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NADIR AND OBLIQUE UAV PHOTOGRAMMETRY TECHNIQUES FOR QUANTITATIVE ROCK FALL EVALUATION IN THE RIMROCKS OF SOUTH-CENTRAL MONTANA

Micah Gregory-Lederer

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by

Micah Gregory-Lederer

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Abstract

As our cities expand into geologically sensitive areas across the greater Rocky Mountain region and beyond, quantitative methods of assessment are increasingly critical for the development of evidence-based alternatives to avoid or mitigate geologic hazards. Unmanned Aerial Vehicle (UAV) photogrammetry can improve these geologic investigations by enabling remote visual inspection, measurement, and spatial analysis while eliminating many of the physical access limitations that contribute to field sampling bias and human error. UAV photogrammetry technology was employed to evaluate fragmental rock fall hazards at two locations in the Rimrocks region of south-central Montana, Zimmerman Trail Road and Phipps Park. At these sites, active retrogressive rock slope instability caused by differential erosion has produced damaging rock fall. Nadir and oblique imagery of the 35-acre Zimmerman Trail Road and 13-acre Phipps Park study areas was acquired with a DJI Phantom 4 Pro UAV and processed into digital photogrammetry with Pix4Dmapper. Remote methods of analysis were employed to measure the orientation of discontinuities in rock fall source areas and to quantify rock fall susceptibility. At Zimmerman Trail Road, photogrammetry data products were used to numerically differentiate rock fall hazard zones along the 0.3-mile long rock slope in accordance with the detailed Rock Fall Hazard Rating System (Pierson, 1991). At Phipps Park, photogrammetry was used to measure the size, run out distance, and change in elevation of high energy rock fall and to generate 2D and 3D slope profiles, which were used to model potential future rock fall. The methods and findings demonstrate how nadir and oblique UAV photogrammetry can be used to implement quantitative, defensible approaches for evaluating rock fall susceptibility and run out potential in geologic investigations of fragmental rock fall hazard areas.

Keywords: Unmanned aerial vehicle, photogrammetry, rock fall, Rimrocks, geologic hazards.
Dedication

This thesis is dedicated to the engineers and geologists who mentored me throughout my early professional career, for trusting me with the responsibility I needed to challenge myself and grow while providing me with the support I needed to succeed. And to Elaine, for always choosing to believe that the ride down will be worth the skin up, and for dropping in with me even when it is too steep to see the bottom.
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# Table of Contents

ABSTRACT .......................................................................................................................... II

DEDICATION ....................................................................................................................... III

ACKNOWLEDGEMENTS .................................................................................................... IV

LIST OF TABLES .............................................................................................................. VIII

LIST OF FIGURES ......................................................................................................... IX

1. INTRODUCTION ............................................................................................................. 1
   1.1. Previous Work ........................................................................................................ 4
       1.1.1. Phipps Park ................................................................................................... 6
       1.1.2. Zimmerman Trail Road ............................................................................... 7

2. GEOLOGIC BACKGROUND ....................................................................................... 10
   2.1. Lithology and Stratigraphy .................................................................................. 11
       2.1.1. Phipps Park ............................................................................................... 13
       2.1.2. Zimmerman Trail Road ............................................................................ 14
   2.2. Influence on Slope Instability ............................................................................ 16

3. ENGINEERING ROCK CHARACTERIZATION ................................................................. 17
   3.1. Sampling and Testing Methods ......................................................................... 18
   3.2. Lab Test Results .................................................................................................. 20
   3.3. Geomechanical Classification ........................................................................... 23

4. PHOTOGRAMMETRY DATA ACQUISITION ................................................................ 25
   4.1. FAA Regulatory Compliance ............................................................................ 26
   4.2. UAV Photogrammetry Methods ......................................................................... 27
       4.2.1. Scale and Orientation Methods ................................................................. 28
   4.3. Flight Data Summary ......................................................................................... 29

5. PHOTOGRAMMETRIC PROCESSING .......................................................................... 31
5.1. Merging Oblique and Nadir Photogrammetry ........................................ 31
5.2. Quality Analysis ..................................................................................... 33
  5.2.1. Ground Sampling Distance ................................................................. 36
  5.2.2. Mean Reprojection Error ................................................................. 37
6. DISCONTINUITY MAPPING IN ROCK FALL SOURCE AREAS ................. 38
  6.1. Software Technology Summary ............................................................. 39
  6.2. Remote Discontinuity Mapping Methods .............................................. 40
  6.3. Phipps Park Discontinuities ................................................................. 41
  6.4. Zimmerman Trail Road Discontinuities ................................................ 45
7. ROCK FALL HAZARD RATING AT ZIMMERMAN TRAIL ROAD .................. 47
  7.1. Detailed RHRS Rating Criteria ............................................................. 47
  7.2. Remote RHRS Rating ........................................................................... 49
8. ROCK FALL CHARACTERIZATION AT PHIPPS PARK ................................ 52
  8.1. Methods of Measurement .................................................................... 52
  8.2. Characterizing Historic Rock Fall ....................................................... 54
  8.3. Evaluating the 2016 Rock Fall Event ................................................... 57
9. ROCK FALL MODELING AT PHIPPS PARK .......................................... 60
  9.1. Modeling Rock Fall with CRSP-3D ..................................................... 61
      9.1.1. Slope Construction Methods ........................................................... 62
      9.1.2. 3D Rock Fall Model Calibration ...................................................... 63
      9.1.3. Modeling Potential Future Rock Fall with CRSP-3D ...................... 68
  9.2. Comparison with 2D Modeling Results ............................................... 71
      9.2.1. 2D Rock Fall Model Calibration ....................................................... 72
      9.2.2. Modeling Potential Future Rock Fall with RocFall 6.0 .................... 77
10. SUMMARY OF FINDINGS ........................................................................ 79
    10.1. Geomechanical Characteristics ......................................................... 79
    10.2. Remote Discontinuity Mapping .......................................................... 81
10.3. Zimmerman Trail Road........................................................................................................ 82
10.4. Phipps Park.......................................................................................................................... 84
10.5. Limitations.......................................................................................................................... 86
10.6. The Future of UAV Photogrammetry in the Geosciences ............................................... 87
11. BIBLIOGRAPHY .................................................................................................................. 90
12. APPENDIX A: Phipps Park Rock Fall Inventory.................................................................... 100
# List of Tables

Table I: Unconfined Compressive Strength and Tensile Strength - Dry ........................................... 20

Table II: Unconfined Compressive Strength - Wet ............................................................................. 20

Table III: Ultrasonic Velocity Test Results ......................................................................................... 20

Table IV: Density Measurement Results ............................................................................................ 21

Table V: Geomechanical Classification of Intact Rock ......................................................................... 24

Table VI: Phantom 4 Pro Calibrated Camera Lens Parameters ......................................................... 27

Table VII: Phipps Park Photogrammetry Flights ................................................................................ 29

Table VIII: Zimmerman Trail Road Photogrammetry Flights ......................................................... 30

Table IX: Computer Specifications .................................................................................................... 31

Table X: Phipps Park North Discontinuity Strike/Dip Data Comparison .................................. 42

Table XI: Phipps Park Bedding Strike/Dip Data Comparison ............................................................... 44

Table XII: Zimmerman Trail Road Mean Set Planes ........................................................................ 45

Table XIII: Minimum Visible Sight Distance – Zimmerman Trail Road ........................................ 49

Table XIV: Zimmerman Trail Road RHRS Score ............................................................................. 50

Table XV: Large Boulder Rock Fall Metrics - Phipps Park Runout Zone ....................................... 55

Table XVI: Shadow Angle of Outlying Rock Fall in Phipps Park Runout Zone ............................ 57

Table XVII: CRSP-3D Calibration Simulation Results – Phipps Park 2016 Failure .................... 68

Table XVIII: CRSP-3D Simulation Results – Phipps Park NE ............................................................ 69

Table XIX: RocFall 6.0 Talus Slope Material Parameters ................................................................. 75

Table XX: RocFall 6.0 Calibration Simulation Results – Phipps Park 2016 Failure ...................... 75

Table XXI: RocFall Simulation Results – Phipps Park NE ................................................................. 77

Table XXII: Phipps Park Large Outlying Rock Fall (Pre-2016 Event) ........................................ 100

Table XXIII: Phipps Park Large Outlying Rock Fall (2016 Rock Fall Event) ............................. 101
List of Figures

Figure 1: Study Area Site Vicinity Map ................................................................. 3

Figure 2: Foreland basin system. Illustration from DeCelles, 2004. ......................... 11

Figure 3: Overhanging northeastern corner block at the Phipps Park study area .......... 14

Figure 4: The Transgressive Wave Revinement Surface at Zimmerman Trail Road .... 15

Figure 5: Stress/strain curves of Phipps Park sandstone samples .......................... 21

Figure 6: Stress/strain curves of Zimmerman Trail Road sandstone samples .......... 22

Figure 7: Placement and calibration of Phipps Park orientation constraint ............... 29

Figure 8: 2D and 3D camera orientations at Phipps Park ....................................... 30

Figure 9: 2D and 3D camera orientations at Zimmerman Trail Road .................... 30

Figure 10: Photogrammetry processing workflow in Pix4Dmapper v.4.3.33. ............... 32

Figure 11: Phipps Park point cloud measurement accuracy .................................. 35

Figure 12: Clipped point cloud segment of Phipps Park North outcrop .................. 42

Figure 13: Stereonet comparison of discontinuity measurements at Phipps Park ....... 43

Figure 14: Stereonet comparison of bedding plane measurements at Phipps Park .... 44

Figure 15: Density-concentration plots of discontinuity measurements at Phipps Park ... 45

Figure 16: Remote discontinuity measurements at Zimmerman Trail Road .......... 46

Figure 17: Measuring visible sight distance at Zimmerman Trail Road .................. 49

Figure 18: Zimmerman Trail Road RHRS zones ..................................................... 50

Figure 19: Example of differential erosion features at Zimmerman Trail Road ........ 51

Figure 20: Example of large block failure at Zimmerman Trail Road (Zone 3) ........ 51

