the sediments to be examined in this study (Brunk 2010).

CHAPTER III

METHODS

The methods used in this study aim to address the objectives in both a qualitative and quantitative manner. Sampling of the facies were conducted with great care to insure that each sample is indicative of the observed facies. However the unconsolidated nature of the outcrops will have led to some sample contamination. Additionally during the field work all precautions will be utilized to avoid any unnecessary safety risks. LiDAR scans and panoramic images were taken from set distances both from the outcrop as well as from each other, 18 m and 9 m spacing respectively. In this study the bulk of work analysis were on the Cory Grade outcrop because of the extent of outcrop and the complexity of its facies.

Reinterpret the Outcrops Using a New Technique and Technology

A full reinterpretation of the outcrops using a new technology and technique was completed. To accomplish this goal ten days was spent in the field performing traditional field work to set the basis as well as to become familiar with the area. During this time a detailed notebook was kept to refer to upon return. The outcrops were examined and described by means of sample collection and stratum measurement as outlined by Compton (1985) and Graham (1988). Each sample was carefully collected by use of rock hammer and collection tube and stored in plastic zip top bags (Figures 4 and 5). These bags were designated a number to correspond to a description, facies designation, outcrop, and exact location. These descriptions were used in conjunction with all

available data to interpret the environment of deposition and compared to previous interpretations.

Photographs were taken of any and all points of interest in the field using a digital high- resolution camera and given a designation. Cory Grade and Hotchkiss Grade were described and measured in detail to create stratigraphic columns as outlined by Compton (1985) to show relative grain size and depositional features. The samples were then transported back to the lab and were processed by standard techniques (Krumbein, 1934; Sahu, 1964; King, 1967; Folk, 1974; McManus, 1988; Dalsgaard et al., 1991; McCave and Syvitski, 1991; Ritter et al., 2002). The sieve analysis used sieve sizes of ½ in, ¼ in, #5, #10, #14, #18, #25, #35, #60, #120, and #230 (Φ sizes ½ in, ¼ in, -2, -1, -0.5, 0, 0.5, 1, 2, 3, and 4 respectively). The samples were placed in a Gilson SS-8R sieve/rotap shaker and processed for ten minutes. The resulting grain sizes and composition were logged for use in later interpretation.

Figure 4. Sample collection using a rock hammer and collection bag.

Figure 5. Sample collection using PVC collection pipe.

A tripod mounted Leica® C10 LiDAR scanner was used to scan Cory Grade, Hotchkiss Grade, and Redlands Mesa Grade outcrops to create a 3D point mesh (Figure 6). Each scan was performed normal to the outcrop face approximately 18 meters from the outcrop and approximately 9 meters apart. These scans were located with a gps and their orientation recorded to provide better interpretation of the data. At each of these

locations a panoramic image were taken using a tripod mounted GigaPan® to produce

an ultra high-definition image of the outcrop for later interpretation (Figure 7).

Figure 6. LiDAR scan station in use.

Figure 7. GigaPan® in use.

The LiDAR data was then analyzed in the lab using Cyclone® visualization software to view the images in real 3D space. This software was utilized to accurately measure individual beds on a mm scale as well as draw realistic boundaries and geometries of beds. The ability to accurately measure and traverse the outcrop in 3D space is significant. The GigaPan® images were analyzed in conjunction with the LiDAR images to match the photographed facies with their 3D space realizations in Cyclone®.

Paraview® software was the final program used to visualize the data in an immersive 3D view. The Immersive Visualization Center (IVC) was the basis for this where a truly dynamic view of the LiDAR imagery is significant.

Utilizing all collected data, grain size and composition data, sedimentary structures, strata geometries, LiDAR imagery, GigaPan® Panoramic imagery and an understanding of glacial and fluvial sedimentology, depositional environments and processes were interpreted to explain the formation of the outcrops and the depositional history of the area.

Detailed Description of the Facies in the Grand Mesa Area

Preforming a full interpretation of the facies was a significant step in the final understanding of the outcrops. Once interpretations were completed, a final association of the facies at the outcrops was performed using all available data. Facies were distinguished by grain size, depositional features and observed geometries. These facies were outlined and compared to descriptions of similar areas by Pettijohn (1975), Miall (1978), Rust (1978), Rust and Koster (1984), Collinson and Thompson (1982), Nemec

and Steel (1984), Bradzikowski and van Loon (1991), Collinson (2006), Miller (2006), and Brunk (2010).

Model the Depositional Environments and Processes

Once interpretations of the facies and depositional environments were conducted facies models were created to explain the processes at work at several key periods in the depositional history. Facies models are an excellent way to illustrate geologic systems and explain depositional processes and geometries in complex systems (Dalrymple 2010, Lobek 1924). Three facies models (Figures 44-46) were created to illustrate how each of the facies in the area were formed and how the environments of deposition changed through time. These facies models were compared and contrasted to the geomorphic evaluation of Brunk (2010).

CHAPTER IV

ANALYSIS OF DATA

Overview of Collected Data

Qualitative and qualitative observations were taken during the field portion of this study. A total of sixty samples were collected from the outcrops as well as the modern Gunnison River. These samples were sieved to provide a grain size distribution and to be compared and contrasted to previous work (Brunk 2010).

Thickness measurements were also taken of marker beds using a measuring tape to assess the accuracy of LiDAR measurements. All LiDAR and GigaPan® images were collected during this time.

Samples and Measurements

Of the 60 samples aquired in the field, 24 were chosen to represent the facies described in the field. These samples were labeled with their designated facies, location of collection, and number corresponding to a description in a field notebook. These were sieved in the lab as described above and the data was input to a statistical program created by Blott (2010) to derive grain size statistics as well as output cumulative frequency plots. The results of these sieve analyses are discussed later. In Facies Description.

Field Descriptions

Descriptions of facies, as well as a stratigraphic column, was completed in the field. Being a remote sensing technology field descriptions were a necessary step for

further interpretation as calibration in needed to accurately interpret the LiDAR and GigaPan® images later (Moore 2012).

Photographs

Along with the collected GigaPan® images and LiDAR data, additional photographs were taken of pertinate features using a digital camera. These included unit geometries, facies, anomalous features, representative sections, etc. These images were used in conjunction with the following data for final interpretations.

GigaPan® Collection

A total of Thirteen GigaPan® panoramic images were taken perpendicular to the outcrop. Eleven were from Cory Grade, one from Hotchkiss Grade, and one from Redlands Mesa Grade. Tripod stations were placed approximately 18 meters away from the outcrop and spaced 9 meters apart. The GigaPan® panoramic image was stitched together from several pictures taken at set intervals by the tripod mounted hardware. These images are of very high quality and can provide the viewer a high resolution image at varying scales (Figure 8).
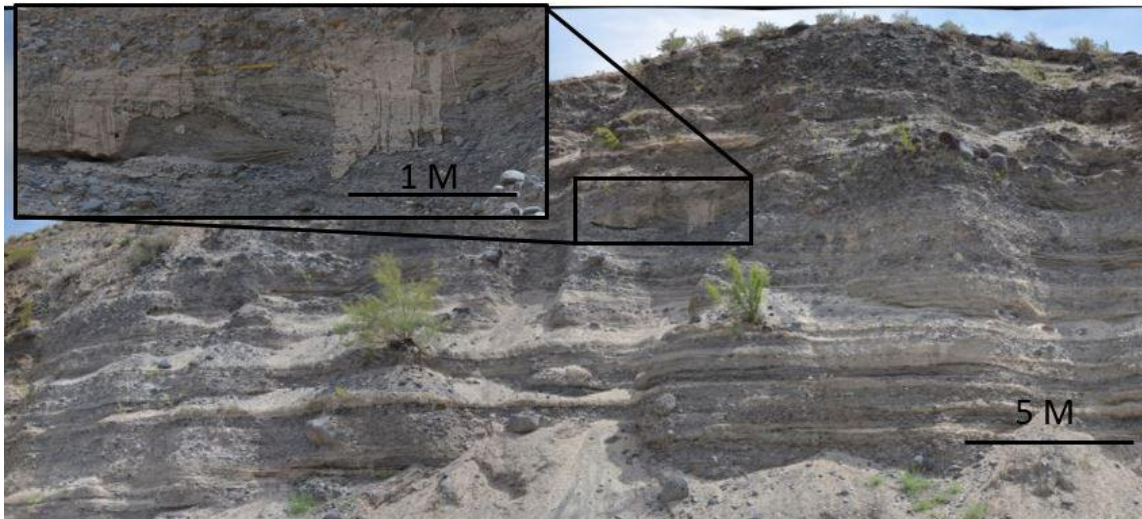
Figure 8. Example of GigaPan® resolution.

In this study the GigaPan® images were used in conjunction with the LiDAR images to examine the entire succession of strata present in the outcrops. The cm scale resolution provided by the GigaPan® allowed for interpretations to be performed accurately where direct field observations are limited.

LiDAR Collection

A total of thirteen LiDAR scans were taken perpendicular to the outcrop. Eleven were from Cory Grade, one from Hotchkiss Grade, and one from Redlands Mesa Grade. Tripod stations were placed approximately 18 meters away from the outcrop and spaced 9 meters apart. These scans were taken in the same spots as the GigaPan® images for direct correlation in. The LiDAR scans were loaded into Leica Cyclone® visualization software and were analyzed extensively.

The Cyclone® software allowed for user manipulation of the data. The 3D aspect of these scans allowed for the user to view any scan from any prospective giving a unique tool for interpretation (Bellian 2005; Moore 2012). These perspective changes can help interpret geometries and stratal relationships that digital images may not provide (Figure 9). Another unique aspect of LiDAR is its data, Cyclone® allows the user to display the point clouds in either intensity or RGB data collected during the scan (Figure 10). These alternate views allowed for greater correlations to the GigaPan® images or a unique view that could aid in facies distinction by differentiating reflection intensities (Moore 2012).
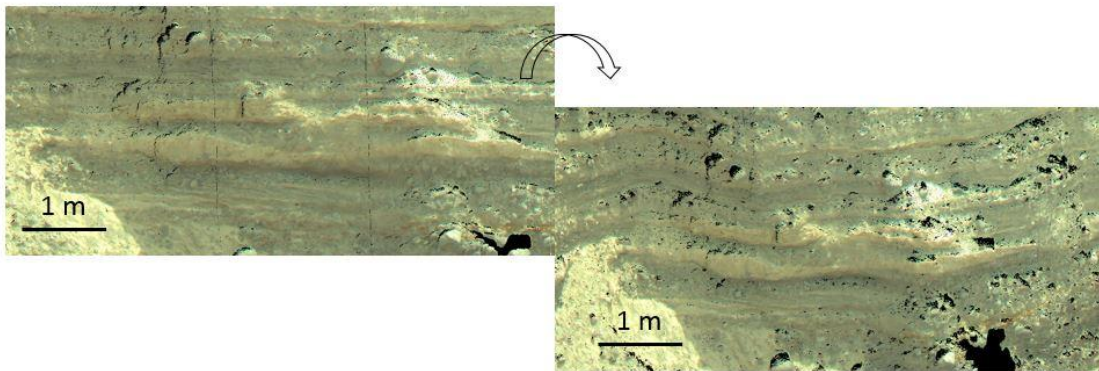
Figure 9 Example of rotated LiDAR. Note the apparent lenticular beds (left) are actually channelized (right) when viewed normal to the outcrop face.
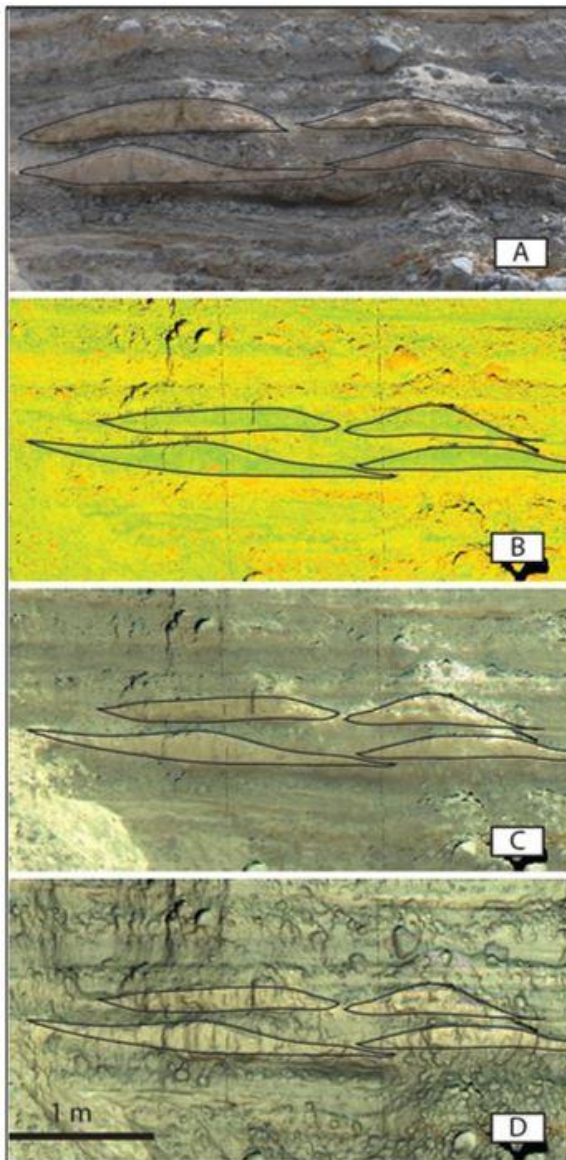
**Figure 10. Examples of LiDAR data displayed in different formats. (A) GigaPan®
image for reference. (B) LiDAR data shown in intensity values. (C) LiDAR data
shown in RGB values. (D) LiDAR data shown in RGB and texturally enhanced.**

An additional use of LiDAR data in this study was to perform direct

measurements of strata. Because LiDAR data is represented in XYZ space and are

spatially referenced from the scanner, point to point measurements can be taken and accuracy is assured (Bellian 2005 Moore 2012). Figure 11 shows an example of the accuracy to three decimal places in modeled space. The ability to perform measurements on the fly is significant in that the interpreter could generate accurate length references anywhere on the virtual outcrop to aid in interpretation.
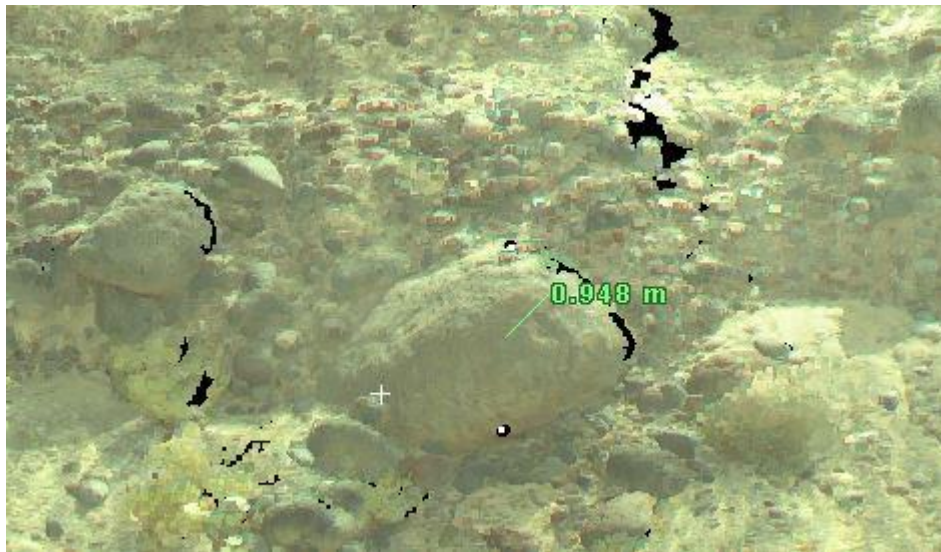
Figure 11. Example of measurement accuracy to three decimal places in 3D space.