Figure 21: Calculating the volume of rock fall with Pix4Dmapper ......................... 54

Figure 22: Shadow angle concept sketch (Stock et al., 2012). ................................. 56

Figure 23: Shadow angle and size of large outlying rock fall at Phipps Park ............ 57
Figure 24: 2015 NAIP imagery of Phipps Park study area prior to 2016 failure. ...............58
Figure 25: 2019 UAV photogrammetry of Phipps Park after 2016 failure. .....................59
Figure 26: Analysis partitions from CRSP-3D rock fall simulations at Phipps Park ..........65
Figure 27: CRSP-3D calibration simulation of 2016 event ........................................66
Figure 28: CRSP-3D Phipps Park calibration simulation rock fall velocity results ..........67
Figure 29: CRSP-3D simulation velocity and runout, Phipps Park NE .......................69
Figure 30: CRSP-3D rock fall velocity and kinetic energy, Phipps Park NE ...............70
Figure 31: RocFall 2D slope profiles for calibration simulation and Phipps Park NE ....72
Figure 32: RocFall 2D calibration simulation slope profile (A-A’) ............................74
Figure 33: Bar chart comparison of RocFall and CRSP-3D calibration simulations ....76
Figure 34: RocFall 2D potential rock fall simulation slope profile, Phipps Park NE ......78
1. Introduction

Unmanned Aerial Vehicle (UAV) photogrammetry is a powerful data collection tool for geological hazard assessment that enables remote visual inspection, measurement, and spatial analysis. By eliminating many of the physical access limitations that contribute to field sampling bias and human error, remote data acquisition can improve the quality of geological site characterizations while simultaneously reducing the time and cost required to complete them (Tonon and Kottenstette, 2006). Unlike ground-based remote sensing methods such as terrestrial laser scanning (TLS) and terrestrial photogrammetry, which have been used extensively to monitor rock fall and evaluate rock fall susceptibility (Stock et al., 2012b; Matasci et al., 2018), UAV photogrammetry can be deployed rapidly to survey complex topography at a range of scales. UAVs also reduce or eliminate exposure to many of the occupational hazards associated with rock slope assessment, which can include rock fall, steep slopes, and traffic hazards.

UAV platforms and Structure-from-Motion (SfM) photogrammetry software technology have improved dramatically over the past decade, and a growing body of work demonstrates that UAV photogrammetry has already begun to optimize many aspects of the geologic hazard assessment workflow. In particular, oblique aerial photogrammetry has been used successfully for outcrop-scale structural mapping (Blistan et al., 2016; Chesley et al., 2017), rock fall measurement (Manousakis et al., 2016), geotechnical characterization of rock slopes (Tannant, 2015), and even rock fall hazard emergency response (Giordan et al., 2015). The relatively low cost of acquiring, processing, and exporting UAV photogrammetry data also makes it an appealing alternative to traditional topographic land surveying for a variety of mapping applications (Westoby et al., 2012).
This geologic investigation of two locally significant rock fall hazard areas in the Rimrocks region of south-central Montana, Phipps Park and Zimmerman Trail Road (Figure 1), explores how UAV photogrammetry can be used to measure, characterize, and evaluate fragmental rock fall hazards and rock fall source areas. Applied methods for oblique and nadir UAV photogrammetry acquisition and post-processing analysis are explored in the context of the investigation, which emphasizes how UAV photogrammetry data can be exploited to perform four critical aspects of quantitative rock fall hazard assessment:

- Measuring the orientation of discontinuities in rock fall source areas (Section 6).
- Evaluating the relative risk of rock fall along transportation corridors using the Rock Fall Hazard Rating System (RHRS) (Pierson, 1991) (Section 7).
- Characterizing the size, runout distance, and shadow angle (Evans and Hungr, 1988) of historic rock fall (Section 8).
- Generating complex slope topography for numerical rock fall modeling (Section 9).

The geographic range and functional scope of this project are limited. However, the UAV photogrammetry and post-processing analysis tools presented here may be applied to the investigation of a variety of rock slope stability problems. As our cities expand into geologically sensitive areas throughout the greater Rocky Mountain region and beyond, the resulting economic and public safety impacts have highlighted the need for quantitative methods of assessing geologic hazards so that informed development setbacks can be established based on the risk tolerance of the land user. This investigation demonstrates the capabilities of UAV photogrammetry to augment and enhance this type of quantitative geologic hazard assessment.
Figure 1: Study Area Site Vicinity Map - Yellowstone County, Montana. 2015 NAIP Imagery and Esri USGS Topo Basemap (regional inset).
1.1. Previous Work

The Cretaceous Eagle Sandstone forms a dramatic backdrop for the Yellowstone River valley in the Billings vicinity, where the prominent vertical rock cliffs are known as the Rimrocks. Local residences and infrastructure are frequently impacted by rock fall and rock topples originating from the Rimrocks. In addition to the obvious public safety hazards associated with rock fall, these events frequently damage utilities and roadways, interrupting public access, altering local traffic patterns, and delaying emergency response services. The recurring rock fall hazards that exist throughout the Rimrocks in the Billings vicinity were first described in a geologic context in a 1:48,000-scale map depicting areas of potential rock fall that was published by the Montana Bureau of Mines and Geology (MBMG) in 2003 (Lopez and Sims, 2003). The authors attribute “progressive” (retrogressive) slope instability in the Rimrocks to differential erosion of the underlying Telegraph Creek Formation, which “removes support for the overlying sandstone... to form rock falls” (Lopez and Sims, 2003).

The stratigraphic boundary between the Telegraph Creek Formation and the Eagle Formation is placed “at the base of the first cliff-forming sandstone,” where Lopez describes a gradational contact with the slope-forming Telegraph Creek Formation in his map of the Billings 30’ x 60’ Quadrangle (Lopez, 2000). The somewhat ambiguous contact has led to diverging interpretations regarding the location of lower boundary of the Eagle Sandstone. A 2014 University of Montana master’s thesis on the internal facies and architecture of the Eagle Sandstone, which describes the lowermost member of the Eagle Sandstone as “interbedded siltstone and mudstone that coarsens upward into interbedded siltstone and sandstone,” notes that “Lopez (2000) mapped [the lowermost member of the Eagle Sandstone] as the Telegraph Creek Formation in the [thesis] study area” (Spangler, 2012). Detailed stratigraphic mapping was beyond the scope of this investigation, which does not presume to further constrain the sequence...
stratigraphy described by others. However, the stratigraphic correlations suggested in this investigation, which rely on an unpublished sequence stratigraphic model for the Eagle Sandstone (Hauer et. al., 2009), appear to corroborate the lower boundary interpretation described in Spangler (2012). Regardless of these mapping distinctions, weak sandstone as well as shale, mudstone, siltstone, and coal interbeds are known to occur within the Eagle Sandstone stratigraphy (Hanson and Little, 1989), and the relative erodibility of these facies may be as significant a factor in evaluating rock fall susceptibility as the presence (or absence) of the Telegraph Creek Formation at the base of the Rimrocks. A description of the geology of the Eagle Sandstone and a discussion of previous work related to the sedimentology and sequence stratigraphy of the formation is provided in Section 2.

Since the late 1970’s, undergraduate students at Rocky Mountain College (RMC) in Billings have used hand tape to measure the distance between nails spanning tension cracks at several locations in the Rimrocks. More recently, this intermittent strain monitoring has been performed in partnership with the MBMG, which established 14 monitoring locations in the Big East region of the Rimrocks near the Billings airport in 2001. A 2017 undergraduate honors thesis at RMC included monthly measurements of tension crack displacement at these locations (Shaules, 2017). These data were used in conjunction with MBMG monitoring data from 2009 – 2010 to examine the influence of temperature and precipitation on slab movement in the Rimrocks (Shaules, 2017). The project included a TLS of the Big East region that was performed in association with the university geosciences and geodesy support organization UNAVCO. The MBMG strain monitoring program, which relies on physical measurements to monitor and record displacement, has historically occurred on an inconsistent basis due to limited staffing resources, and the stations were not being actively monitored at the time of writing (S. Kuzara,
personal communication, April 3, 2019). Ongoing research at RMC regarding the occurrence, historical distribution, and potential triggering mechanisms of Rimrocks rock fall was not reviewed in any detail during this investigation.

1.1.1. **Phipps Park**

Phipps Park is in the NW 1/4 of Section 24, Township 01 N, and Range 24 East of the Montana Meridian. The 13-acre study area includes a gently sloping 7-acre rock fall runout zone that grades into a moderately steep talus slope and steep colluvial apron at the base of the U-shaped cliffs of Eagle Sandstone. The 600-linear ft outcrop is located approximately 1000 ft south of the Phipps Park parking lot on Molt Road. A segment of the Burlington Northern-Santa Fe (BNSF) railway and associated right of way cut into the base of the talus slope approximately 400 feet east of the outcrop. Recent rock fall at Phipps Park has limited public access to pedestrian trails in the northeast corner of the park that traverse across the talus slope at the base.

![Photo 1: Phipps Park study area, facing south.](image-url)
of the cliffs (Photo 1). As reported by the Billings Gazette (Ferguson, 2016), a significant rock fall event on May 18, 2016, prompted the City of Billings to close the park for three months while a geotechnical survey was completed and the trails were rerouted to avoid the rock fall hazard area. Inquiries to the City regarding this survey or any other records related to rock fall assessments at Phipps Park were unanswered at the time of writing, and it is unclear if any such records exist. Signs advising against access to Phipps Park due to rock fall hazards were posted at the time of the 2019 summer field assessment.

1.1.2. Zimmerman Trail Road

The roughly 35-acre Zimmerman Trail Road study area (Photo 2) is in the southwest ¼ and southeast ¼ of Section 27, Township 01 North, and Range 25 East of the Montana Meridian. It is 4 miles east of Phipps Park and stratigraphically lower. The historic rock fall runout zone at Zimmerman Trail Road includes the ~2,000-ft long outcrop segment and steep talus slope

![Photo 2: Zimmerman Trail Road study area, facing west.](image-url)
immediately north the roadway as well as the public lands south of the roadway, which abut private residential developments near the estimated extent of historic rock fall deposition. The steep talus slope at the base of the cliffs was too steep and exposed to traffic hazards to be safely accessed from below.