Analysis

All available data, was analyzed to interpret the depositional processes and environments recorded in the outcrops accurately. Grain size, composition, sedimentary structures, and stratal geometries are discussed here and are the basis for the descriptions and interpretations to follow.

Grain Size

Grains present in Cory Grade, Hotchkiss Grade, and Redlands Mesa Grade have been extensively sampled and analyzed by Brunk (2010). He collected a total of 136 samples and sieved them to determine population means and in turn correlate them to facies and depositional environments. The results of this study showed a wide range of grains present in each outcrop. Φ values ranged from .961 to -3.014. These samples were sorted into four categories ($\geq 0 \ \Phi$), (-1.0 to 0 Φ), (-2.0 to -1.0 Φ), and ($\leq$ -2.0 Φ) (Brunk 2010). The Φ values observed from sieve analysis in this study range from a low of 4.6 and a high of -1.9 the majority of samples sieved were within the observed range of Brunk however the Fm and Fl samples were anomalously low (See Facies Description: Fm, Fl) with values ranging from 4.6 to 4.1 these facies do not fit into the previous description of depositional environments and are discussed later.

Composition

Basalt, rhyolite, granite, cohesive rock fragments, chert, quarts, silt, and mud constitute the observed clasts. Larger clasts were primarily basalt, and both vesicular and non-vesicular basalt were seen. These clasts represented approximately 95% of the granule and larger grains. Lesser amounts of exotic clasts (rhyolite, granite, cohesive rock fragments of sandstone and shale, chert) were observed in the outcrops. These observations are in accordance with the observations of Brunk (2010). Finer grained sediments (Φ values > 0) contained mixtures of basalt, quartz, and exotic clasts. The finer the sediment size, the higher the percentage of quarts became. The largest

26

percentage of quartz occurs in the Fl facies where quartz was the largest percentage grain (~80%). This is also in accordance with the observations of Brunk (2010).

Sedimentary Structures

A variety of sedimentary structures were observed in the outcrops. These include planer laminations, ripple, trough, and low angle cross-bedding, clast imbrication, normally graded and inversely graded bedding, massive bedding, and outsized clasts. These structures were recorded in detail for later use in analysis where facies were designated by their grain size as well as their specific sedimentary structures.

Laminations

Laminations occured in sediments ranging from silt to granule size. Laminae varied in thickness from mm to cm scale (Figures 12 and 13). Laminations were noted at Cory Grade, Hotchkiss Grade and Redlands Mesa Grade.
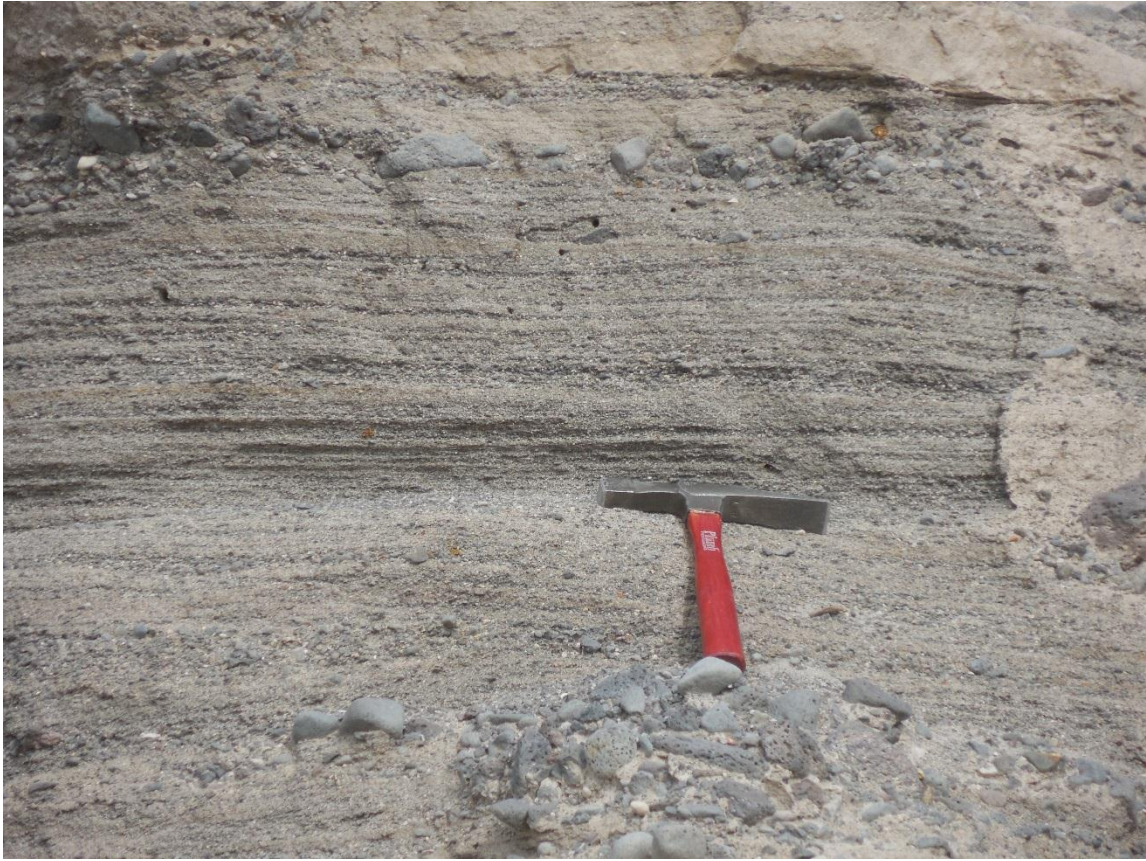
Figure 12. Sand laminations at Cory Grade.

Figure 13. Fine sand laminations at Cory Grade.

Cross-Bedding

Cross-bedding was formed in sediment ranging from medium sand to granule. Ripple cross-bedding and trough cross-bedding (Figures 14-16) were seen in medium and coarse sand beds and are very difficult to distinguish from one another. These types of cross-bedding were observed at Cory Grade, Hotchkiss Grade, and Redlands Mesa

Grade. Low angle cross bedding (Figure 17) was also seen at Cory Grade in coarse sand to granules.

Figure 14. Ripple cross-bedding at Cory Grade.
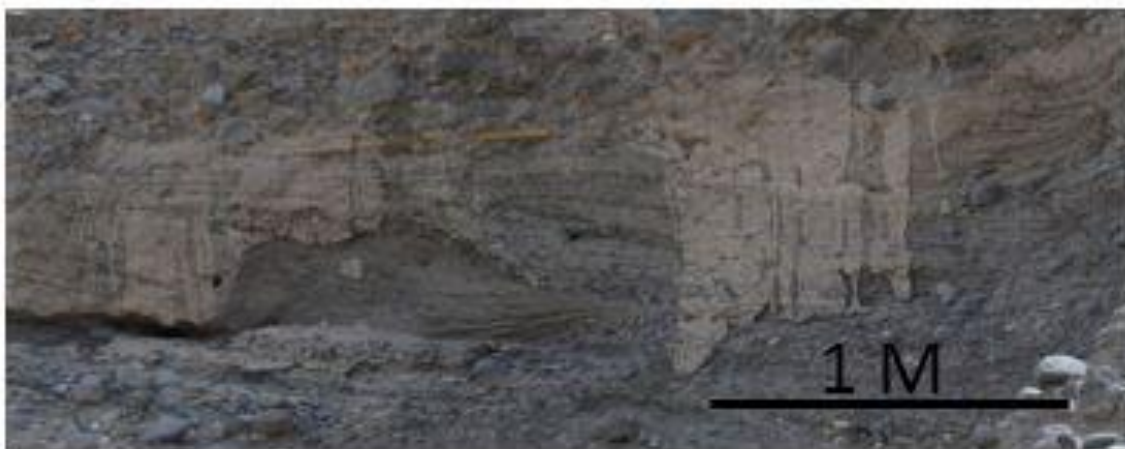
Figure 15. Trough cross-bedding at Cory Grade.

Figure 16. Trough cross-bedding at Redlands Mesa Grade.

Figure 17. Low angle planer cross-bedding at Cory Grade.

31

Imbrications

Imbrications were present in laminated beds and orthoconglomerates containing granules to boulders. Figure 18 shows an example of imbricated clasts at Cory Grade. Imbrications were present in Cory Grade, Hotchkiss Grade, and Redlands Mesa Grade and their orientation of imbrications were collected and used to show paleocurrent directions of S25W by Brunk (2010)

Figure 18. Imbricated clasts at Cory Grade. Orientation of clast is S25W.

Graded Bedding

Graded bedding formed in sediment from granule to boulder in orthoconglomerate beds (Figure 19). These graded beds were observed in Cory Grade, Hotchkiss Grade, and Redlands Mesa Grade. Both normal and reverse grading were noted

Figure 19. Inversely graded bed at Cory Grade.

Massive Bedding

Massive bedding was observed in sediments ranging from silt to boulder size (Figures 20 and 21). Massive bedding was observed in Cory Grade, Hotchkiss Grade, and Redlands Mesa Grade.

Figure 20. Massive bedded orthoconglomerate at Cory Grade. Clasts are composed mostly of basalt

Figure 21. Massive bedded fine sand unconformably overlying low angled planer cross bedded sand at Cory Grade.

Outsized Clasts

       Outsized Clasts were found randomly distributed in sediment of all sizes in each outcrop (Figures 22 and 23). The clasts are comprised strictly of vesicular or non-vesicular basalt.

Figure 22. Outsized clast at Cory Grade.

Figure 23. Outsized clast at Hotchkiss Grade.

Stratal Geometries

There were a variety of stratal geometries and bedding structures observed in these outcrops. These include sheets, channels, ribbons, lenses, wedges, and scour fill. The most common geometries were the sheet, designated by lateral extent and correlatability of beds across erosional surfaces; and the channel, ribbon and lense, designated by thin laterally discontinuous beds.

Sheets

Sheets occur in all outcrops and contained sediment ranging from medium sand to boulder size. These beds were characterized by long lateral extents where continuous, and correlatable across erosional surfaces such as incised channels where discontinuous. These types of deposits were used to build the framework of a stratigraphic column discussed later.

Ribbons and Lenses

Ribbons and lenses occur at Cory Grade and Hotchkiss Grade. Ribbons have varied lengths between a few cm to several meters and thicknesses of less than 10 cm. Lenses were measured to be approximately 2-5 meters in length and 0.2 to 0.5 meters in depth. The shape of these beds are convex both on top and bottom (Figures 24 and 25) show examples of these features in outcrop.
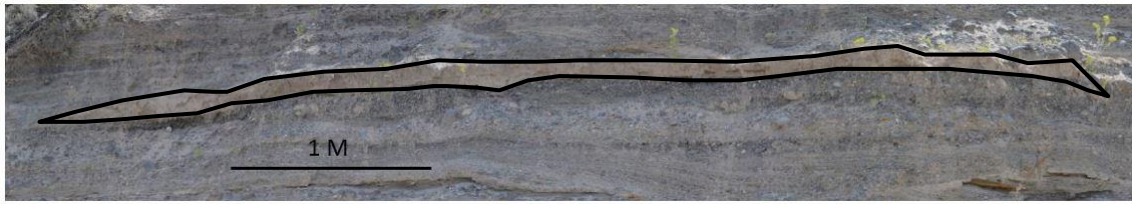
Figure 24. Lense at Cory Grade.

Figure 25. Ribbon at Cory Grade.

Channel Forms

Channel form beds occur at Cory Grade and are between approximately 2 and 5 meters in length and between approximately .2 and .5 meters thick. These channels occurred as both isolated beds and rarely as amalgamated beds. The base of these channels were scoured and sometimes preserved basal ripples (Figures 26 and 27).

Figure 26. Channel form bed 1 at Cory Grade. Channel is preserved with truncations above and below the marked line. Internal laminae are angled differently than those in the exterior.

Figure 27. Channel form bed 2 at Cory Grade.

Wedges

Wedges occurred at Cory Grade and are between approximately 1 and 3 meters in length and between a few cm to a meter thick. These wedges were comprised almost exclusively of fine grained laminated silt and sand (Figure 28).

Figure 28. Wedge at Cory Grade.