Emergency rock fall hazard mitigation was required at Zimmerman Trail Road in the spring of 2014 following a series of damaging rock fall events, including large rock falls on March 25 and May 12, 2014. Rock fall had caused numerous road closures prior to the 2014 mitigation project and keeping the travel lanes open required relatively frequent road clearing and repair (personal communication, Rod Nelson, 6/28/2019). Zimmerman Trail Road was reopened on June 13, 2014, following a 73-day closure (Van Dyk and Gabrian, 2019), during which rock bolting, blasting, and scaling with bars and air bags was performed by geohazard mitigation contractor GeoStabilization International (GSI) and roadway restoration and improvements were completed.

A copy of the pre-construction survey and original bid package for the 2014 mitigation project was provided by the Montana Department of Transportation (MDT) during a June 28, 2019, meeting held at the Billings, MT, field office (MDT, 2014). While not all the specifications and design plans related to this project were reviewed in this investigation, the geotechnical engineering report prepared by Terracon Consultants Inc. for the 2014 Zimmerman Trail Road project was obtained from Dan Nebel of Terracon. That report summarized the findings from the 2014 field assessment, and includes a kinematic analysis of major joint systems, a stability analysis of specific blocks, and rock fall modeling results, which were obtained using the Colorado Rock Fall Simulation Program (CRSP) and slope profiles from a terrestrial LiDAR scan of a portion of the rock slope (Terracon Consultants Inc., 2014). A
qualitative 2016 rock fall hazard evaluation performed by Terracon Consultants, Inc. for the proposed Rimrock to Valley public trail system was also reviewed; the report describes the rock fall hazard for the Stagecoach Trail segment adjacent to Zimmerman Trail Road as “very high” due to the “number of loose rock blocks that have separated from the cliff face” (Terracon Consultants Inc., 2016). Activated road closure gates were installed on Zimmerman Trail Road in 2018 to quickly restrict access in the likely event of future rock fall.
2. Geologic Background

The Upper Cretaceous (Santonian-Campanian) Eagle Sandstone of the Montana Group is a marine sedimentary sequence that was deposited along the western margins of the Late Cretaceous-age epicontinental Western Interior Seaway, a narrow north-south trending inland sea that once inundated the depressed continental interior of North America from the Gulf of Mexico to the Arctic Ocean (Rice, et. al., 1983). Marine sediment deposition in the foreland basin system (Figure 2) occurred over a period spanning ∼110 - 70 Ma, during which time the foreland basin system continued to evolve due to flexural and (later) dynamic subsidence associated with contractile deformation behind the orogenic wedge of the Cordilleran thrust belt (DeCelles, 2004; Liu et al., 2011; Painter and Carrapa, 2013). The stratigraphic diversity in the Eagle Sandstone has been attributed to dynamic changes in relative sea level during the Late Campanian Age of the Late Cretaceous Epoch (83.6 - 72.1 Ma) (Hanson and Little, 1989), which influenced the provenance, transport energy, and depositional environment of sediment inputs. Coastal geomorphic processes such as accretion and scour also contribute to the pronounced local variability in facies composition and structure found within each depositional sequence (Auchter, 2012).

Cretaceous marine sedimentary units deposited in the shallow water deltaic and shoreface environment of the relict seaway are found across southwestern and central Montana today, and include the Muddy and Mowry formations in addition to the Eagle (Vuke-Foster, 1982). Lithostratigraphic variability associated with marine transgression and regression is an important characteristic of these marine sedimentary units, which commonly grade to shale to the east, towards the center of the relict foreland basin, and exhibit facies reflecting a general eastward progradation of the basin margin during periods of marine regression; this phenomenon has been
observed in the Eagle Sandstone, which grades eastward into marine siltstone and shale (Rice and Shurr, 1983).

![Diagram of Foreland basin system](image)

**Figure 2: Foreland basin system. Illustration from DeCelles, 2004.**

### 2.1. Lithology and Stratigraphy

Laterally continuous exposures of the Eagle Sandstone are visible in the Billings vicinity, where the skyline is dominated by the Rimrocks. However, the type locality (as redefined from that of Weed, 1899) occurs at the confluence of the Missouri River and Eagle Creek, approximately 60 miles northeast of Great Falls (Roberts, 1972). Early mapping projects identified five discrete sandstone units associated with the formation (Shelton, 1965), which were later described as thickly bedded fine to medium grain sandstone with sandy shale, siltstone, mudstone, and coal interbedding (Vuke et al., 2007). Contemporary mapping efforts combined surface mapping with subsurface borehole log data to refine the stratigraphic characterization of the Eagle Sandstone, ultimately identifying nine distinct genetic sequences associated with regressive-transgressive sediment deposition in marine shelf, shoreface, and
paralic (fluvio-deltaic) environments (Hanson and Little, 1989). These facies are commonly bounded by “time-significant surfaces” (unconformities) caused by changes in relative sea level during the Campanian (Hauer et al., 2009).

A review of thin section petrographic analyses performed on a representative subset of Eagle Sandstone member facies indicates a range in quartz (Q) content of 50 – 75% and approximately equal proportions of feldspar (F) and lithic fragments (L) (Auchter, 2012; Spangler, 2012; Staub, 2017), consistent with recycled orogen sands (Dickinson et al., 1983). When plotted on ternary QFL diagrams, this modal compositional data suggests a lithic arkose to feldspathic litharenite sandstone lithology (Folk, 1974). X-ray diffraction (XRD) analysis presented in Staub (2017) also revealed the presence of iron-rich phyllosilicate (clay) minerals of glaucony and verdine facies, including chamosite, an iron-rich member of the chlorite group. These minerals can form framework grain coatings that inhibit quartz cementation during diagenesis (Bahlis and de Ros, 2013; Saïag et al., 2016). It is possible that some of the variability in rock strength (differential cementation) observed in the Eagle Sandstone could be attributed to this phenomenon, although no petrography was performed to evaluate this hypothesis. The application of dilute hydrochloric acid to hand samples collected from Phipps Park and Zimmerman Trail Road during this investigation did not produce any observable reaction, suggesting that in at least some of the facies present at these locations, non-carbonate cements such as silica predominate. The influence of differential cementation on rock slope stability is discussed in Section 2.2.

The rock descriptions provided in this section are intended to facilitate correlations with existing geologic descriptions and sequence stratigraphic models for the Eagle Sandstone and are a departure from the engineering geology terminology preferred elsewhere in the text. In
subsequent sections, rock descriptions are intended to highlight the engineering properties of the material rather than mineralogy or depositional environment. In keeping with this objective, these rock classifications may include gradation (sorting) and particle size criteria adapted from the Unified Soil Classification System (USCS), a descriptive system for soils and “materials that exist in-situ as [sedimentary rock] but convert to soils after field or laboratory processing” (ASTM, 2009).

### 2.1.1. Phipps Park

The basal sedimentary unit at the Phipps Park study area consists of weak, hummocky cross-stratified sandstone with interbedded weak, friable siltstone and mudstone, which underlies strong, trough cross-stratified shoreface sandstone that forms the bottom half of a dramatic, 45-foot tall suspended block overhanging the northeast corner of the outcrop by approximately 14-feet (Figure 3). The sharp, planar unconformity below this overhang is interpreted to represent the so-called Regressive Surface of Marine Erosion (RSME), which marks the onset of forced marine regression (Hauer et al., 2009; Catuneanu et al., 2011).
A second paleoerosional surface occurs near the middle of the outcrop, approximately 20 ft above its base. This surface, comprised of weak to moderately strong sandstone with interbedded siltstone and evaporites, divides the strong lower block-forming shoreface sandstone from the strong upper block-forming facies, a locally channelized, trough cross-stratified paralic (deltaic) sandstone. This subaerial unconformity is interpreted to be the sequence boundary associated with fluvial erosion in a shallow near-shore deltaic environment, as described in (Hauer et al., 2009). The regressive depositional sequence represented in the Phipps Park stratigraphy reflects an evolution from marine shelf to shoreface to fluvio-deltaic depositional environment.

2.1.2. Zimmerman Trail Road

Three distinct sandstone facies interpreted to represent the transition from a lowstand systems track to a transgressive system track depositional sequence can be observed at the Zimmerman Trail Road study area outcrop (Hauer et al., 2009). A notable sequence boundary,
the so-called Transgressive Wave Revinement Surface (TWRS) of regional extent (Hauer et. al, 2009), divides the lower and middle zones of the Eagle Sandstone at Zimmerman Trail Road (Figure 4). This unconformity forms the boundary between the two lower sandstone wedges (identified in Figure 4 as Sandstone 5 and Sandstone 5b) and the uppermost stratum, a glauconitic bioturbated lower shoreface sandstone with a distinct concretion layer (Hauer et. al., 2009). The upper glauconitic bioturbated lower shoreface sandstone contains abundant honeycomb weathering features, including some deep concavities that form overhangs. The steep talus slope north of Zimmerman Trail Road is presumably formed by the Telegraph Creek Formation, which grades into the Eagle Sandstone at the base of the outcrop.

Figure 4: The Transgressive Wave Revinement Surface (TWRS), a regional unconformity, divides the lower and middle zones of the Eagle Sandstone at Zimmerman Trail Road (Hauer, et. al., 2009).
2.2. Influence on Slope Instability

Differential erosion, which is the primary cause of instability at both Phipps Park and Zimmerman Trail Road study, leads to retrogressive rock slope instability due to the accumulation of gravitational stress in overhanging strata (Young et al., 2009). When this stress exceeds the tensile strength of the material, tension cracks begin to form parallel or subparallel to the cliff face. These fractures propagate downwards from the upper inside face of the overhang, providing a conduit for water to enter the rock mass, which weakens the material. Tension cracks eventually intersect the plane of weakness (often an unconformity or bedding contact) at the base of the overhang, and the overhanging rock will fall or topple if it is not held in place by friction acting on the joint surfaces between adjacent blocks.