CHAPTER V

INTERPRETATION AND DISCUSSION

LiDAR Interpretation

The LiDAR data collected in this study was used extensively as an interpretive tool. The unique aspects of 3D scanned surfaces allowed for a more complete analysis and interpretation of the outcrops. Manipulation of the data in 3D space allowed for more precise examination of the outcrop that is impossible with static images (Figure 9). The ability to examine the data in different formats (intensity, RGB, enhanced texture) allowed the interpreter to examine the outcrop more accurately and to better correlate between GigaPan® images and the 3D scans (Figure 10). The ability to measure objects in 3D space to three decimal places also allowed the interpreter to make measurements on the fly with great accuracy and confidence (Figure 11). Finally the ability to scan the outcrops and interpret them outside the field made this application an economic use of time. These aspects made the LiDAR data a markedly useful tool in this study to examine, describe and interpret the outcrops.

Facies Description

Using all available data, field descriptions, photographs, Gigapan® panoramics LiDAR and samples, facies were defined and are shown in Table 1. These facies were designated a code based on Miall (1977) description of silisiclastic facies. The distinction of facies were determined by their grain size, sedimentary structures, and clast composition. These facies were compaired to published descriptions of similar

43

facies (Miall 1977). Interpretation of these facies was based on Miall's (1978) table of alluvial type sediments and Moody (1966).

Facies Code	Lithofacies	Clast Composition	Sedimentary Structures	Interpretation
Gmm	Matrix-Supported Massive Gravel	Basalt, Mud, Silt, Rare Exotic Clasts	Massive, Weak Grading	Plastic Debris Flow Deposits, Glacial Outwash
Gcm	Clast-Supported Massive Gravel	Basalt, Mud, Silt, Rare Exotic Clasts	Massive, Weak Grading, Imbrications	Massive Debris Flow Deposits
Sh	Fine to Very Coarse Sand, Usually Containing Pebbles	Basalt, Quartz, Silt, Mud, Rare Exotic Clasts	Horizontal Laminations, Imbrications	Bedload Transported Deposis
Sl	Fine to Very Coarse Sand, Usually Containing Pebbles	Basalt, Quartz, Silt, Mud, Rare Exotic Clasts	Low Angle Cross Bedding	Scour Fill , Bedload Transported Deposis, Bar Migration
St	Fine to Very Coarse Sand, Usually Containing Pebbles	Basalt, Quartz, Silt, Mud, Rare Exotic Clasts	Complex Trough Cross Bedding	Braided River Deposits Medium Flow
Sr	Fine to Very Coarse Sand, Usually Containing Pebbles	Basalt, Quartz, Silt, Mud, Rare Exotic Clasts	Ripple Cross Bedded	Braided River Deposits, Low to Medium Flow
Fl	Very Fine Sand, Silt, Mud	Clay, Quartz, Bassalt	Horizontal Laminations	Overbank Deposits
Fm	Very Fine Sand, Silt, Mud	Clay, Quartz, Bassalt	Massive, Ripples	Abandoned Channel Deposit

Table 1. Facies summary of the area. Modified from Miall (1977).

The distinction of facies allowed for an interpretation based on these predictive descriptions and their stratal relationships. Five distinct facies occur in the outcrops based on a glacio-fluvial interpretation of the sediments (Brunk 2010). The facies were described as Fl, Str, Sl, Gmm, and Gms. In his paper he describes a facies stacking pattern of these outcrops recording a history of overall energy increase.

Facies Fl and Fm: Fine Grained Massive and Laminated Sands

The finest grained sediments in the outcrop were those of facies Fl and Fm. These facies had an average Φ grain size of approximately 4 which was markedly lower than any other sediment collected (Table 2 and 3). The composition of these sediments is also unique to this facies with a distinctly higher percentage of quartz ~80% (where observable) and a large percentage of silt and mud. These facies are deposited in channels, ribbons, lenses, and wedges. They were usually unconformable to the facies above and below, though scour at the base of lenses and channels were sometime preserverd.

Sieve Data Fl						
Sample	Bedding	Mean(φ)	Median(φ)	Sorting	Skewness	Kurtosis
Flc1	Wedge	4.389	3.888	1.124	0.680	4.404
Flc2	Lense	4.572	3.906	1.278	0.69	1.559
Flc3	Wedge	4.138	3.884	1.307	0.407	4.710
Flc4	Wedge	4.134	3.879	1.329	0.403	4.092

Table 2. Facies Fl sieve data.

Sieve Data Fm						
Location	Bedding	Mean(φ)	Median(φ)	Sorting	Skewness	Kurtosis
Fmc1	Channel	4.632	3.923	1.302	0.705	1.349
Fmc2	Channel	4.641	3.925	1.308	0.706	1.316
Fmc3	Channel	4.582	3.916	1.258	0.706	1.592
Fmc4	Massive	4.490	3.896	1.211	0.681	2.233

Table 3. Facies Fm sieve data.

Rare preserved ripples also occur in this facies at the base of many of the channels with waves flowing in a roughly east-west direction. Clasts of underlying sediment were also observed within the matrix of many Fm beds indicating basal scour.

Facies Fl usually formed wedges as described earlier. These were interpreted to be over bank deposits formed during cyclic floods of the paleo-Gunnison River. In many cases such as in Figure 29 these overbanks are found unconformibly overlain by glacio-fluvial sediment.

Figure 29. Fl wedge at Cory Grade unconformibly overlain by Gcm.

Fm facies were most commonly deposited in channels and channel form features. The sharp erosional convex base and flat top indicate an ancestral meandering river abandoned channel that was abandoned and filled up by fine grained material. This sediment was produced from slow suspention fall out (Moody 1966). (Figure 30) These channel forms were only present in the Cory Grde outcrop.

Figure 30. Fm abandoned channel at Cory Grade showing distinct erosional lines.

Elsewhere Fm facies can occur as long thin ribbons or as smaller lenticular beds. These lenticular beds pinch out laterally and do not have scoured erosive bases. These deposits are interpreted to be produced by dammed portions of the river flooding and spilling out fine sediment or as crevasse splays from the channel bodies (Figures 24 and 25, 31). Fl facies were interpreted to be waning flood events of melt water coming off Grand Mesa and is likely be incorrect. The channelized features of the Fm facies and wedge shaped Fl facies are not reconciled easily as into waning flood-type deposits (Miall 1977). Instead they more closely match the criteria for the the abandoned channel and over bank deposits (Miall 1977, Moody 1966).
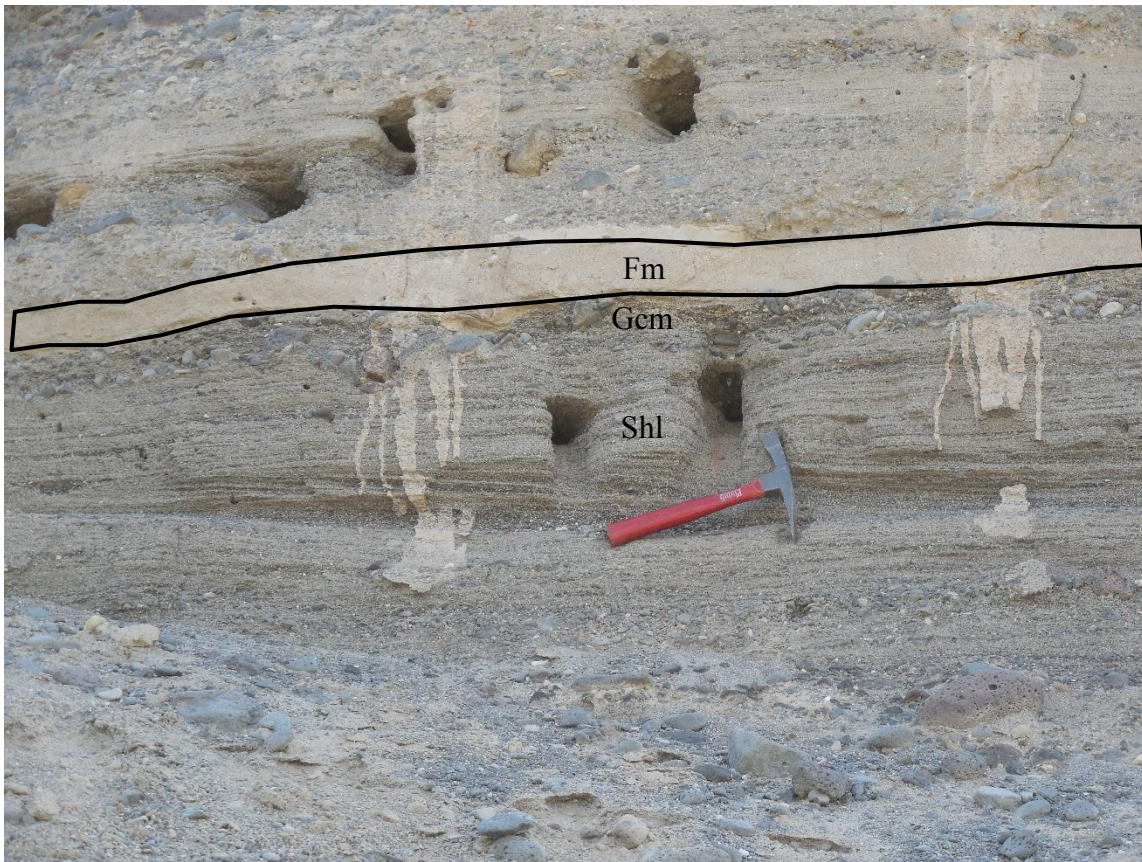
Figure 31. Fm lense above Shl and Gcm. Potentially a crevasse splay from overriding river.

Facies St and Sr: Ripple and Trough Cross-Laminations

Two types of high-angle cross bedding were observed at each location: rippled cross lamination and trough cross lamination (Figures 14 and 15). These facies usually unconformably overlie the sediment beneath them either across a sharp unconformity or across an irregular erosional unconformity. The grain size for these facies ranges from 1.141-2.803 Φ with an average grain size of 1.752 Φ (Table 4). Distinguishing between

rippled and trough cross laminations is difficult, and their similar grain size and conformable nature to each other; these facies are lumped together in the Str facies for the purposes of description and later interpretation. The composition of these facies are primarily basalt (~50-75%) with increasing amounts of quarts as grain size decreased. The Str facies is usually deposited in discontinuous sheets with erosive contacts horizontally and laterally.

Sieve Data Str						
Sample	Bedding	Mean(ϕ)	Median(ϕ)	Sorting	Skewness	Kurtosis
Strc1	Sheet	1.381	1.8	1.009	-0.593	1.429
Strc2	Sheet	1.141	0.824	1.493	0.280	1.014
Strh3	Sheet	2.803	2.8	1.289	0.022	1.760
Strc4	Sheet	1.685	1.88	1.436	-0.218	1.074

Table 4. Facies Str sieve Data.

The direction of flow of these deposits was recorded by Brunk (2010) to be approximately north-south. Examination of these facies and comparison to descriptions of similar facies in Miall (1977, 1978) and the interpretation of Brunk (2010) have led to the interpretation of a gravel bedded braided stream environment. The occurrence of cross laminations of these types is consistant in areas with glacio-fluvial influence (Miall 1977). This type of depositional environment is common in glacially influenced areas because of the large amounts of sediment being delivered from the melt waters of the glacier and their relatively high energy levels. Because these types of deposits are short

lived and rapidly change course and direction within their ever changing environment, the lateral discontinuity and erosive nature of the Str facies supports this interpretation..

Facies Sh: Horizontally Bedded Sand

Facies Sh was observed to have a distinctly coarser grain size than the Str facies. These horizontally bedded sands had grain sizes ranging from -0.533 to 1.243 and an average size of 0.312 (Table 5). The energy involved to move this sediment must have increased in order to entrain coarser sediment. Sh usually conformably overlies Str however it can unconformably overlie any of the observed facies. Grain composition was similar to that of Str, however with an increase in the amount of Bassalt and exotic clasts noted.

		Sieve Data Sh				
Sample	**Bedding**	**Mean(ϕ)**	**Median(ϕ)**	**Sorting**	**Skewness**	**Kurtosis**
Shc1	Sheet	1.243	1.853	2.152	-4.71	1.322
Shc2	Sheet	-0.657	-0.194	2.462	-.163	0.607
Shc3	Sheet	-0.533	-0.579	2.264	0.029	0.606
Shc4	Sheet	1.195	1.832	2.155	-.474	1,884

Table 5. Facies Sh sieve data.

This facies is also deposited in laterally and horizontally discontinuous beds similar to Str. This facies is interpreted to be representative of a higher flow regime with a Froude number great enough to produce a super critical flow causing plainer bedforms and in some cases imbrications (Miall 1978). The imbrications in these beds were logged

and recorded by Brunk 2010 and paleo-flow directions showed an approximate North-South direction of flow as well. Figure 32 and 33 shows examples of these plainer beds. It is important to note that this facies is conformably bedded with the following facies Sl in many cases.
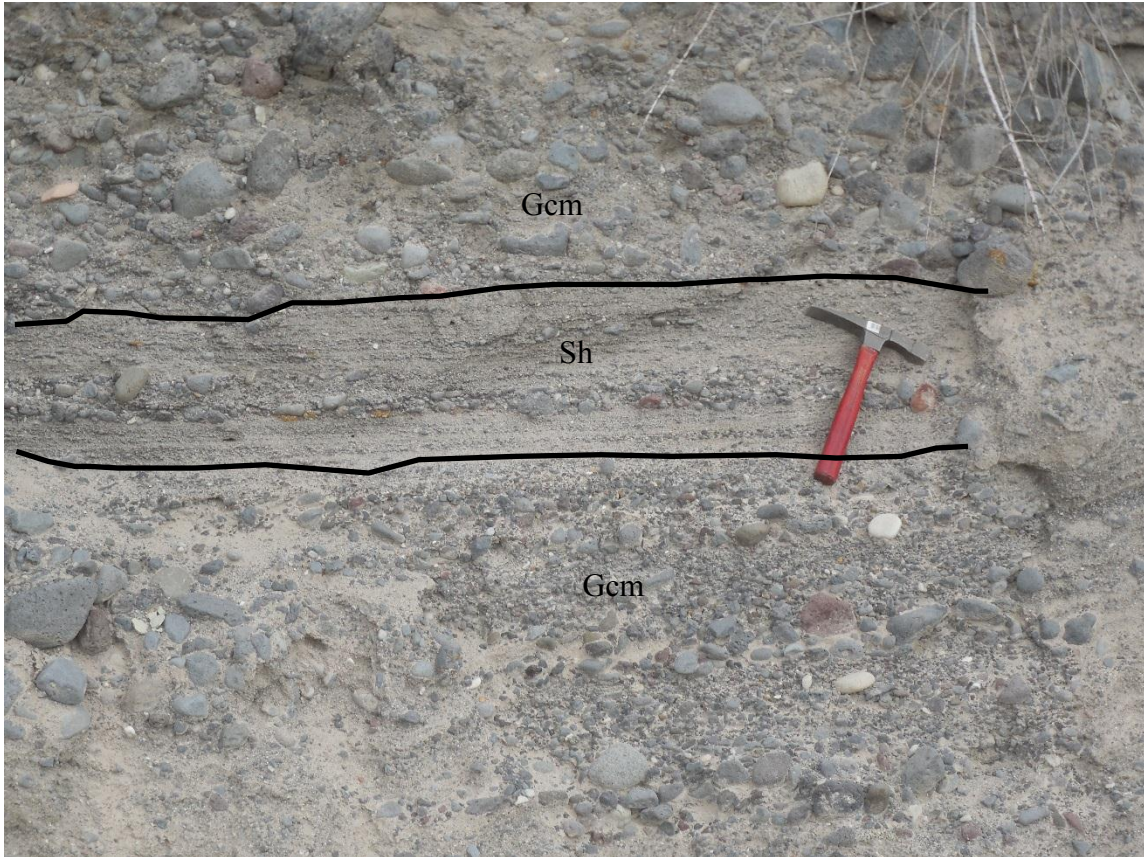
Figure 32. Example of Sh facies 1 at Cory Grade

Figure 33. Exmple of Sh facies 2 at Cory Grade.

Facies Sl: Low Angle Cross-Bedded Sand

Cross beds that were very low angled (<10°) occur at Cory Grade. The grains that made up this facies had average values of -0.887 and ranged from 0.337 to -1.324 (Table 6). Compositionally this facies is similar to Sl and Str and showed a similar increase in basalt percentage up to approximately 90%. Two distinct geometries of bedding were observed in this facies: interbedded and conformable with Sl as described

above, sharing a similar discontinuous sheet like bedding (Figure 34); and channel form fill with an angular unconformity at its base (Figure 35). The interpretation of Sl where it is interbedded with Sh is that of fluctuations in flow regime transitioning from planer deposition to that of a higher flow rate. This higher flow rate would produce washout dunes that would be preserved in outcrop (Miall 1977).

			Sieve Data Sl			
Sample	Bedding	Mean(φ)	Median(φ)	Sorting	Skewness	Kurtosis
Slc1	Sheet	-1.176	-1.08	1.709	-0.025	1.094
Slc2	Sheet	-1.050	-0.739	1.715	-0.185	0.943
Slc3	Sheet	0.337	0.361	1.66	-0.231	0.839
Slc4	Sheet	-1.324	-0.761	1.931	-0.250	0.768

Table 6. Facies Sl sieve data.
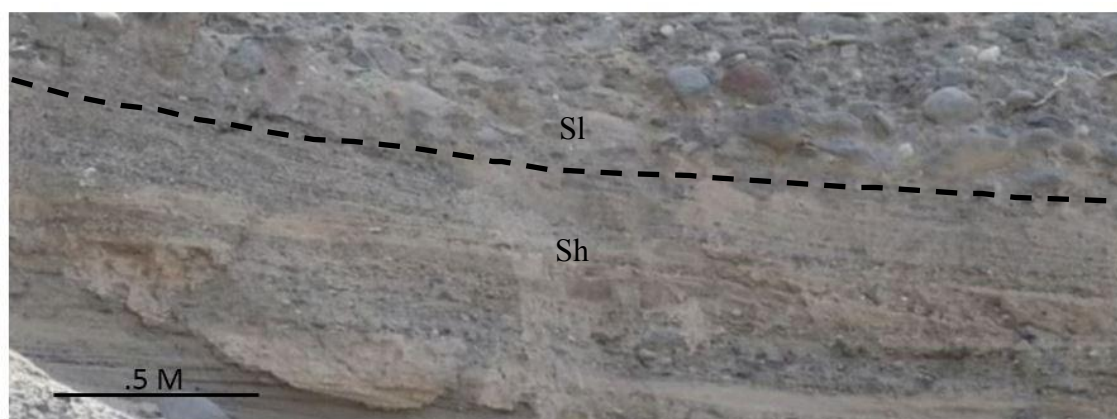
Figure 34. Example of Sl at Cory Grade. Note the conformity with Sh.
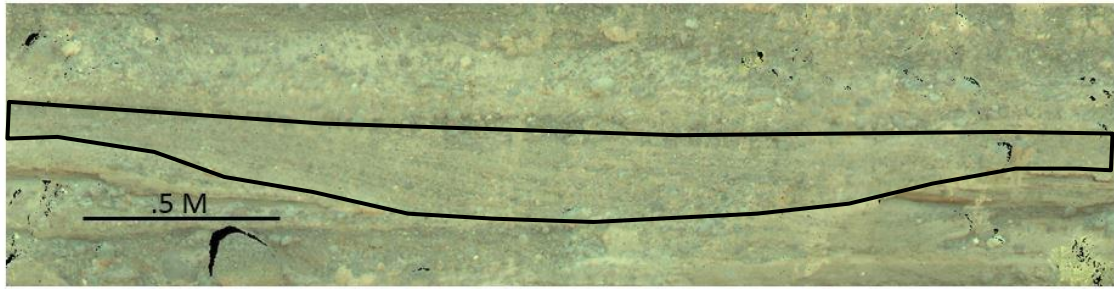
Figure 35. LiDAR view of a channel form Sl bed.

Where Sh is interbedded with Sl these two facies are designated as Shl for descriptions and later interpretations. The second interpretation is that of the channel filling Sl. Here the bedding angle is slightly higher and appears to prograde across an incised chanel form. This type of deposit was described as a migrating channel bar and is indicative of a highly sinuous river (Moody 1966). The major difference between the two Sl deposits is their geometries. Facies associations for Sl are described later. Facies Sl was not described by Brunk (2010).

Facies Gmm: Massively Bedded Matrix-Supported Gravel

The first of the two gravel conglomerates is the Gmm facies, a massively bedded paraconglomerate. The grain size analysis shows grain sizes between -0.631 and -2.277 Φ and an average of -1.42 Φ. (Table 7) These values are misleading however because the matrix is composed of a mixture of mud, silt and sand with gravel to boulder sized basalt clasts forming the conglomerate (Figure 36). The nature of this type of facies is very random distributions of very fine grained sediment mixed with very coarse sediments.

This random nature makes it difficult to get an accurate grain size in the analysis. The clasts were almost entirely basaltic with some exotic clasts and cohesive rock fragments. Gmm facies occur as a sheet or tabular bodies deposited randomly throughout the outcrops. Gmm has unconformable tops and bottoms.

		Sieve Data Gmm				
Sample	Bedding	Mean(φ)	Median(φ)	Sorting	Skewness	Kurtosis
Gmmc1	Sheet	-1.847	-2.046	1.177	.391	.923
Gmmc2	Sheet	-.631	-1.104	2.750	.274	.593
Gmmh3	Sheet	-2.277	-2.754	1.755	.587	1.082
Gmmc4	Sheet	-.925	-1.139	2.533	.223	.709

Table 7. Facies Gmm sieve data

Figure 36. Example of facies Gmm at Hotchkiss Grade.

This facies is interpreted to be a plastic debris flows (Brunk 2010). This interpretation is based on the abundance of large basalt clasts that could only be sourced from the mesa and the mud matrix that indicates water present in the flow (Rust 1978).

Facies Gcm: Massive and Crudely Bedded Clast Supported Gravel

The second type of gravel conglomerate is the Gcm Facies. The grain size of this facies was measured remotely through the LiDAR to obtain representative clast size. The grain sizes of the conglomerate clasts were granule to boulder with some infill of coarse sand. The grain size was so large that a modern sieve could not handle it, so no average values or distributions are reported. The largest percentage of the clasts were basalt (~95%) with some rare exotic clasts and cohesive rock fragments.

These facies were the most laterally continuous deposits presumably because of the sheer grain size and the inability of rivers and streams to move such large clasts. Facies Gcm is a clast supported orthoconglomerate. Some weak grading is present though the dominate bedding is massive (Figure 37). The facies is interpretated to be a mass wasting debris flow such as a rock fall or an outburst flooding event (Miall 1987, Brunk 2010). This type of debris flow is typical in alpine regions especially those with glacial influence (Miall 1977).

Figure 37. Gcm deposit at Cory Grade.

Facies Association

Once facies were identified and described in detail, depositional environments could be associated and the facies grouped (Table 8). Four distinct depositional environments were interpreted: debris flow, transitional flow, braided stream and meandering stream. These interpreted environments were used to create facies models to illustrate depositional patterns.

Depositional Environment	Facies Assemblage	Bedform Geometry	Interpretation
Debris Flows	Gmm, Gcm	Sheet	Rockfall, Mud Flow
Transitional Flow	Sh, Sl, (Shl)	Scour Fill, Sheet	Glacio-Fluvial Drainage (Upper Flow Regime)
Braided Stream	St, Sr, (Str)	Sheet, Channel	Glacio-Fluvial Drainage (Lower Flow Regime)
Meandering Stream	Fl, Fm, Sl	Lense, Channel, Wedge, Ribbon	Ancestral Gunnison River (High and Low Sinuous)

Table 8. Summary of facies association.

Debris Flows

Facies Gcm and Gmm are interpreted to be debris flow deposits. These massively and crudely bedded orthoconglomerate and paraconglomerate deposits are dispersed horozontally throughout the outcrop at random positions. These deposits are the most laterally continuous and thickest types of deposits seen in outcrop. The clasts that make up the deposits are primarily basalt (~95%) with rare exotic clasts. These units are similar to those of (Miall 1977, Rust 1977 and Miller 2006). The source of basalt is the Miocene basalt cap on Grand Mesa north of the outcrops (Brunk 2010). The exotic clasts, such as chert possibly had a source in the underlying tertiary strata where pieces of *in situ* chert were found in this study. Imbrication of clast indicates that the paleo flow direction of these types of deposits is away from the mesa in a general southward direction (Brunk 2010). This is in accordance to the position of the assumed sediment source for these debris flows.

During times when the ice cap exposed the basalt cap, outwash and rockfalls could occur sending massive amounts of sediment down the slopes of the mesa and eventually come to rest downslope. These deposits would are tabular in nature having sharp erosional surfaces at their base because of the amount of energy present during these types of flows. The random distrobution of these types of deposits would suggest they did not follow a genetic type sequence of stratigraphy. However, their presence does provide insight to the types of environments during their deposition.

For instance the orthoconglomerate, clast-supported Gcm facies has been interpreted to be a rockfall type debris flow (Miall 1978). This type of flow is characterized by occuring randomly and not having much water in its matrix. The paraconglomerate Gmm however is a plastic type debris flow and would likely include more water to support the mud in its matrix. It can be assumed then that where Gmm is preserved greater volumes of meltwater were present in the system and most likely supersaturated the ground at the top of the mesa resulting in large amounts of sediment being washed down and distributed downslope (Rust 1978).

Transitional Flows

Two types of transitional flows were interpreted from the facies described previously: 1) planer bedflow and 2) low-angle cross-bedding. The high energy environment was recorded in the rock record as planer laminations found in coarse to very coarse sands. These horizontal laminations (Facies Sh) have been interpreted to represent times when melt coming off the mesa began to increase and reach a Froude number exceeding normal flow regimes (Miall 1977). This super critical type flow

conformably overlies lower flow regime beds such as facies Str indicating a transition from a lower flow regime to a higher flow regime. (Brunk 2010)

The second type of transitional flow is low angle cross bedding (<10°). These types of sediment conformably over and underlie the horizontally laminated beds commonly however there is an increase in grain size (very coarse sand) in the deposits. These types of deposits indicate that the amount of water coming from the mesa increased further causing washout dunes and scour fill type deposits (Miall 1978). These types of deposits are fairly laterally extensive and occur as sheets and tabular bodies punctuated by erosional surfaces throughout the outcrop. The usual succession to follow these types of deposits are unconformable debris flows marking a time that the ice cap had retreated exposing the basalt layer as discussed above. Because of their interbeded and conformable nature, facies Sh and Sl have been combined to Shl for the purpose of this study.

Braided Streams

In glacio-fluvial settings, one of the dominant methods of removing material and water is the gravel-bottomed braided stream (Miall 1977). Facies St and Sr are interpreted as expressions of this depositional environment. These deposits unconformably overly either the Fl, Fm, Gcm or Gmm facies. Facies St and Sr are very difficult to distinguish in the field or from the LiDAR images. The inherent difficulty is compounded by the orientation of the road cut. Since the source of the basalt is from the north and the paleo currents in these deposits are southward, the north-south road cut results in difficulties in interpretation. Trough crossbedding appears to be rippled in

strike view and can be difficult to differentiate because of it. (McKee 1953) Because the difference in depositional environment is small here these two facies have been lumped into Str. (Brunk 2010)

Str facies occur in all outcrops showing that the braided stream environment was well developed along the slopes. The lateral discontinuity of these beds is common in braided stream systems. Braided streams have short lived channels that are rapidly infilled by sediment and avulse and change flow directions to accommodate changes in environmental conditions or slope changes (Miall 1977). Str facies commonly are conformably overlain by facies Shl marking an increase in both flow strength and grain size indicating an increase in energy. Although braided streams are commonly described as fining upward, in areas of glacial influence and where there is little subsidence braided streams can coarsen upward. (Eyles and Miall, 1984; Nemec and Steel, 1984; Rust and Koster, 1984; Miller, 2006, Miall 1977, 1978) This is interpreted to be because of erosion of the finer grained sediments off the top of the succession as a new braid overrides an older or if these braided streams are infilling low lying areas. (Miall 1977) The braided stream environment interpreted in this study is in accordance to the findings of Brunk (2010).