The joint systems that parallel and intersect the cliff face at both study areas also provide a natural conduit for meteoric water to enter the formation. The mechanical process of frost wedging (crack initiation and propagation due to the expansion of water during freeze-thaw cycles) has long been implicated as a mechanism that contributes to rock fall in the Rimrocks (Lopez and Sims, 2003), and the loss of strength that accompanies the saturation of sandstone and other porous sedimentary rock is not confined to any season. Repeated cycles of wetting and drying can have deleterious effects on the strength and erodibility of some earth materials, particularly poorly cemented shales and mudstones, which are susceptible to slaking (Goodman, 1993). These factors may help to explain the dramatic differential erosion occurring below the RSME at Phipps Park, where the lithology includes weak sandstone and weak, friable siltstone and mudstone. The numerous, densely spaced vertical joints (<0.5 foot spacing) in the weak sandstone indicates that crushing (compressive failure) has already occurred below the contact. More information regarding jointing and discontinuities in the rock masses at Phipps Park and Zimmerman Trail Road is provided in Section 6.
3. Engineering Rock Characterization

The stiffness, strength, and density of rock fall influences its trajectory, velocity, and kinetic energy as it rolls, bounces, and slides downslope (Wyllie, 2014). Given the significance of these engineering properties, the lack of any published laboratory rock testing data for the Eagle Sandstone was identified as a significant data gap. The natural variability inherent to rock and other geomaterials presents an engineering challenge regardless of our knowledge or expertise; however, knowledge-based uncertainties can be significantly reduced by increasing our understanding of local rock properties and incorporating known variability into all aspects of analysis and design (Aladejare and Akeju, 2020). While the laboratory testing and geomechanical classification presented here is a departure from the remote methods of assessment emphasized elsewhere in this investigation, it is an essential complement to this analysis.

Rock material properties are used to classify and describe rock in an engineering context. Intact rock strength influences the initiation and propagation of fractures in jointed rock masses (Hoek, 1983), and unconfined compressive strength (UCS) is an important parameter in many popular rock mass characterization systems, including the Unified Rock Classification System (URCS) (Williamson, 1983) and the Rock Mass Rating (RMR) system (Bieniawski, 1989). Numerical rock fall modeling requires the mass or unit weight of the rock fall to be accurately parameterized, and rock slope deformation modeling (which was not attempted during this investigation) requires additional material testing data, including rock strength and deformability parameters.
3.1. Sampling and Testing Methods

Sandstone hand samples collected from the Phipps Park and Zimmerman Trail Road study areas were cored and tested at the Montana Tech rock testing laboratory to obtain basic rock index properties, including wet and dry UCS, tensile strength, ultrasonic velocity, and unit weight. Qualitative field estimates of intact rock strength were performed prior to and during sample collection using a geologic pick in general conformance with the methods presented in (Hoek and Brown, 1997). These field strength tests revealed a range in estimated rock strength from weak to strong (R2 – R4, estimated UCS 725 – 14,500 psi). Sandstone rock hand samples representing both upper and lower bounds of this range were collected from the respective field areas. At Phipps Park, samples were collected from the 2016 runout zone (PP1) as well as directly from the interbedded mudstone/sandstone unit at the base of the outcrop (PP2). At Zimmerman Trail Road, recent rock fall was sampled from the catchment ditch on the north side of the road (ZP1 and ZP2).

Four core specimens were drilled from each of the four hand samples using a size NQ (47.6 mm ID/ 75.7 mm OD) diamond coring rig, for a total of sixteen core specimens (Photo 3). The unit weight and density of each sample was calculated from the mass and dimensions of the respective cores, which were prepared for UCS or Brazilian testing in accordance with laboratory best practices under the guidance of Montana Tech rock lab technician Steve Berry. Each core specimen, which had been trimmed and ground flat to within .0001-in on each end, was placed inside a loose plastic sleeve prior to testing in the load frame to avoid damaging the sensitive axial linear variable differential transformers (LVDTs), which were attached to the specimen to measure axial strain throughout the test. Six “dry” UCS tests (1 or 2 two core specimens per sample) were performed at natural lab moisture content, and four “wet” UCS tests were performed on a single core specimen from each sample that had been submerged in water for 24
hours immediately prior to testing. Five Brazilian tests were performed for each sample on lab
dry specimens cut from each of the remaining cores using the Montana Tech GCTS Brazilian
Test apparatus, and the tensile strength data presented in Table 1 represents the average of five
Brazilian test per sample (n = 5). Wet core specimens were oven dried immediately after testing
to determine the moisture content of the rock at the conclusion of the test, which is reported in
Table 2.

Photo 3: Phipps Park hand samples (PP1, PP2) and Zimmerman Trail Road hand samples (ZP2, ZP1)
after coring (clockwise from upper left). Photo reference scale is 1.0-feet (12 in) end to end.
3.2. Lab Test Results

The following tables present rock strength testing data (Tables I and II), Ultrasonic Velocity Test data (Table III), and unit weight and density data (Table IV) of the core specimens from the Phipps Park (PP) and Zimmerman Trail Road (ZP) sandstones. The difference in strength between the core specimens at natural moisture content (dry) and after being submerged in water for 24 hours (wet) is shown graphically in the plots of stress (psi) versus axial strain (%) presented in Figures 5 and 6.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Unconfined Compressive Strength</th>
<th>Tensile Strength (n = 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unconfined Compressive Strength</td>
<td>Tensile Strength (n = 5)</td>
</tr>
<tr>
<td></td>
<td>UCS (psi)</td>
<td>UCS (MPa)</td>
</tr>
<tr>
<td>PP1</td>
<td>8,562</td>
<td>59.0</td>
</tr>
<tr>
<td>PP2</td>
<td>3,933</td>
<td>27.1</td>
</tr>
<tr>
<td>ZP1</td>
<td>2,183*</td>
<td>15.1</td>
</tr>
<tr>
<td>ZP2</td>
<td>8,971*</td>
<td>61.9</td>
</tr>
</tbody>
</table>

*Average of two tests.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Wet* Unconfined Compressive Strength (n = 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UCS (psi)</td>
</tr>
<tr>
<td>PP1</td>
<td>5,795</td>
</tr>
<tr>
<td>PP2</td>
<td>2,342</td>
</tr>
<tr>
<td>ZP1</td>
<td>1,258</td>
</tr>
<tr>
<td>ZP2</td>
<td>6,196</td>
</tr>
</tbody>
</table>

*Wet core samples were submerged in distilled water for 24 hours prior to testing.  
**Moisture content of wet core samples at conclusion of test.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Ultrasonic Velocity (n = 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P-Wave (m/s)</td>
</tr>
<tr>
<td>PP1</td>
<td>2,457</td>
</tr>
<tr>
<td>PP2</td>
<td>1,797</td>
</tr>
<tr>
<td>ZP1</td>
<td>1,689</td>
</tr>
<tr>
<td>ZP2</td>
<td>2,758</td>
</tr>
</tbody>
</table>
Table IV: Density Measurement Results

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Bulk Unit Weight (lb/ft³)</th>
<th>Wet* Unit Weight (lb/ft³)</th>
<th>Dry Unit Weight (lb/ft³)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP1</td>
<td>144.7</td>
<td>149.8</td>
<td>143.7</td>
<td>2.32</td>
</tr>
<tr>
<td>PP2</td>
<td>124.1</td>
<td>134.6</td>
<td>122.8</td>
<td>1.99</td>
</tr>
<tr>
<td>ZP1</td>
<td>124.3</td>
<td>135.3</td>
<td>125.2</td>
<td>1.99</td>
</tr>
<tr>
<td>ZP2</td>
<td>151.7</td>
<td>154.2</td>
<td>149.8</td>
<td>2.40</td>
</tr>
</tbody>
</table>

*Wet core samples were submerged in distilled water for 24 hours prior to testing.

Figure 5: Stress/strain curves of Phipps Park sandstone samples PP1 (top) and PP2 (bottom).
Figure 6: Stress/strain curves of Zimmerman Trail Road sandstone samples ZP1 (top) and ZP2 (bottom).
3.3. **Geomechanical Classification**

Many systems have been developed to classify rock based on its engineering properties, and the decision of which classification system to use must be made on a project by project basis. The unique properties of sandstone make classification based on strength inherently complicated; wet sandstone is often weaker than dry sandstone, and the UCS of heterogeneous, anisotropic materials like sandstone can deviate by as much as 40% from the mean (McNally and McQueen, 2000). It should also be noted that the strength of even moderately strong sandstone is low compared to many crystalline rocks, and classification schemes developed for use with all rock types may lack the resolution to capture the relatively subtle strength differences between sandstone facies. For example, despite the pronounced differences in strength between the various sandstone facies tested during this investigation, all four of the hand samples would be classified as “weak to moderately weak” rock according to the International Society for Rock Mechanics classification scheme (Brown, 1981).

The geomechanical classification of the sandstone from Phipps Park and Zimmerman Trail Road presented in Table V was made in accordance with the system presented in McNally and McQueen (2000) and republished in the book *Sandstone Landforms* (Young et al., 2009). The system is unique among rock classification systems in that it was developed specifically for sandstone and considers the effects of moisture and cementation on rock strength. The RMR\textsuperscript{89} intact rock strength rating for each dry rock sample is also included in Table V to facilitate correlation with the popular Rock Mass Rating system (Bieniawski, 1989).
### Table V: Geomechanical Classification of Intact Rock

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Geomechanical Classification (McNally and McQueen, 2000)</th>
<th>Rating (RMR&lt;sub&gt;89&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td><strong>Description</strong></td>
<td></td>
</tr>
<tr>
<td>PP1</td>
<td>Class I</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Strong sandstone</td>
<td>High strength (UCS 20-60 MPa). Breakage both around grains and through cemented grain contacts.</td>
</tr>
<tr>
<td>PP2</td>
<td>Class II/III</td>
<td>Weak Sandstone</td>
</tr>
<tr>
<td>ZP1</td>
<td>Class II/III</td>
<td>Weak sandstone</td>
</tr>
<tr>
<td>ZP2</td>
<td>Class I</td>
<td>Indurated Sandstone</td>
</tr>
</tbody>
</table>
4. Photogrammetry Data Acquisition

The UAV photogrammetry flights at Phipps Park and Zimmerman Trail Road were performed during the summer of 2019 with the understanding that complete coverage of rock outcrops and rock fall runout zones in the respective field areas was critical to the success of the investigation. A high-quality and continuous photogrammetric data set would be needed for the remote mapping, spatial analysis, and rock fall modeling that was integral to the project, and the limited duration of the regulatory permissions granted for the flights coupled with impending seasonal snowfall made the possibility of repeating the surveys unlikely in the event that the resulting data was insufficient. Preparations for the UAV photogrammetry flights, which began during AY 2018-2019, included obtaining a sUAS Remote Pilot Certificate from the Federal Aviation Administration (FAA), developing and field testing methods to scale and orient photogrammetry data, and completing numerous nadir and oblique photogrammetry flights to gain proficiency operating the Montana Tech DJI Phantom 4 Pro research UAV. The summer 2019 field work began with a preliminary reconnaissance of the Phipps Park and Zimmerman Trail Road study areas on June 6, 2019, to evaluate site access and identify the location of any overhead hazards or obstructions that could adversely affect the feasibility of the sites for UAV photogrammetry. Permission to access the Phipps Park outcrop for the planned UAV photogrammetry flights was obtained from Mark Jarvis of the City of Billings Parks Department on June 10, 2019. Yellowstone County Public Works Engineer Mike Black and Yellowstone County Parks Department Superintendent Cal Cumins were informed of the proposed research
project at Zimmerman Trail Road on June 6, 2019, and permission to access the Zimmerman Trail Road field area from Zimmerman Park was granted on June 13, 2019.

Representative cell mapping was performed at Phipps Park on June 25 - 26, 2019 to obtain data for the comparison and validation of remote measurements of the rock mass. The field mapping included lithologic identification, direct measurement of structural orientations using a Brunton geologic compass, characterization of joint attributes (including measurements of joint roughness, aperture, persistence, spacing, and infill), observation of geologic structures, estimation of intact rock strength using a rock hammer, and the collection of representative hand samples for laboratory testing. No field mapping was performed at Zimmerman Trail Road.

4.1. FAA Regulatory Compliance

The Phipps Park study area is approximately 5.6 miles southwest of the Billings Airport (BIL), and the Zimmerman Trail Road study area is approximately 1.5 miles southwest of BIL. Both locations are in Class C airspace, and preparations to ensure compliance with FAA regulations were made several weeks in advance of each UAV photogrammetry flight. Permission for the flights under Part 107 rules was confirmed with Billings Air Traffic Controller David Hauger on June 12, 2019, and Low Altitude Authorization and Notification Capability (LAANC) notifications for the flights at Phipps Park and Zimmerman Trail Road were submitted to the FAA via Airmap on June 24, 2019, and July 19, 2019, respectively. The Phipps Park flights were conducted on June 27 – 28, 2019, and the Zimmerman Trail Road flights were conducted on August 6 – 7, 2019.
4.2. UAV Photogrammetry Methods

The relatively flat, unobstructed plateaus atop the cliffs at Phipps Park and Zimmerman Trail Road served as the base for UAV operations throughout the investigation. The study areas were divided into multiple overlapping nadir flight grids using the flight planning application DroneDeploy prior to accessing the field area. An optimal elevation above ground level (AGL) was determined for each nadir flight grid to maximize the resolution of the photogrammetry while ensuring that the UAV would not impact trees and other overhead hazards or exceed the regulatory elevation ceiling during its flight path. All flights were performed using the Montana Tech DJI Phantom 4 Pro research UAV. The Phantom 4 Pro is equipped with an onboard camera capable of producing 12.4 megapixel (4864 x 3648) RGB images (Table VI). Nadir flights were performed before OAP to maximize battery resources.

<table>
<thead>
<tr>
<th>Model</th>
<th>Sensor Width (mm)</th>
<th>Sensor Height (mm)</th>
<th>Pixel Size (µm)</th>
<th>Focal Length (mm)</th>
<th>Principal X (mm)</th>
<th>Principal Y (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC6310</td>
<td>11.4074</td>
<td>8.55554</td>
<td>2.34527</td>
<td>8.6</td>
<td>5.7037</td>
<td>4.27777</td>
</tr>
</tbody>
</table>

Oblique imagery was acquired in general conformance with the best practices for OAP developed by photogrammetry software developer Pix4D (Pix4D, 2019a). The UAV camera angle was set to a fixed position of ~45 degrees below horizontal before takeoff, and the UAV was positioned 50 – 100 feet from the outcrop while shooting oblique imagery. A pattern of repeating vertical strips was flown slowly along the length of the outcrop while taking still images on a timed interval of three or five seconds, a rate that ensured sufficient overlap between
images (~70% or greater). The duration of each flight was limited by battery capacity to less than 20 minutes.

4.2.1. **Scale and Orientation Methods**

Scaling and orienting photogrammetry can ensure that measurements of length, volume, and orientation are internally accurate throughout the photogrammetric reconstruction (Rieke-Zapp et al., 2009). This is an effective alternative to surveyed ground control only when the data do not need to be georeferenced relative to a specific coordinate system. As measurement accuracy was of paramount importance in this investigation and a surveying ground control points was infeasible, each project was scaled and oriented using photogrammetric targets and an orientation constraint.

Six brightly colored 2.0 ft x 2.0 ft photogrammetric targets were positioned across each site before flying to serve as scale constraints and manual tie points between flight grids. Tie points are used to identify objects or feature that appears in two or more images, which assists the photogrammetric software in establishing a geometric connection between the images. A single 1.0 m x 1.0 m 3D orientation constraint constructed from 1-inch PVC pipe painted with pink high-visibility fluorescent paint was placed in a prominent location at the top of the cliffs, where it would be visible in both nadir and oblique imagery (Figure 7). The 3D orientation constraint was then calibrated by aligning the square frame of the structure so that the Y-axis of the frame pointed to true north (azimuth 0/180 degrees), the X-axis pointed to azimuth 90/270 degrees, and the Z-axis was vertical (90 degrees from horizontal). Several of the photogrammetric targets were used as planar reference surfaces during processing to improve 3D mesh quality, and the orientation constraint, which was not used for scaling purposes, was also
used as a checkpoint to verify length measurement accuracy. A description of these methods is provided in Section 5.

4.3. Flight Data Summary

The still imagery acquired during the UAV photogrammetry flights performed at Phipps Park on June 27 and 28, 2019, and at Zimmerman Trail Road on August 6 and 7, 2019, is summarized in Tables VII and VIII. Note that the flight duration represents the time spent acquiring the imagery rather than the total flight time. The 2D and 3D camera locations recorded by the onboard GPS for each image from the respective flights are shown in Figures 8 and 9.

![Figure 7: Placement and calibration of Phipps Park orientation constraint.](image)

<table>
<thead>
<tr>
<th>Flight ID</th>
<th>Date</th>
<th>Time (start)</th>
<th>Time (end)</th>
<th>Duration (min:sec)</th>
<th>Max Elevation (ft) (AGL)</th>
<th>Number of Images</th>
<th>Camera Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6/27/19</td>
<td>10:52:43</td>
<td>11:01:12</td>
<td>09:55</td>
<td>270</td>
<td>152</td>
<td>Nadir</td>
</tr>
<tr>
<td>3</td>
<td>6/27/19</td>
<td>11:16:57</td>
<td>11:26:38</td>
<td>09:41</td>
<td>N/A</td>
<td>169</td>
<td>Oblique</td>
</tr>
</tbody>
</table>
Table VIII: Zimmerman Trail Road Photogrammetry Flights

<table>
<thead>
<tr>
<th>Flight ID</th>
<th>Date</th>
<th>Time (start)</th>
<th>Time (end)</th>
<th>Duration (min:sec)</th>
<th>Max Elevation (ft) (AGL)</th>
<th>Number of Images</th>
<th>Camera Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>8/7/2019</td>
<td>10:09:52</td>
<td>10:28:32</td>
<td>18:40</td>
<td>N/A</td>
<td>225</td>
<td>Oblique</td>
</tr>
<tr>
<td>5</td>
<td>8/7/2019</td>
<td>10:41:25</td>
<td>11:01:10</td>
<td>19:45</td>
<td>N/A</td>
<td>396</td>
<td>Oblique</td>
</tr>
</tbody>
</table>

Figure 8: 2D (a) and 3D (b) camera orientations from Phipps Park. Each point represents the location of the UAV at the time of image acquisition. A total of 788 images were used in the reconstruction.

Figure 9: 2D (a) and 3D (b) camera orientations from Zimmerman Trail Road. Each point represents the location of the UAV at the time of image acquisition. A total of 1,482 images were used in the reconstruction.
5. Photogrammetric Processing

Advanced photogrammetric processing techniques were employed to fully capture the complex 3D geometry of the outcrops at both field locations and to optimize the data products used for geospatial analysis and remote rock mass assessment. All photogrammetric processing was performed using Pix4Dmapper v.4.3.33. The dual objectives of maximizing data resolution while minimizing photogrammetry processing times and latency are always in conflict. Limited computing power also introduces practical constraints on the size and density of point clouds as well as the resolution of orthophotos and digital surface models used for post-processing analysis. Computationally intensive operations sometimes required splitting area into multiple overlapping tiles or reducing the resolution of the data (downsampling), which increases the pixel size. A Montana Tech Dell T5500 and a Dell Precision 5810 desktop computer were used for all processing and post-processing analysis. Specifications are provided in Table IX.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Dell T5500</th>
<th>Dell Precision 5810</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS</td>
<td>Windows 7 Enterprise</td>
<td>Windows 10 Enterprise</td>
</tr>
<tr>
<td>CPU</td>
<td>Intel Xeon 2.4 GHz Quad-Core E5620 CPU</td>
<td>Intel Xeon 3.5 GHz Quad-Core ES1620 CPU</td>
</tr>
<tr>
<td>RAM</td>
<td>12 GB</td>
<td>16 GB</td>
</tr>
<tr>
<td>Hard Disk</td>
<td>500 GB HDD</td>
<td>500 GB HDD</td>
</tr>
<tr>
<td>GPU</td>
<td>Nvidia Quadro 6000</td>
<td>Nvidia Quadro M2000</td>
</tr>
</tbody>
</table>

5.1. Merging Oblique and Nadir Photogrammetry

Steep topography often contains low-density regions or voids in nadir photogrammetry, while oblique photogrammetry, which is ideal for capturing steep to vertical surfaces, is inefficient (and ineffective) for large mapping projects in varied topography. Fortunately, nadir and oblique imagery can often be processed together or merged after processing to produce a
single model with improved quality and completeness (Rossi et al., 2017). Most contemporary SfM photogrammetry software processing applications, including Pix4Dmapper, Agisoft Metashape (formerly PhotoScan), and Bentley ContextCapture, allow oblique and nadir imagery to be processed together. However, this so-called “batch processing” method was observed to produce substantial vertical offset between nadir and oblique imagery, possibly due to insufficient overlap between the sets of images.