Meandering Stream

At Cory Grade glacio-fluvial sediments dominate the outcrop. Each of the previously described and associated facies have had their source from the north as their grains were mostly basaltic from the Miocene basalt cap of Grand Mesa. Melt waters from the ice cap delivered the sediment in either braided streams or supercritical flows, and the debris and plastic flows were from gravity-driven events of rockfalls or massive

flows. However, there are two types of deposits that are completely different than those previously described. They have an east-west flow direction and are composed almost entirely of quartz and mud. Facies Fm, Fl, and in some places Sl are associated with a meandering stream that constantly attempted to establish a stable channel. This meandering stream parallels the modern Gunnison River that flows approximately half a mile south of the outcrop. The channel form bedded Fm facies are interpreted to be abandoned channels that were cut off when the river avulsed to change position. The river had low sinousosity because of the lack of a migrating bar (Moody 1966).

The erosive bottom indicates that the paleo flow was approximately perpendicular to the incoming braided streams and debris flows. Rare ripples with wave heights on the order of a few cm show paleocurrents capable of producing 2D bedforms before being cut off and having suspension load fall out infill the channel. Facies Fl was usually deposited as wedges indicating that some of the channels existed long enough to create overbank deposits and they had flooding events. In cases where the Fl was either lenticular or in channelized beds they are interpreted as suspension fallout that created fine laminations in this environment.

In several cases Fm and Fl occur in long thin ribbons or in rare cases as large bedded deposits (thickness >10 cm) these deposits pinch out laterally and are lenticularly or massively bedded with erosive tops and bottoms. These cases have been interpreted to be where the river became dammed and the channel filled up beyond its banks, flooded and pooled in low lying areas. This sudden and rapid decrease in flow caused a large amount of fine sediment to accumulate. These flood events are assumed to be common

in this type of environment where the meandering river is short lived because of the influx of sediment from the north. The lateral discontinuity of the beds is also expected because these floods were confined to small channels and floodplains from the short lived channel.

During times that the meandering river had enough energy to become highly sinuous Sl migrating bars were developed within the channel forms. These were easily identifiable by their angular unconformable terminations to the bottom of the channel form and their apparent lateral migration within it (Moody 1966). These channels are rare and only seen where the high sinuous river existed long enough to create bars that were preserved. In all cases however the channel form features of the meandering stream are unconformably overlain by either braided stream deposits or debris flows. This indicates that while the river was able to establish itself perpendicular to the other types of deposits, its environment rapidly changed with the influx of sediment from the north. Additionally these channelized features were never amalgamated, they appeared as lone channel features dispersed throughout the outcrop.

Comparison to Modern Sediments

With the modern Gunnison River flowing just south of the interpreted outcrops, comparison of modern and ancient sediments could easily be conducted. The observations of sediment composition and grain size can provide support to the interpretations of facies. The two facies primarily associated with an ancestrial meandering river are Fm and Fl. Samples from an interpreted Fl overbank deposit and Fm abandoned channel were compared to samples from the modern day Gunnison River.

The results showed a very similar grain size and composition between the modern and ancient sediments (Figure 38). where observable the dominate clast is quartz with a very fine silt and mud matrix. In contrast the coarsest sample collected from the Gunnison was compaired to interpreted Str braided stream deposits (Figure 39). A clear difference in grain size is present with the Str braided stream being much coarser. Additionally the composition of the Str grains shows a greater percentage of basalt along with the addition of exotic clasts. The examination of modern sediments provides support to the interpretations in this study.
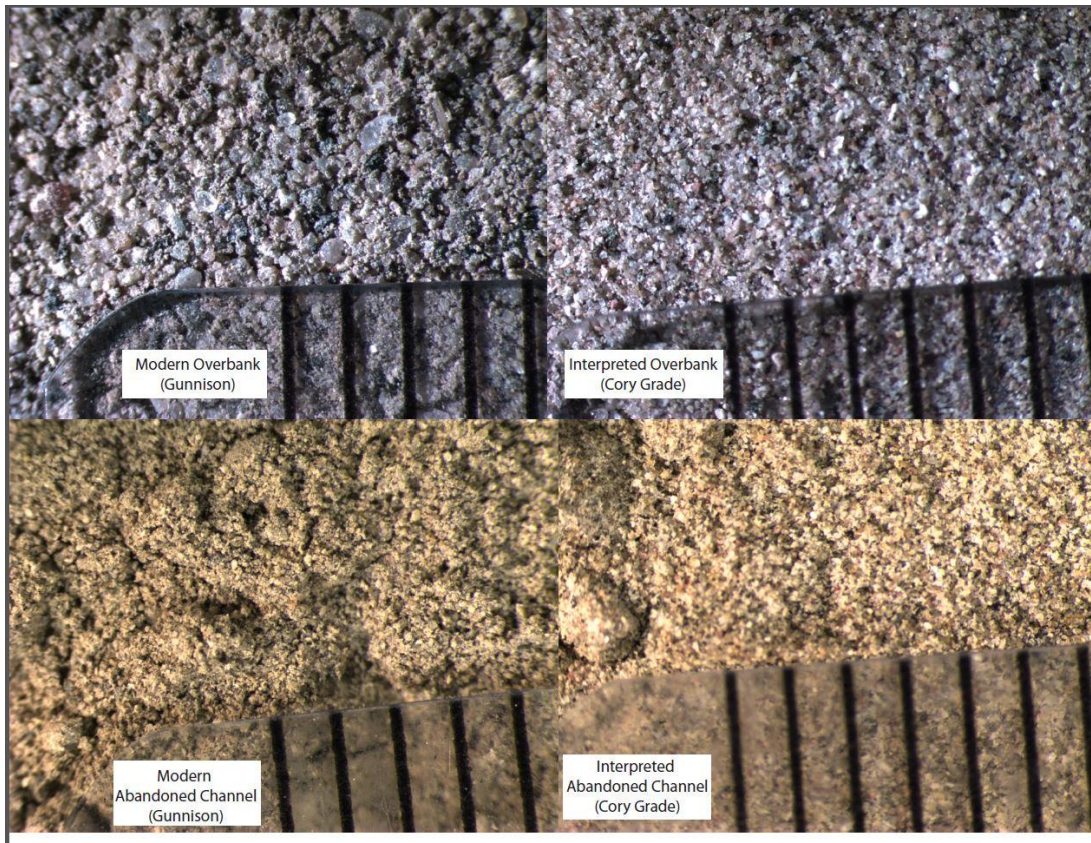
Figure 38. Comparison of modern and ancient sediments showing similarities in interpreted facies and their modern equivalent. A c-thru® ruler is shown to provide scale. Note there is some minor difference in grain size but composition and texture is the same.
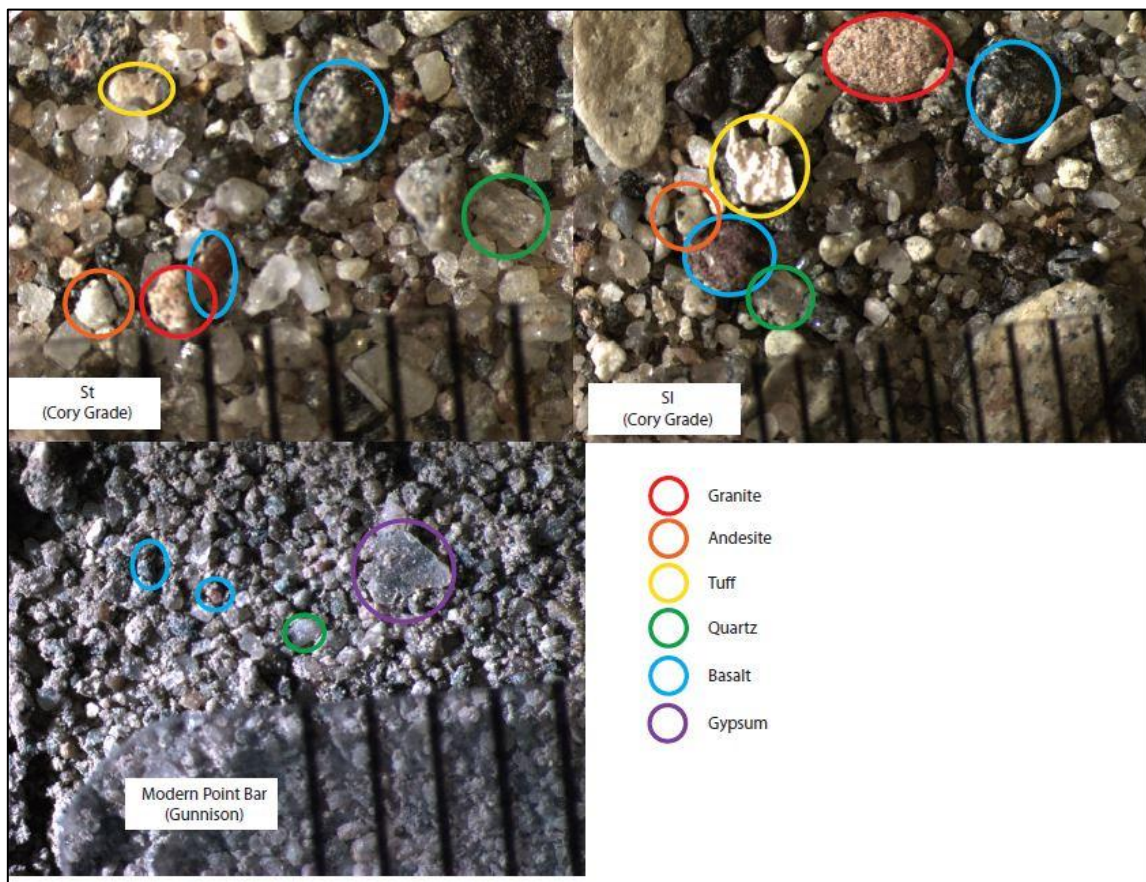
Figure 39. Comparison of modern Gunnison River sediments to interpreted braided river sediments. The much coarser Str paired with its difference in composition shows a different environment of deposition and a different sediment source.

Stratigraphic Architecture and Depositional Trends

The stratigraphy of the study outcrops is very difficult to constrain because of the

lateral variability as described in detail in Brunk (2010) (Figure 40). The reason for the

discontinuities are twofold: Firstly the deposits described above are laterally

discontinuous, and secondly the diverging orientations of the channels create more heterogeneity. The area is dominated by glacio-fluvial braided streams and super critical short lived gravel bedded streams. This leads to a difficulty in correlating measured section over large distances, additionally large amounts of erosion are recorded in the rock record as sharp contacts between beds (Figure 41). The amount of erosion and its relative local influence makes it difficult to understand the thickness of successions during deposition as complete depositional sequences are rare. The only strata that seem to have preserved depositional sequencse are that of the Str, Shl, Gcm. This sequence is similar to the one described by Brunk (2010) however in his description Fl is the lowest facies in that succession (Figure 42). This pattern of energy increase and grain size coarsening is expected from glacio-fluvial drainage as discussed before (Miall 1977).

Figure 40. Example of lateral discontinuity of beds. Adapted from Brunk (2010)

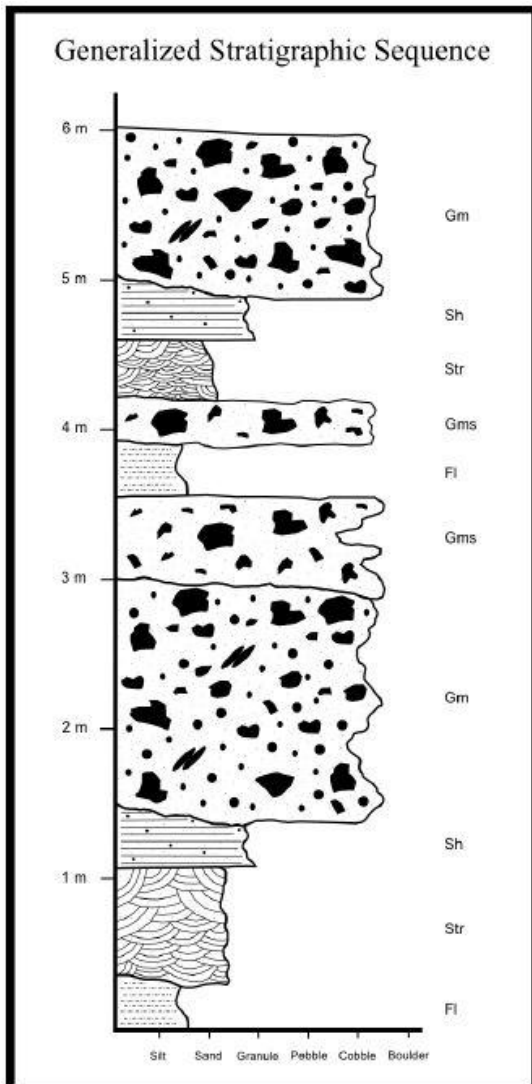**Figure 41. Example of the sharp erosional lines seen in outcrop.**

Figure 42. Idealized stratigraphic succession from Brunk (2010)