To overcome this problem, nadir and oblique imagery was processed separately and then merged into a single project using manual tie points, which were assigned to each of the brightly colored photogrammetric targets visible in the respective image sets. By forcing the software to recognize these points as common features and following the progression illustrated in Figure 10, oblique and nadir imagery from multiple individual flights could be merged seamlessly into complete models that fully captured the varied, complex topography at each of the respective field areas. The photogrammetric reconstructions were then scaled by assigning scale constraint

![Figure 10: Photogrammetry processing workflow in Pix4Dmapper v.4.3.33.](image)
tie points to the edge of each 2.0 ft x 2.0 ft photogrammetric target, marking the exact location of the corners of the target in several images, and entering the actual length of the edge of the target in the modal dialogue box. Orientation was accomplished by assigning X, Y, and Z-axis orientations to the corresponding sides of the orientation constraint and marking the corresponding tie points in the aerial imagery. Each project was also roughly georeferenced to the Montana State Plane coordinate system (US feet) using image geotags from the onboard GPS.

Merged, scaled, and oriented point clouds were edited to remove unnecessary points and then exported in LAS format for post-processing analysis using the 3D visualization and measurement software CloudCompare (Section 6). An RGB color orthomosaic and Digital Surface Model (DSM) (GeoTIFF format) were also generated to enable spatial analysis in ESRI’s ArcMap v.10.6 and to facilitate the generation of additional raster data using ArcGIS Spatial Analyst and 3D Analyst tools. An orthomosaic is a planimetrically correct 2D aerial image generated from the 3D photogrammetric reconstruction that has been orthorectified to remove the effects of image perspective (tilt) and terrain relief, while a DSM is digital grid that contains elevation values representing the highest surface detected by the sensor.

5.2. Quality Analysis

While there are many factors that influence the quality of a photogrammetric reconstruction, for the purposes of this investigation I define quality primarily as a function of resolution, which is the smallest discrete step width between two measurements, and measurement accuracy, which is how closely measurements made in the photogrammetric reconstruction correspond to real-world measurements. Unlike features such as point cloud
density, which can vary depending upon user-defined parameters applied during processing, resolution and measurement accuracy are primarily functions of the imaging configuration, sensor quality, image scale, environmental conditions, and the bundle adjustment process used by the photogrammetry software (Luhmann, 2011).

Accurately estimating measurement error in photogrammetry requires comparison with a known reference value (such as a calibrated scale bar or surveyed ground control point) that has been measured by a system of higher order accuracy and has a measurement uncertainty sufficiently small so as to be considered error-free (Luhmann, 2011). It is demonstrative of the quality of the UAV photogrammetry produced during this investigation that such error estimates could not be made with any degree of confidence, as digital measurements of the length and orientation of calibrated field standards did not deviate from physical measurements made with a hand tape and Brunton compass by more than the estimated measurement uncertainty of the physical measurements (± 0.005 m / ± 1.0 degree). Vertical Z-axis measurement accuracy is illustrated in Figure 11 (a), which depicts a polyline measurement of the vertical portion of the 1 m³ orientation constraint in the Phipps Park point cloud; in this instance, the relative measurement accuracy in the model appears to be greater than the reported internal measurement error (0.17 ft) calculated by the software; the polyline measures 3.28 feet (1 m) in length, which is identical to the physical length of the object measured in the field. The X- and Y-axis planimetric measurement accuracy and orientation of the Zimmerman Trail Road orthomosaic is also demonstrated in Figure 11 (b and c), which depicts the orientation constraint alongside a 1 m scale bar and north arrow inserted in ArcGIS ArcMap. While this method of assessing measurement accuracy is relatively crude, quantifying measurement error would require a greater number and wider spacing of reference scales measured with a higher order of accuracy, which
was neither feasible with the tools and instrumentation available nor necessary for this study. Furthermore, the quality of the high-resolution photogrammetry data products often exceeded the computational capabilities of the software used for post-processing analysis, and the down sampling that was required to use these applications negated many of the advantages associated with higher order measurement accuracy.

Figure 11: Phipps Park point cloud 3D Z-axis measurement accuracy in Pix4Dmapper (a) and XY-axis planimetric accuracy of Zimmerman Trail Road orthomosaic shown by 1 m³ orientation constraint (b) relative to scale bar and north arrow in ESRI ArcMap (c).
5.2.1. **Ground Sampling Distance**

Ground sampling distance (GSD), or the distance between pixel centers on the ground, is a critical baseline for measuring photogrammetric resolution (Pix4D, 2019a). Pixel size on the ground is a function of the sensor width and focal length of the camera lens, the distance to the object being imaged (flight height), and the pixel size of the image, which are related by the following equation (Pix4D, 2019a):

\[
GSD = \frac{\text{Flight height} \times \text{Sensor width}}{\text{Focal length} \times \text{Image width (pixels)}}
\]

Thus, assuming a maximum altitude of 270 feet (82.3 m) AGL, the greatest nadir GSD at the Phipps Park study area was 0.88 in (2.24 cm) / pixel. At Zimmerman Trail Road, where the maximum nadir flight altitude was approximately 350 feet (106.7 m) AGL, the greatest GSD was 1.15 in (2.91 cm) / pixel. However, it should be noted that these values represent the pixel size at the maximum altitude attained during nadir flights over the respective field areas, and represent the lowest resolution of the resulting photogrammetric model; for oblique imagery, which was generally obtained at a distance ranging from 50 – 100 ft (15.24 - 30.48 m) from the target outcrop, the GSD ranged from 0.16 - 0.33 in (0.42 - 0.83 cm) / pixel. The average GSD of the photogrammetric models generated from merged nadir and oblique imagery was 0.28 in (0.71 cm) at Phipps Park and 0.63 in (1.61 cm) at Zimmerman Trail Road. The minimum GSD of the orthomosaic and DSM generated for both study areas was increased to 1.0 in (2.54 cm) / pixel to reduce the size of the data products, which were exported for analysis in ESRI ArcGIS ArcMap (v. 10.6).
5.2.2. Mean Reprojection Error

Mean reprojection error refers to the average distance (in pixels) between the 3D reprojection of a point (often an automatically detected tie point) and the same point as it was detected in the original 2D imagery (Luhmann, 2011). It is a valuable metric for evaluating the quality of the internal calibration and bundle adjustment algorithms used by the software. Bundle adjustment is the process of geometric triangulation by which images are oriented in space and the 3D location of every object in the image is calculated. The shape and position of the object is determined by constructing a “bundle of rays” that defines the spatial orientation of the image point relative to the perspective center (origin) within the camera (Luhmann, 2011). Bundle adjustment provides an optimal balance between adjusted coordinates and fixed orientation parameters, although the process still requires enough point and network geometries (a function of image quality and overlap) to avoid “singularities or weak solutions” (Luhmann, 2011). A low mean reprojection errors (≤1.0 pixels) indicates good accuracy, internal calibration, and alignment of the photogrammetry relative to the imagery used for the reconstruction (Manousakis et al., 2016; Pix4D, 2019b). The merged oblique and nadir photogrammetric reconstructions from Phipps Park and Zimmerman Trail Road had mean reprojection errors of 0.144 pixels and 0.197 pixels, respectively. In summary, the resolution and internal accuracy of the scaled and oriented UAV photogrammetry was deemed to be acceptable for the purposes of this investigation, and the remote analysis performed with this data is the focus of the remainder of this report.
6. Discontinuity Mapping in Rock Fall Source Areas

The size and failure mechanics of rock fall is influenced by the structural fabric of the rock mass at its source, which may include joints, bedding surfaces, and other discontinuities (Cruden and Varnes, 1996). Unfavorably oriented discontinuities can cause structurally controlled instabilities to develop. Unlike direct rock falls, which are caused by a lack of strength (i.e., brittle fracture of overhanging strata) rather than a lack of stability (Young et al., 2009), structurally controlled instabilities can be identified in the study area by the presence of two intersecting high-angle master joints oriented roughly parallel and perpendicular or sub-perpendicular to the rock slope face. The most persistent of these tensile joints appear to terminate in a third master joint (often a low-angle bedding plane discontinuity) at the base of the outcrop. The resulting “suspended” block failures, such as the overhanging northeast corner block at Phipps Park, are bounded by widely spaced joints, often with significant aperture, that appear to propagate through multiple strata. At two locations along Zimmerman Trail Road, these intersecting joint sets have produced self-supported, suspended blocks where rotational movement and sliding on the basal plane would be required to induce a release. Evaluating the stability of these suspended blocks with respect to plane sliding or toppling requires detailed measurement of joint and bedding plane orientations, which can be performed using UAV photogrammetry data.

The orientation (strike and dip or dip/dip direction) of discontinuities can be used to identify the potential modes of failure of structurally controlled instabilities using kinematic analysis (Cruden and Varnes, 1996), and many rock mass classification schemes account for the orientation of discontinuities in addition to their physical attributes such as persistence, aperture, spacing, and infill. These include RMR<sub>89</sub> (Bieniawski, 1989), Q-Slope (Bar and Barton, 2017),
and the Geological Strength Index (Marinos et al., 2007), among others. Measuring the orientation of discontinuities remotely from digital point clouds has recently emerged as an alternative to traditional scan line or representative cell mapping in the field, which can be a repetitive and time-consuming task (Tonon and Kottenstette, 2006). For this investigation, UAV photogrammetry point clouds from Phipps Park and Zimmerman Trail Road were used to measure joint and bedding plane orientations using the CloudCompare Compass plugin. The following sections present an overview of this remote mapping technology and the methods that were used to perform the analysis, in addition to a summary of the measurement results.

6.1. Software Technology Summary

Remote structural geology mapping software applications, such as Sirovision, SplitFX, ShapeMatrix3D, and Adam Tech 3DM Analyst, have been commercially available for over a decade. These programs allow the user to map and measure geologic features from LiDAR or photogrammetric point clouds. The areal extent of 3D mapping projects grew exponentially with the improvements in UAV technology that accompanied the advent of SfM computer vision algorithms, and attempts to assist and even automate repetitive mapping tasks soon began to appear in academic research and commercial software applications (Assali et al., 2014).

The CloudCompare FACETS and Compass plugins were introduced in 2016 and 2017 (respectively) to detect and measure geologic features in the open-source point cloud visualization software CloudCompare (Dewez et al., 2016; Thiele et al., 2017). In contrast to most commercial remote mapping software applications, which are expensive to license and often require the payment of annual subscription fees to maintain update and support services, CloudCompare is free and as such has obvious appeal for academic researchers and other non-
commercial users. An added benefit to open-source software is that it tends to be updated frequently; CloudCompare is currently on v.2.10.2, and the stability and functionality of the software continues to improve with each successive release.

The CloudCompare Compass tool enables the user to manually digitize and measure planes and traces from geologic features, while the FACETS plugin is a semi-automated algorithmic solution developed by the French Geological Society (BRGM) for extracting planar features (facets) from the point cloud (Dewez et al., 2016). Both plugins were validated provisionally by their developers prior to release, and the accuracy of the software relative to field measurements has been corroborated by other researchers in the interim; a recent study comparing the planar orientations of two major discontinuity sets that were extracted from a photogrammetric point cloud using the FACETS plugin with manual measurements of the same discontinuities obtained in the field with a geological compass found less than 2 degrees of variation in dip and dip direction between the two data sets (Tung et al., 2018).

### 6.2. Remote Discontinuity Mapping Methods

Scaled and oriented oblique UAV photogrammetry point clouds were edited in Pix4Dmapper and clipped to isolate the outcrop region before it was exported in LAS format for discontinuity mapping in CloudCompare. The Phipps Park outcrop point cloud was 48,942,573 points and had an average density of 365.3 points per ft$^3$. The Zimmerman Trail Road outcrop point cloud was 71,498,228 points and had an average density of 229.2 points per ft$^3$. Due to the large file size of the Zimmerman Trail Road point cloud, the data were exported as three separate point cloud files (tiles) representing different regions of the outcrop. The spatial accuracy of the respective data sets was confirmed prior to mapping discontinuities by comparing measurements.
of the calibrated orientation constraint made in the point cloud using the Lineation tool in the CloudCompare Compass plugin with field measurements of the same standard (see Section 5.2 for quality analysis).

Discontinuities were mapped systematically in the virtual outcrop model by visually identifying joints or bedding planes in the point cloud and using the Plane and Trace tools in the CloudCompare Compass plugin to measure the planar orientation (strike and dip) of each discontinuity. The Plane tool is used by activating the tool in the Compass plugin and adjusting the radius of the circle projected by the tool to delineate the surface of interest. The tool then uses a least-squares algorithm to fit a plane to all the points within the user-defined circle (Thiele et al., 2017). The Trace tool, which employs a least-cost algorithm to follow discontinuities between user-defined endpoints and then fits a plane to the resulting trace using a least-squares algorithm, was used in lieu of the Plane tool when bedding plane or joint surfaces were poorly exposed. The trace tool requires both high point cloud density and high relief in the region of the point cloud containing the discontinuity to perform properly. Tabulated orientation data was imported into Rocscience Dips 6.0 to generate stereographic projections for the analysis and presentation of discontinuity measurements.

6.3. Phipps Park Discontinuities

Remote discontinuity measurements at Phipps Park were validated by comparing the mean set planes from 18 remote strike and dip measurements of the three primary discontinuities (J1 – J3) at the northern segment of the outcrop (Phipps Park North) with the mean set planes from 7 measurements of the same discontinuities obtained in the field using a Brunton compass. The northern outcrop point cloud segment is shown in Figure 12; several of the surfaces that
were measured are visible as semi-transparent planes in the image. All orientation measurements are reported in azimuth (0° – 360°) using the right-hand rule convention, which assumes a dip direction + 90° from strike. The comparison revealed an average variation in strike of 3° and an average variation in dip of 4° between the respective data sets (Table X).

![Image of point cloud segment of Phipps Park North outcrop](image)

**Figure 12:** Clipped point cloud segment of Phipps Park North outcrop depicting several of the planes measured using the CloudCompare Compass tool.

**Table X: Phipps Park North Discontinuity Strike/Dip Data Comparison**

<table>
<thead>
<tr>
<th>Label</th>
<th>Field Measurements (n = 7)</th>
<th>Remote Measurements (n = 18)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strike (deg)</td>
<td>Dip</td>
<td>Strike (deg)</td>
</tr>
<tr>
<td>J1</td>
<td>289°</td>
<td>14°</td>
<td>291°</td>
</tr>
<tr>
<td>J2</td>
<td>247°</td>
<td>87°</td>
<td>249°</td>
</tr>
<tr>
<td>J3</td>
<td>148°</td>
<td>83°</td>
<td>153°</td>
</tr>
</tbody>
</table>
The mean discontinuity measurement data from Table 12 is presented stereographically in Figure 13. Note the high-angle intersection vector between joints J2 and J3, which form large rectangular blocks when they intersect the low-angle bedding plane (J1) at the base of the outcrop:

![Figure 13: Lower hemisphere, equal angle stereonet comparison of field discontinuity measurements (a) and point cloud discontinuity measurements (b) at Phipps Park North outcrop segment (Table 12).](image)

Mean bedding plane orientations were also compared to evaluate the variation between remote and field measurement data across the entire Phipps Park study area. This comparison, which included 11 field and 37 remote bedding plane orientation measurements, revealed a variation in strike of 10° and a variation in dip of 1° between the mean set planes for the two bedding plane orientation data sets. Mean bedding plane strike and dip data from Phipps Park is presented in Table XI. This data is presented stereographically in Figure 14. Note that the stereonets also depict the pole of each discontinuity measurement at Phipps Park; poles to the bedding plane (J1), which has a very shallow dip angle, appear clustered near the center of the
stereonets, while poles to the joints sets, which dip steeply and have a strike roughly parallel and perpendicular that that of the U-shaped cliff line, appear around the perimeter of the stereonets.

This spatial variation in joint orientation across Phipps Park is highlighted in density-concentration stereographic pole plots of the 44 field discontinuity measurements and 120 remote discontinuity measurements from Phipps Park (Figure 15).

<table>
<thead>
<tr>
<th>Label</th>
<th>Field Measurements (n = 11)</th>
<th>Remote Measurements (n = 37)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strike (deg)</td>
<td>Dip</td>
<td>Strike (deg)</td>
</tr>
<tr>
<td>J1</td>
<td>298°</td>
<td>04°</td>
<td>308°</td>
</tr>
</tbody>
</table>

Figure 14: Lower hemisphere, equal angle stereonet comparison of mean bedding plane discontinuity data measured at Phipps Park (Table XI) from (a) field measurements and (b) point cloud measurements.
Planar structural orientations were measured remotely at the Zimmerman Trail Road outcrop. Due to the large site area and the corresponding size of the point cloud LAS file, each of the three tiles were mapped individually in CloudCompare and the resulting 93 discontinuity measurements were exported and recombined to generate the mean set plane discontinuity data presented in Table XII and projected stereographically in Figure 16. The mean strike and dip of the bedding plane (J1) at Zimmerman Trail Road was 296°, 02° (n = 56).

**Table XII: Zimmerman Trail Road Mean Set Planes**

<table>
<thead>
<tr>
<th>Label</th>
<th>Strike (deg)</th>
<th>Dip</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>296°</td>
<td>02°</td>
</tr>
<tr>
<td>J2</td>
<td>080°</td>
<td>85°</td>
</tr>
<tr>
<td>J3</td>
<td>188°</td>
<td>82°</td>
</tr>
</tbody>
</table>
Figure 16: Lower hemisphere, equal angle stereonets depicting 93 point cloud measurements of discontinuities at Zimmerman Trail Road, including (a) all planes and (b) mean set planes.
7. Rock Fall Hazard Rating at Zimmerman Trail Road

The Rock Fall Hazard Rating System (RHRS) is an additive, exponential rating system that was developed by the Oregon Department of Transportation (ODOT) in 1991 to quantify the relative risk of rock fall along public transportation corridors (Pierson, 1991). Since then, it has been adopted and customized by numerous state highway departments (including Montana and Colorado) to standardize quantitative rock fall hazard assessment and facilitate risk-based decision making with regard to mitigation efforts (Anderson et. al., 2017). The Preliminary Rating System is the first step in the RHRS assessment process. A preliminary hazard rating (A – C) is assigned to highway slopes based on evidence of historic rock fall and the potential for future rock fall to impact to the roadway. Slopes with an “A” rating (which signifies a high rock fall hazard potential) are prioritized for detailed assessment. MDT adopted the RHRS in 2005, and since then they have used the system to assign preliminary ratings to over 2,600 slopes and detailed ratings to 869 "A" rated slopes (Beckstrand et al., 2017b). The MDT Rock Slope Asset Management Program (RAMP), which was introduced in 2017, includes improvements to the RHRS to better quantify risk by isolating specific slope attributes and making the results more accessible to non-geotechnical professionals (Beckstrand et al., 2017a; Mines et al., 2018).