Altough the Str-Shl-Gcm produces small-scale successions (cm to meter scale) in order to produce a full stratigraphic column of the outcrop idealization of successions and patterns of depositional processes were combined Figure 43. The final idealized

stratigraphic column of the Cory Grade outcrop was created by detailed analysis of all available data (e.g. field description, LiDAR scans, GigPan® Images) to produce a framework of strata and depositional trends through time. The column shows that background sedimentation is Str, Shl, and Gcm deposition punctuated by nearly random Gmm and Fl/Fm deposits. The lenses and wedges of Fl and Fm respectively record the abandoned channels, pools, and banks associated with the Ancestral Gunnison River. The two larger bedded Fm units could represent larger scale flood events, however they are interpreted to record large-scale river damming and its resulting pooling. This stratigraphic column is very similar to the published Scott type succession of proximal glacio-fluvial deposits seen in Miall (1977) with the inclusion of the fine grained sediments associated with the meandering river. The concentration of fine grained sediments varies from bottom to top, with the bottom two thirds of the section containing greater amounts of Gmm plastic debris flows and Fm abandoned channels. This grades upward into a higher concentration of Gcm debris flows with less stream deposits. The concentration of Str and Shl braided streams appears to stay relatively constant throughout deposition of this section.
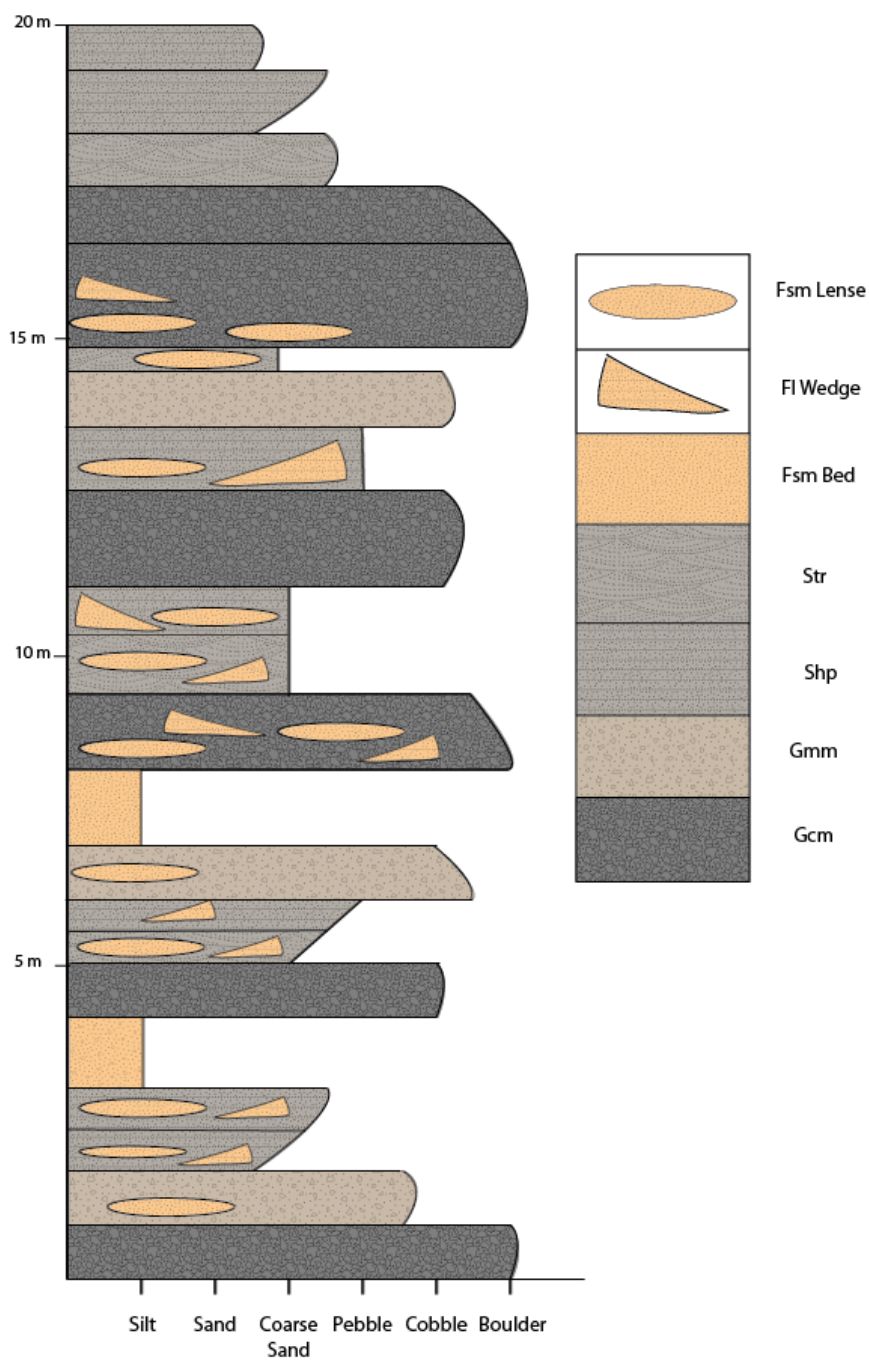
Figure 43. Idealized full Stratigraphic column of Cory Grade. (Scale is approximate)

Depositional Models

Once facies analysis and association was completed and depositional environments were interpreted, analysis of the straigraphic column lead to an understanding of depositional relationships. Facies models were constructed to illustrate how each facies was deposited in the context of ice cap formation, melting and retreat. The geomorphic interpretation provided by Brunk (2010) provides the context of these facies models by outlining the formation and morphology of the outcrops. These models were created using all available data and an understanding of the use of facies models for illustration of paleoenvironments (Dalrymple 2010, Lobeck 1924).

Onset of Melting

The first facies model illustrates the environment during times of glaciation and the onset of waning and melting (Figure 44). It has been well established that a glacier covered Grand Mesa during the Pleistocene (Retzer, 1954; Richmond, 1965; Robinson and Dea, 1981; Richmond, 1986; Armour et al., 2002). Shortly after the final glaciation event melting and retreat began to occur which would result in an influx of sediment and water downslope. During this time the glacier that covered Grand Mesa was at a maximum and completely covered the Miocene basalt cap. Melt water slowly percolated from the glacier and traveled down the slopes of the mesa to the floodplain of the ancient Gunnison River, which was flowing parallel to the modern day river. As the amount of melt water increased so did the grain sizes that the braided rivers could carry and the higher flow regimes were produced. This melt water and outwash is interpreted to have formed the Str and Shl deposits seen in outcrop. Each time that an influx of sediment

72

was brought down from the mesa the paleo Gunnison River would avulse and change its course to come into equilibrium with its new environment. This left a number of abandoned channels that were either damned forming a pool, or left as a false bayou to fill up with suspended fine grained materials (Moody 1966, Toonen 2012) (Facies Fm and Fl). The interactions of the braided river and perpendicular meandering stream are recorded in the rock record as north-south facing gravel bedded streams heterogeneously bedded with east-west facing meandering stream deposits. Difference in flow direction between the channelized Gunnison River and the basaltic-rich glacio-fluvial deposits suggest that these streams developed perpendicular to one another. During this time Gmm and Gcm deposits formed rare debris flows however, were less common in the lower portions of the section than in the overlying strata.
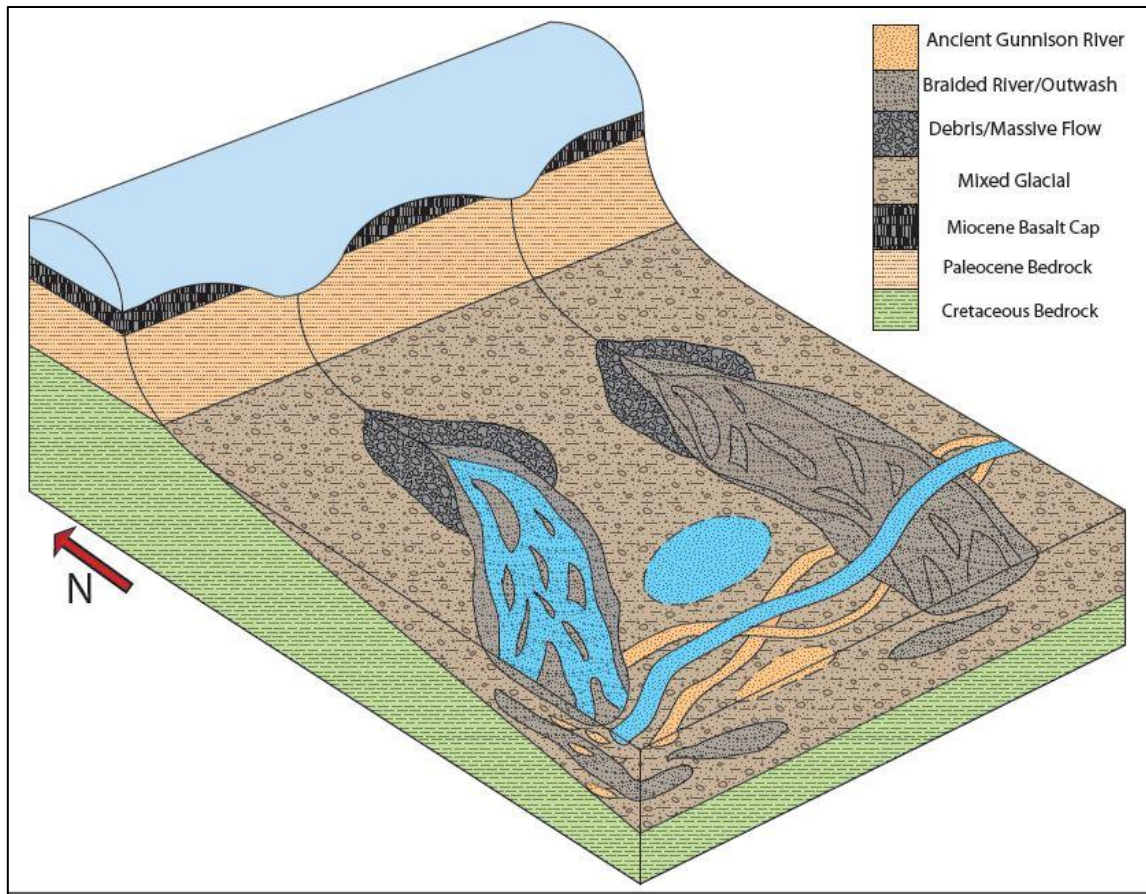
Figure 44. Onset of Melt facies model. Here melt water brings sediment down slope in the form of gravel bedded braided streams. These streams interact with the perpendicular facing Gunnison River to create abandoned channels that fill up with fine sediment.

Further Melt

As the glacier continued to melt it would have begun to expose the Miocene basalt capping the mesa and a change in depositional environment would occur (Figure 45). During this time substantial amounts of melt water would have brought large

quantities of sediment off the mesa. The sediment was distributed by gravel bedded braided rivers flowing south off the mesa and deposited in the low lying areas of the floodplain. This addition of water would also increase the sinuosity of the paleo Gunnison River and allow it to transport larger sediments. The higher sinuosity river would have preserved its migrating bars (Channelized facies Sl) (Moody 1966, Toonen 2011). As the glacier continued to retreat the exposure of the basalt cap would begin to be undercut by the flow of water eroding the softer underlying Paleocene bedrock. This undercutting would produce mass wastings of the basalt in the form of both massive and plastic debris flows (facies Gcm and Gmm). During this time the paleo-Gunnison River would continue to attempt to establish itself in lower lying areas and would continue to avulse when a new influx of sediment caused a change in topography or damned the river. As the glacier continued to retreat exposing more and more of the basalt cap a greater concentration of debris flows in the area would have been preserved as rockfalls became more common. The stratigraphic shows an increase in the concentration of massive debrsis flows up section. The debris flows might have had a large impact on the position of the Gunnison River as each event would push the river. The stratigraphy here records less abandoned channels in the upper portions of the column and this is interpreted to be a result of the southward migration of the Gunnison River.
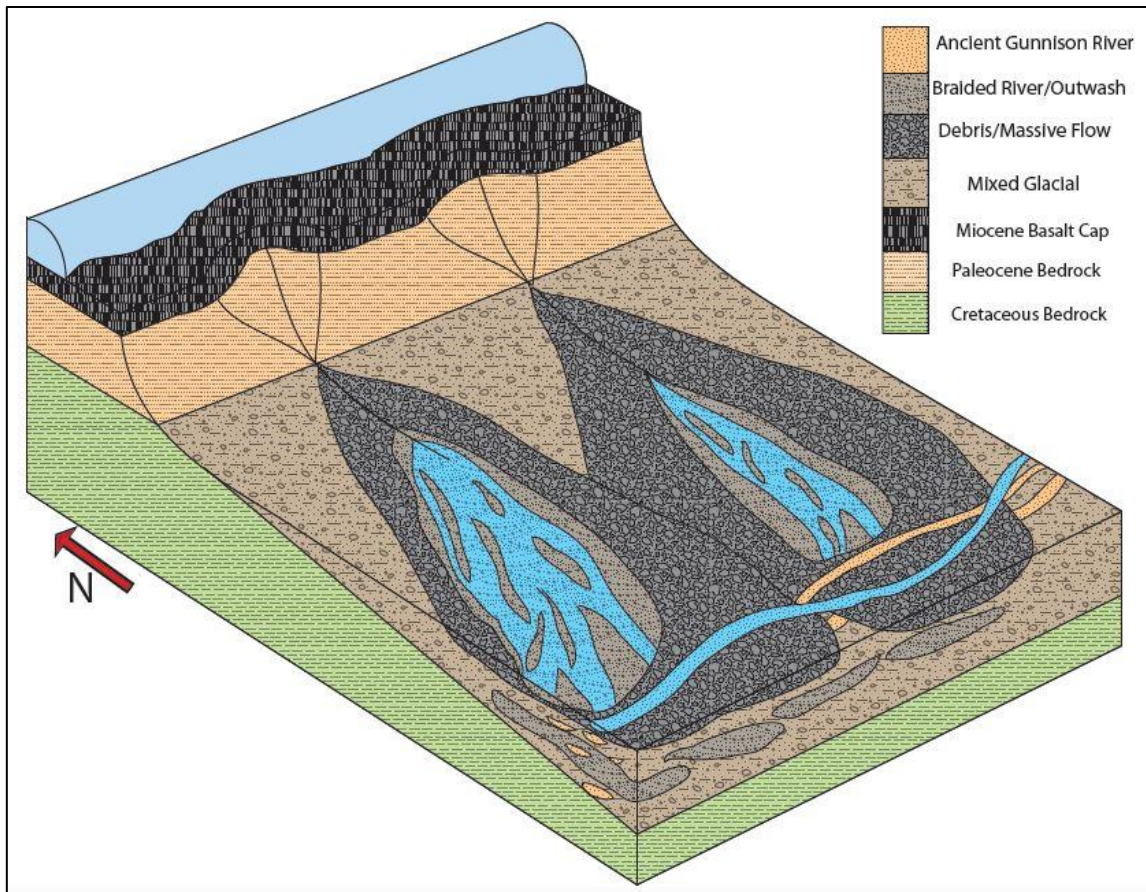
Figure 45. Further Melting facies model. Here the ice cap has exposed the basalt layer causing greater mass wastings. These events push the river further south and create abandoned channels.

Modern Day Mesa Formation

Once the glacier had fully retreated the depositional system could come into equilibrium and produce the landforms and landscape seen today. Previously the influx of sediment was from the north and with the melting of the glacier sediment began to be transported in an east-west direction by the Gunnison River (Figure 46). With the

frequent changes of topography driven by glacio-fluvial drainage shut down, the Gunnison River established a permanent floodplain south of the current "Surface Creek Mesa" (Cory Grade). This new floodplain is not shown in the figure. The new equilibrium state allowed for drainage basins to create small "Finger Mesas" along the southern slopes of the current day Grand Mesa. (Brunk 2010) the formations of small creeks along the ridges of these mesas allow for drainage of precipitation off the current mesa and these creeks now feed into the current Gunnison River. The remaining proximal mesas are what is left of the ancient outwash flows. Remnants of more distal portions of these mesas were mapped south of the current Gunnison River floodplain by Noe and Zawaski (2013) suggesting that the paleo river was not only age equivalent to the glacio-fluvial outcrop described but has eroded down through it since the disappearance of the glacier.
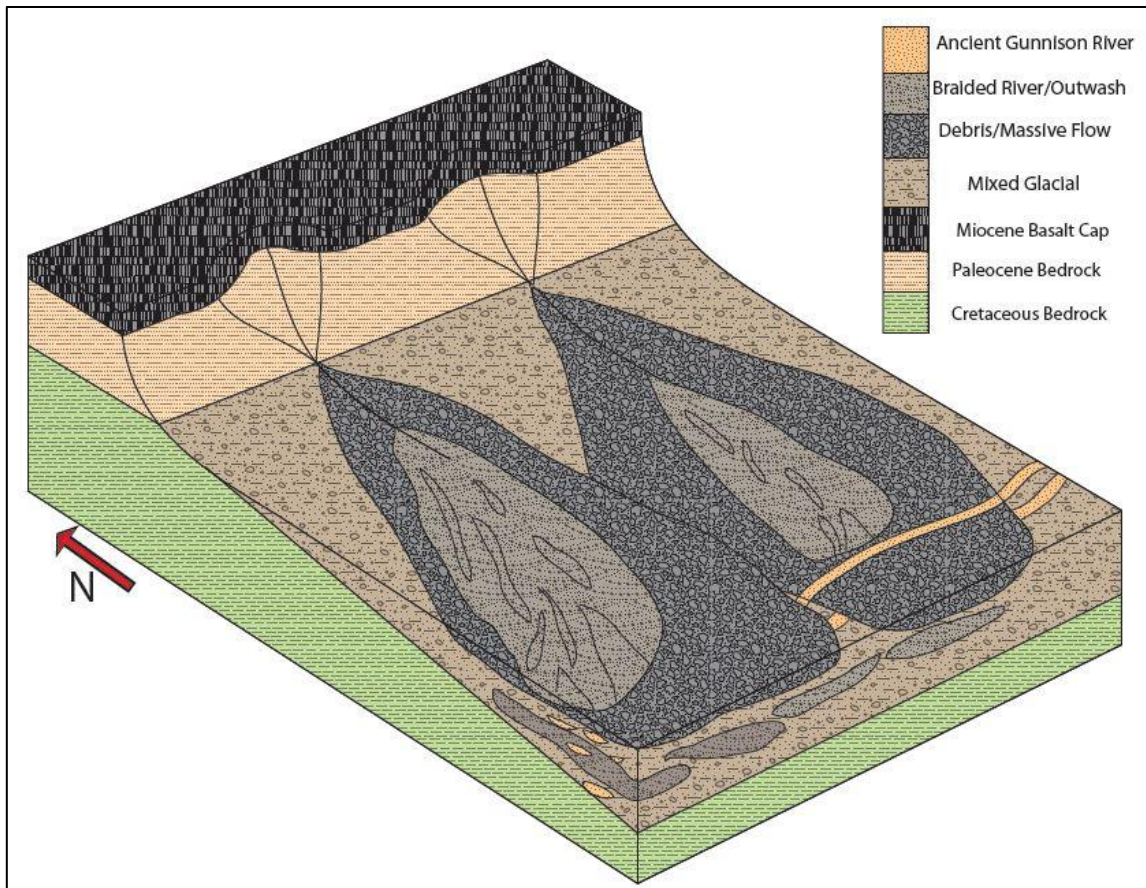
Figure 46. Modern Day Mesa facies model. Here the glacier has disappeared and the influx of sediment from the north is shut down. The Gunnison River is able to establish a permanent floodplain south of the outcrop.

Discussion of Interpreted History

The measured outcrops described here record an overall change in deposition from glacio-fluvial outwash punctuated by ancient river deposits to debris flows and lesser fluvial influence. During this time the climate was warming and the Grand Mesa glacier was melting. (Brunk 2010, Cole and Sexton 1981, Henderson 1923, Retzer, 1954;

Richmond, 1965; Robinson and Dea, 1981; Richmond, 1986; Armour et al., 2002). An initial melting released small amounts of water and lower energy deposits that grade up into higher energy environments as the glacier melted causing an overall interpreted geomorphic change in the area (Brunk 2010). In his paper two distinct time periods are discussed, "Event One Melting and Event Two Melting". These two periods can be roughly correlated to the two melting phase facies models described above.

Event One Melting

Event One Melting would have released less amounts of water and deposited lower flow regime braided rivers in low lying areas and down cutting of drainage basins would have occurred allowing for these glacio-fluvial sediments to accumulate. The lower section of the stratigraphic column shows these braided streams however both lower and upper flow regimes are recorded showing that during this time changes in melt water fluctuated. The biggest difference between the event one melting and the onset of melt facies model is the presence of the paleo Gunnison River. As previously discussed this river would have been continuously avulsing and changing course as these sediments changed the paleotopogrophy. The observed singular, shallow abandoned channels show that these rivers did not downcut far into the underlying sediments before having to change course as more basaltic sediment was deposited.

Event Two Melting

Event Two Melting as described in Brunk (2010) indicates a period of increased melt water production and formation of higher energy braided streams. This is roughly equivalent to the further melt model discussed previously with some major differences. Event two melting takes into account the larger amount of water flowing from the mesa,

however it did not discuss the concentration of debris flows caused by exhuming the basalt cap. Additionally since the previous interpretation did not include an east-west flowing paleo Gunnison higher sinuosity river deposits were not included. The geomorphic interpretation is however in accordance with the overall interpretation of melt water creating larger amounts of sediment that was deposited in the north-south braided streams. As melting events began to decrease the concentration of massive debris flows increased in the stratigraphic record because of the instability of the exhumed basalt cap. During this time paleotopography continued to change creating a need for the river to avulse and establish itself to meet the state of punctuated equilibrium.

Modern Day

The location of the modern-day Gunnison River is stable because of the lack of topographic changes caused by sediment influx from the mesa. When this system shut down the river downcut through underlying sediment and create a floodplain to match its new state of equilibrium. A Google Earth image with the location of the Cory Grade outcrop and modern Gunnison River is provided below (Figure 47). The "Surface Creek" mesa that the Cory Grade road cut exposes is terminated against the modern floodplain this is interpreted to be evidence the paleo river is age equivalent to the mesa. The occurance of more distal portions of the mesa on the opposite side of the floodplain as mapped by Noe and Zawaski (2013) lends stupport to this argument.
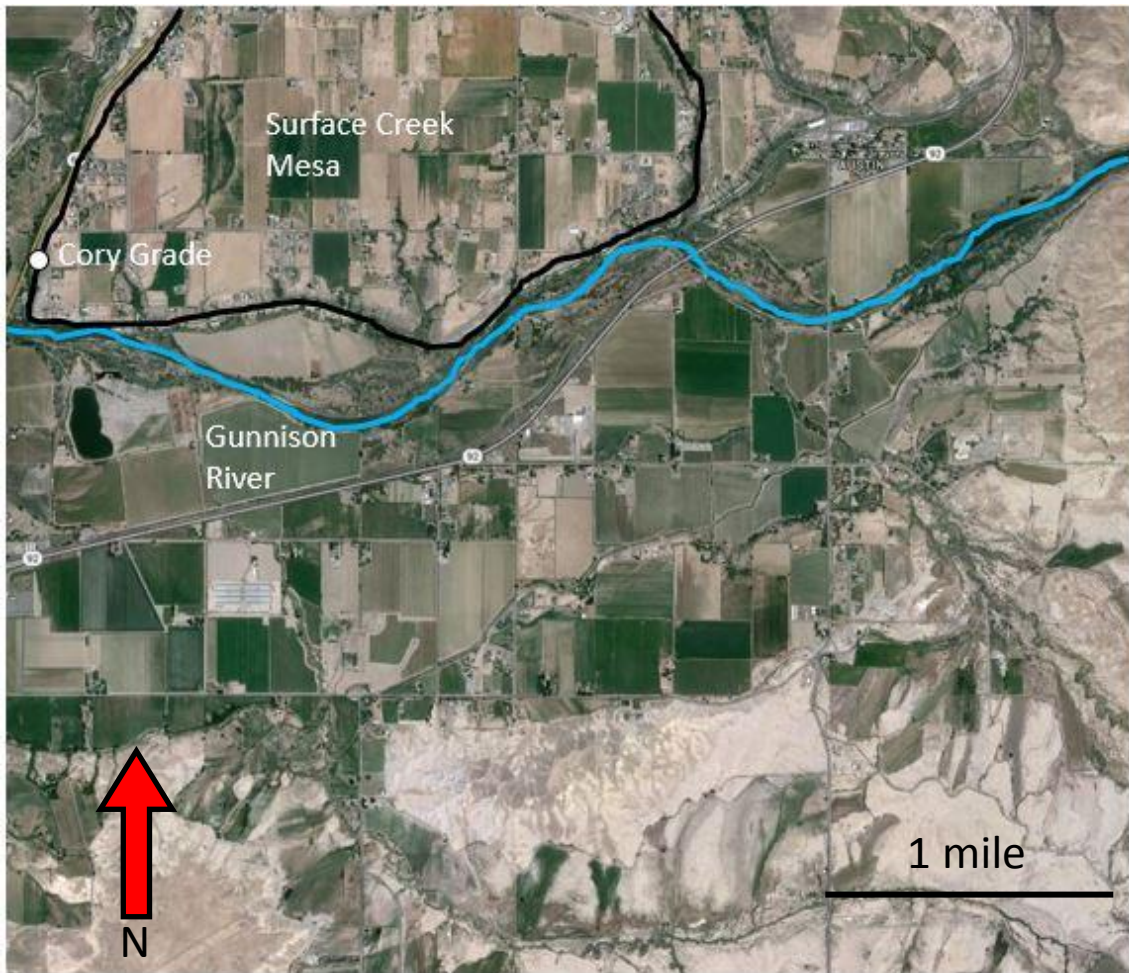
Figure 47. Google Earth® image of the study area showing Cory Grade outcrop in relation to the modern Gunnison River and its floodplain.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The purpose of this study was twofold, to create a full sedimentological description and interpretation of the unconsolidated deposits of the southern flanks of Grand Mesa, and to test the capabilities of LiDAR hyperspectral imaging for use in sedimentological studies. This research addressed the question: What is the origin of the deposits south of Grand Mesa, Colorado? In answering this question, a more accurate and detailed interpretation was completed to explain the depositional processes and environments of deposition of the Grand Mesa area during the Pleistocene. Additionally the test of terrestrial LIDAR for use in examination, description and interpretation of sedimentary facies at outcrop scale is significant.

Multiple working hypotheses drove this research. The hypotheses are:

H_1: The deposits are of glacio-fluvial and fluvial origin associated with the melting of Grand Mesa ice cap and the ancestral Gunnison River.

And the Null Hypothesis:

H_0: The deposits are of glacio-fluvial origin as described by Brunk 2010

Additionally:

H_1: Terrestrial LIDAR is a useful tool in sedimentological studies and will aid in describing the sedimentary facies of the outcrops in greater detail.

And the Null Hypothesis:

H$_0$: Terrestrial LIDAR is not a useful tool in sedimetological studies and will not aid in description of the outcrops.

To test these hypothesis three objectives were established and carried out as follows:

1) Reinterpret the outcrops using a new technique and technology.

2) Produce a detailed description of the facies in the Grand Mesa area.

3) Create a detailed Facies Model to explain the depositional environments and processes throughout the evolution of the area.

Field observations and descriptions were used to calibrate interpretations from LiDAR and GigaPan® images collected in the field. LiDAR is markedly a useful tool in the examination, description and interpretation process. In specific, the abilities to traverse a photorealistic 3D outcrop in virtual space and manipulate the views allows for more accurate interpretations.

Facies were interpreted using grain size, depositional fabric, sedimentary structures, and stratal geometries. From this, eight different facies were interpreted: Fl, Fm, St, Sr, Sh, Sl, Gcm and Gmm. These were then associated to depositional environments based on their characteristics. Facies Fl and Fm were associated with an ancestral low sinuosity meandering river, with Fm consisting of massively bedded channelized fine and silt, and Fl consisting of wedges of laminated fine sand and silt. In a few cases Sl was associated with this river where it was higher sinuosity and could produce coarser grained point bars in its channel.

Facies St and Sr were combined to be Str and associated with paleo braided river systems bringing sediment away from Grand Mesa and depositing them in the surrounding flood plains. The coarse grains and high energy ripples give evidence to this interpretation. Facies Sh and Sl were similarly combined to be facies Shl where associated with transitional type deposits. The grains of these facies are coarser and would take more energy to move. The laminations and low angle cross bedding are interpreted to be indications of an upper flow regime creating wash out dunes as the flow of water off the mesa increased during melting.

Facies Gmm and Gcm are interpreted to be two types of debris flows. The clast-supported Gcm is interpreted to be massive debris flows caused by rock falls when the basalt cap was exposed as the glacier melted. The matrix-supported Gmm is interpreted to be plastic type debris flows where outburst flooding brought down not just clasts but large amounts of mud.

Samples were collected in the field and analyzed in the lab. Grain sizes were established for each facies using sieve analysis and tabulated with their descriptions. The observed grain sizes were in accordance with the ranges seen by Brunk (2010) except for the Fm and Fl facies whose grain size was markedly lower. Composition of grains was observed to be primarily basalt in all facies except for the Fm and Fl facies where the dominant grain type is quartz. This discrepancy in grain size and composition is interpreted to be because the coarse grained basaltic sediment is associated with braided streams and glacial outwash coming from Grand Mesa where the fine grained quartz sediment is interpreted to be from abandoned channels and overbank deposits from the

ancestral Gunnison River. Additionally samples were collected from the modern Gunnison River to compare to those in the outcrops. Abandoned channel samples matched very well with facies Fm and overbank sediments matched with facies Fl.

A complete stratigraphic section was created to show an overall history of change in the study area. The bottom two thirds shows a greater concentration of plastic type debris flows and abandoned channels. The top shows a greater concentration of massive debris flows indicating greater concentrations of mass wastings. The concentration of Str and Shl however does not seem to change in the succession.

The stratigraphy of the outcrops along with a geomorphic understanding of the area allowed for the creation of facies models to illustrate the depositional environments of the area as they changed. The first two models were Onset of Melting and Further Melt. In the Onset of Melting model, the ice cap begins to melt sending large amounts of sediment in the form of braided streams and outwash deposits. These north-south trending deposits are cross cut by low sinuosity east-west trending abandoned channel and overbank deposits from the paleo Gunnison River.

The Further Melting model illustrates that as the ice cap melted and exposed the basalt cap greater amounts of massive debris flows would have occurred. The ancestral Gunnison River would continue to avulse and abandon channels however with the increase in water and influx of sediment, it would have to migrate south to establish stable channels and banks.

The Modern day model shows that once the ice cap fully melted, the influx of sediment from the north would be shut down and small finger mesas would be created.

Additionally with the lack of sediment coming off the mesa, the Gunnison River could establish a more permanent floodplain and is now situated south of the outcrops.

A few obstacles had to be overcome during the course of this study. The LiDAR data did not translate well into the IVC, only the x, y, and z coordinates could be displayed. Therefore Cyclone® software was the dominant visualization software used in this study. Additionally, the individual scans could not be merged to form one continuous scan. Marker beds and clasts were used to correlate the sections between scans. Additional work is necessary to truly assess the depositional history. This includes a better time frame of the deposition through carbon dating of organic matter or some other form of exact age dating. Additionally a trip back to this area would be useful to see if the remote sensing data provided accurate predictions of grain sizes and locations.

In conclusion both hypotheses are correct. The deposits of the southern slopes of Grand Mesa are of both glacio-fluvial and fluvial origin associated with the melting of the Grand Mesa ice cap and the ancestral Gunnison River. Terrestrial LiDAR was used to aid in this interpretation and was proven to be a useful tool in sediemtological studies.

In summary:

- Firstly, with field descriptions and samples as calibration, terrestrial LiDAR was used extensively as an interpretive tool during this process. The unique, dynamic aspects that a 3D scanned surface provides along with its ability to make mm scale measurements on the fly were invaluable to sediemtologic and stratigraphic interpretations remotely

- Secondly, the facies described and associated in the outcrop have been interpreted to be of both glacio-fluvial and fluvial origin. Facies Str and Shl were interpreted to be braided

streams and transitional flows carrying large amounts of basaltic sediment from the mesa during times of melt. Facies Gcm and Gmm were interpreted to be debris and massive flows coming off of the mesa when the basalt cap was exposed. Facies Fm and Fl were interpreted to be abandoned channels and overbank deposits associated with the ancestral Gunnison River that was attempting to establish a stable channel perpendicular to the influx of sediments.

- Lastly the stratigraphy interpreted from the outcrops is in accordance with the interpreted depositional history. An overall change in climate is preserved as this succession of deposits reflects melt of the Grand Mesa glacier. An increase in the concentration of debris flows and a decrease in meandering streams reflects the exposure of the basalt cap over time. The modern Gunnison River is situated in its stable floodplain because the influx of sediment from the mesa has shut off. And the river no longer has to avulse to compensate.

REFERENCES

Aslan, A., Cole, R., 2002. Sedimentological comparison of two new Lava Creek B Ash occurrences in western Colorado. Geological Society of America Denver Annual Meeting Paper No. 58-6.

Armour, Jake, Peter J. Fawcett, and John W. Geissman. "15 ky paleoclimatic and glacial record from northern New Mexico." *Geology* 30.8 (2002): 723-726.

Baker, F., 2002. Weathering rinds on Quaternary basalt gravels from Grand Mesa moraines and terraces. M.S. Thesis, Mesa State College, Grand Junction.

Brunk, T. J. 2010. A Geomorphological Assessment of Armored Deposits Along the Southern Flanks of Grand Mesa, CO, USA. M.S. Theses, Texas A&M University.

Brodzikowski, K., van Loon, A. J., 1991. Glacigenic Sediments. Elsevier Science Publishing Company Inc., New York.

Bellian, J. A., Charles Kerans, and D. C. Jennette. "Digital outcrop models: applications of terrestrial scanning lidar technology in stratigraphic modeling."*Journal of Sedimentary Research* 75.2 (2005): 166-176.

Buckley, Simon J., et al. "Terrestrial laser scanning in geology: data acquisition, processing and accuracy considerations." *Journal of the Geological Society* 165.3 (2008): 625-638.

Buckley, S. J., et al. "Oblique helicopter-based laser scanning for digital terrain modelling and visualisation of geological outcrops." *Int Arch Photogrammetry, Remote Sens Spatial Inform Sci* 37 (2008): 493-498.

Buckley, Simon J., et al. "Terrestrial lidar and hyperspectral data fusion products for geological outcrop analysis." *Computers & Geosciences* 54 (2013): 249-258.

Compton, R. R., 1985. Geology in the Field. John Wiley & Sons, Inc., New York.

Cole, R. D., Sexton, J. L., 1981. Pleistocene surficial deposits of the Grand Mesa, Colorado. New Mexico Geological Society Guidebook, 32nd Field Conference, Western Slope Colorado, pp. 121-126.

Collinson, J. D., Thompson, D. B., 1982. Sedimentary Structures. George Allen & Unwin, London

Collinson, J. D., 2006. Alluvial Sediments. In: Reading, H.G. (ed.), Sedimentary Environments: Processes, Facies and Stratigraphy. Blackwell Publishing, Malden, MA, pp. 37-82.

Dalrymple, Robert W, and Noel P. James, 2010. Facies Models 4. Geological Association of Canada

Dalsgaard, K., Jensen, J. L., Sorensen, M., 1991. Methodology of Sieving Small Samples and Calibration of Sieve Set. In: Syvitski, J. P. M. (ed.), Principles, Methods, and Applications of Particle Size Analysis. Cambridge University Press, Cambridge, pp. 64-75.

Folk, R. L., 1974. Petrology of Sedimentary Rocks. Hemphill Publishing Co., Austin, TX

Graham, J., 1988. Collection and Analysis of Field Data. In: Tucker, M. (ed.), Techniques in Sedimentology. Blackwell Science, Osney Mead, Oxford, pp. 5-62.

Henderson, Junius. "The Glacial Geology of Grand Mesa, Colorado." *The Journal of Geology* (1923): 676-678.

Kurz, Tobias H., et al. "Hyperspectral image analysis of different carbonate lithologies (limestone, karst and hydrothermal dolomites): the Pozalagua Quarry case study (Cantabria, North-west Spain)." *Sedimentology* 59.2 (2012): 623-645.

Kurz, T. H., et al. "Close range hyperspectral and LiDAR data integration for geological outcrop analysis." *Hyperspectral Image and Signal Processing: Evolution in Remote Sensing, 2009. WHISPERS'09. First Workshop on*. IEEE, 2009.

Kokkalas, S., et al. "Quantitative analysis and visualization of nonplanar fault surfaces using terrestrial laser scanning (LIDAR)—The Arkitsa fault, central Greece, as a case study." *Geosphere* 5.6 (2009): 465-482.

Krumbein, William Christian. "Size frequency distributions of sediments." *Journal of sedimentary Research* 4.2 (1934).

King, C. A. M., 1967. Techniques in Geomorphology. Edward Arnold Ltd., London.

Lobeck, Armin Kohl. "Block Diagrams and Ather Graphic Methods Used in Geology and Geography." (1924).

McManus, J., 1988. Grain-size Determination and Interpretation. In: Tucker, M. (ed.), Techniques in Sedimentology. Blackwell Science, Osney Mead, Oxford, pp. 63-85.

D MCKEE, E. D. W. I. N., and Gordon W. Weir. "Terminology for stratification and cross-stratification in sedimentary rocks." *Geological Society of America Bulletin* 64.4 (1953): 381-390.

McCave, I. N., Syvitski, J. P. M., 1991. Principles and Methods of Geological Particle Size Analysis. In: Syvitski, J. P. M., (ed.), Principles, Methods, and Applications of Particle Size Analysis. Cambridge University Press, Cambridge, pp. 1-21.

Miller, J. M. G., 2006. Glacial Sediments. In: Reading, H. G. (ed.), Sedimentary Environments: Processes, Facies and Stratigraphy. Blackwell Publishing, Malden, MA, pp. 454-484.

Miall, A. D., 1978. Lithofacies Types and Vertical Profile Models in Braided-River Deposits: A summary. In: Miall, A. D. (ed.), Fluvial Sedimentology. Canadian Society of Petroleum Geologists, Calgary, pp. 597-604.

Miall, A. D., 1977. A review of the braided-river depositional environment. Earth Science Reviews. 13, 1-62.

Moore, Jessica, et al. "Facies analysis, reservoir characterization, and LIDAR modeling of an Eocene lacustrine delta, Green River formation, Southwest Uinta Basin, Utah." *Lacustrine sandstone reservoirs and hydrocarbon systems: AAPG Memoir* 95 (2012): 183-208.

Moody-Stuart, Mark. "High-and low-sinuosity stream deposits, with examples from the Devonian of Spitsbergen." *Journal of Sedimentary Research* 36.4 (1966).

Nemec, W., Steel, R. J., 1984. Alluvial and coastal conglomerates: Their significant features and some comments on gravelly mass-flow deposits. In: Koster, E. H.,

Steel, R. J (eds.), Sedimentology of Gravels and Conglomerates. Canadian Society of Petroleum Geologists, Calgary. Memoir 10, pp. 1-31.

Noe, David C. and Zawaski, Michael J. "Orchard City Quadrangle Geologic Map, Delta County, Colorado Authors' Notes" Colorado Geological Survey Department of Natural Resources Denver, Colorado (2013)

Pettijohn, F. J., 1975. Sedimentary Rocks. Harper & Row, Publishers, New York.

Quigley, M. Darwin. "Geologic history of Piceance Creek-Eagle basins." *AAPG Bulletin* 49.11 (1965): 1974-1996.

Ritter, D. F., Kochel, R. C., Miller, J. R., 2002. Process Geomorphology. Waveland Press, Inc. Long Grove, IL.

Richmond, G.M., 1965. Glaciation of the Rocky Mountains. In: Wright, H.E. Jr., Frey, D.G. (eds.), The Quaternary of the United States. Princeton University Press, Princeton, New Jersey, pp. 217-230.

Richmond, G.M., 1986. Stratigraphy and correlation of glacial deposits of the Rocky Mountains, the Colorado Plateau, and the ranges of the Great Basin. In: Sibrava, V., Bowen, D.Q. and Richmond, G.M. (eds.), Quaternary Glaciations in the Northern Hemisphere. Pergamon Press, New York, pp. 99-127.

Retzer, J. L., 1954. Glacial advances and soil development, Grand Mesa, CO. American Journal of Science. 252, 26-37.

Rotevatn, Atle, et al. "Overlapping faults and their effect on fluid flow in different reservoir types: A LIDAR-based outcrop modeling and flow simulation study." *AAPG bulletin* 93.3 (2009): 407-427.

Robinson, C., Dea, P., 1981. Quaternary glacial and slope-failure deposits of the Crested Butte area, Gunnison County, Colorado. New Mexico Geological Society Guidebook, 32nd Field Conference, Western Slope Colorado, pp. 155-163.

Rust, B. R., 1978. Depositional Models for Braided Alluvium. In: Miall, A. D. (ed.), Fluvial Sedimentology. Canadian Society of Petroleum Geologists, Calgary, pp. 605-626.

Rust, B. R., Koster, E. H., 1984. Coarse alluvial deposits. In: Walker, R. G. (ed.), Facies Models. Geological Association of Canada, Toronto, Ontario, pp. 53-69.

Sahu, Basanta K. "Depositional mechanisms from the size analysis of clastic sediments." *Journal of Sedimentary Research* 34.1 (1964).

Thurmond, John B. PhD, 2006. Dissertation: Applications of three-dimensional digital mapping in sedimentology: collection, visualization and interpretation.

Tomasso, Mark, et al. "Outcrop versus seismic architecture of deep-water deposits: Use of LIDAR along a slope-to-basin transect of the Brushy Canyon Formation, west Texas." *Reservoir characterization: Integrating technology and business practices: Gulf Coast Section SEPM Special Publication* 26 (2006): 755-770.\

Toonen, Willem HJ, Maarten G. Kleinhans, and Kim M. Cohen. "Sedimentary architecture of abandoned channel fills." *Earth Surface Processes and Landforms* 37.4 (2012): 459-472.

Yeend, Warren E. *Quaternary Geology of the Grand and Battlement Mesas Area, Colorado: Description, Distribution, and Geologic History of Surficial Deposits*

on and Adjacent to Grand and Battlement Mesas, Western Colorado. US

Government Printing Office, 1969.