7.1. Detailed RHRS Rating Criteria

In addition to categories for slope height, ditch effectiveness, road width, geologic character (which accounts for structural condition as well as differences in erosion rates or joint characteristics in the rock mass), block size, climate, and rock fall history, the detailed RHRS includes criteria to quantify the risk to vehicles presented by rock fall. These include the Average
Vehicle Risk (AVR) rating category and the Percent of Decision Sight Distance (DSD) rating category. AVR is calculated using the following equation (Pierson, 1991):

\[
AVR = \frac{ADT \times \text{Slope Length} \div 24 \times 100}{\text{Posted Speed Limit}}
\]

Due largely to the high Average Daily Traffic (ADT) count at Zimmerman Trail Road (10,572 northbound and 9,585 southbound vehicles per day according to 2018 MDT data), the AVR for the 0.35 mile section of highway is greater than 100%; this means that at any given time, more than one vehicle is exposed to rock fall hazards within the measured section (Pierson and Van Vickle, 1993).

DSD is a measure of the distance required for a driver to make a speed, path, or direction change (AASHTO, 2001). The RHRS rating for DSD is based on the percentage of the DSD that is available to drivers to avoid an unexpected hazard. This value is obtained by dividing the actual visible sight distance of the highway segment by the DSD, which is based on vehicle speed and environment (urban, suburban, or rural). To obtain this value remotely, the average sight distance was measured from the point cloud at two locations near the radius of maximum curvature on Zimmerman Trail Road (Table XIII, Figure 15). The shortest line of sight measurement (230 feet) was 43.8% of the 525-foot long Decision Sight Distance for urban roads with a posted speed limit of 25 mph (Layton, 2012).
Table XIII: Minimum Visible Sight Distance – Zimmerman Trail Road

<table>
<thead>
<tr>
<th>ID / Location</th>
<th>Projected 2D Length (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyline 1 - NE</td>
<td>258.3</td>
</tr>
<tr>
<td>Polyline 2 - NE</td>
<td>255.6</td>
</tr>
<tr>
<td>Average (n = 2)</td>
<td>256.9</td>
</tr>
<tr>
<td>Polyline 3 - SW</td>
<td>235.4</td>
</tr>
<tr>
<td>Polyline 4 - SW</td>
<td>225.3</td>
</tr>
<tr>
<td>Average (n = 2)</td>
<td>230.4</td>
</tr>
</tbody>
</table>

7.2. Remote RHRS Rating

A detailed RHRS rating of Zimmerman Trail Road was attempted remotely using the UAV photogrammetry point cloud, DSM, and 3D mesh reconstruction. The slope height (the difference in elevation between the outcrop crest and the road surface below), was measured in ArcGIS from the UAV photogrammetry DSM, and was found to range from ~200 ft at the western extent of the project area to ~100 feet at the eastern extent. Although the RHRS scores for slope height, AVR, percent of DSD, road width, and climate rating were the same for Zones 1 – 4, the additive exponential rating system was effective at highlighting the differences.
between the zones based on the remaining attributes. The photogrammetry point cloud and DSM were used to calculate slope heights, measure road and ditch widths, estimate differences in erosion rates between strata, and calculate the volume of historic rock fall and overhanging or joint-bounded blocks. The 0.35-mile long study area was ultimately divided into four zones based on shared RHRS rating characteristics; this was accomplished by first rating Zone 1 in each category and then navigating from west to east across the slope in the 3D reconstruction until a rating change was identified in any category, at which point a new zone was delineated. Mapping zones and corresponding RHRS scores are presented in Figure 18 and Table XIV, respectively. Examples of differential erosion in the UAV photogrammetry 3D mesh reconstruction, which was used to determine the geologic character category rating across the study area, are shown in Figures 19 and 20.

![Diagram of Zimmerman Trail Road RHRS zones. Contour interval is 20 feet.](image)

**Table XIV: Zimmerman Trail Road RHRS Score**

<table>
<thead>
<tr>
<th>Zone</th>
<th>Slope Height</th>
<th>Ditch Efficacy</th>
<th>AVR</th>
<th>% of DSD</th>
<th>Road Width</th>
<th>Geologic Character (Case 2)</th>
<th>Difference in Erosion Rates</th>
<th>Block Size</th>
<th>Climate</th>
<th>Rock fall History</th>
<th>RHRS Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>81</td>
<td>27</td>
<td>81</td>
<td>81</td>
<td>27</td>
<td>81</td>
<td>27</td>
<td>81</td>
<td>27</td>
<td>81</td>
<td>594</td>
</tr>
<tr>
<td>2</td>
<td>81</td>
<td>9</td>
<td>81</td>
<td>81</td>
<td>27</td>
<td>27</td>
<td>9</td>
<td>27</td>
<td>27</td>
<td>9</td>
<td>378</td>
</tr>
<tr>
<td>3</td>
<td>81</td>
<td>27</td>
<td>81</td>
<td>81</td>
<td>27</td>
<td>81</td>
<td>27</td>
<td>81</td>
<td>27</td>
<td>27</td>
<td>540</td>
</tr>
<tr>
<td>4</td>
<td>81</td>
<td>27</td>
<td>81</td>
<td>81</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>9</td>
<td>414</td>
</tr>
</tbody>
</table>
Figure 19: Example of differential erosion features (Pierson, 1991) in UAV photogrammetry 3D mesh reconstruction of Zimmerman Trail Road (Zone 1).

Figure 20: Example of large block failure (Pierson, 1991) in UAV photogrammetry 3D mesh reconstruction of Zimmerman Trail Road (Zone 3).
8. Rock Fall Characterization at Phipps Park

Avoiding and mitigating rock fall requires detailed geological studies to collect data on the size, shape, and distribution of rock fall as well as the location of potential rock fall source areas (Wyllie, 2014). This information is critical for the application of deterministic approaches to delineate potential rock fall hazard areas (Hungr and Evans, 1988) and for calibrating models to evaluate the impact energy and trajectory of rock fall, which are critical parameters for the design of berms, ditches, and protective structures (Wyllie, 2014). UAV photogrammetry can be used to quickly and accurately measure volumes, heights, and distances (Draeyer and Strecha, 2014), making it particularly well suited for performing this type of quantitative spatial analysis remotely. 2D and 3D measurement tools in Pix4D and ArcGIS ArcMap were used to determine the volume, runout distance, and vertical displacement of high-energy rock fall at Phipps Park and to estimate the size, degree of fragmentation, and recurrence interval of the large May 18, 2016, event. The analysis presented here includes an estimate of the maximum runout distance of high-energy rock fall at Phipps Park using the “shadow angle” approach described in Evans and Hungr, 1993.

8.1. Methods of Measurement

UAV photogrammetry data were used to measure rock fall at Phipps Park. Volumetric calculations were performed in Pix4Dmapper, which calculates the volume of features and objects in the DSM from a user-defined base surface and a 3D grid of cells whose size is determined by the GSD of the data (Pix4D, 2020). The base of each volume being calculated must first be digitized in Pix4D, which was accomplished by tracing the outline of each rock fall block and fitting a triangulated plane to the vertices. The elevation of this base surface was then...
adjusted to closely match the ground surface at the rock fall location, and the volume of the region of the DSM above the base surface was computed using the Pix4D volumes utility (Figure 21).

The amount of measurement error in each volume calculation depends on the spatial resolution of the GSD (Pix4D, 2020). This error is calculated and reported by the software automatically with each computation. Non-computational sources of error are more difficult to quantify. These potential sources of error include inaccurately defining the vertices of the base surface, which could cause adjacent rock fall, vegetation, and ground to be included in the volume calculation. This can be particularly problematic when the point cloud includes dense vegetation and/or steeply sloping topography. While every effort was made to minimize non-computational sources of error, including carefully digitizing and aligning all base surfaces, the internal error estimates provided with the volumetric measurement data in Appendix A should be regarded as the minimum error associated with each calculation. Due the difficulty of accurately defining the base surface of small rock fall, which was often partially obscured by vegetation, rock fall less than ~100 ft³ in size was not measured. This was not deemed a significant limitation, as nearly all the rock fall extending beyond the steep talus slope into the runout zone at Phipps Park exceeded this size.

A unique identification number was assigned to each rock fall block in runout zone. After calculating the volume of each block, the straight-line horizontal run out distance and vertical elevation difference between the apex of the talus slope and the ground surface where the rock fall was deposited was determined from the high-resolution raster DEM in ArcGIS. The horizontal runout distance, vertical displacement, and volume of 32 rock fall blocks in the Phipps Park run out zone were measured using these methods. These data were combined with historic
air photo analysis and remote mapping techniques to perform the analysis presented in Section 8.2 and 8.3.

Characterizing Historic Rock Fall

Rock fall is subject to natural sorting as it rolls, tumbles, and slides downslope. This sorting process is influenced by the degree of rock fall fragmentation, which is a function of the strength of the material, the rock fall height and trajectory, and the stiffness of the impact surfaces; relatively weak materials such as sandstone often become highly fragmented while rolling and bouncing downslope (Corominas et al., 2017). Smaller fragments often accumulate on cone-shaped talus slopes, while larger, higher energy blocks tend to travel beyond the base of the talus slope and are deposited on flatter ground in the runout zone far from the rock fall source.
area (Wyllie, 2014). At Phipps Park, most of the large boulders in the runout zone are comprised of strong sandstone, while the angular, large cobble to small boulder-size rock fall deposited on the talus slope is predominantly weak to moderately strong sandstone.

The 32 large boulders on the talus slope greater than 100 ft³ (~3 m³) that were inventoried in this investigation are shown in Figure 25 (Section 8.3). Note that each label in the figure corresponds to a volume/distance/height measurement and shadow angle calculation in the attached rock fall inventory (Appendix A). As shown in the summary of the volumetric and spatial data collected remotely from the Phipps Park runout zone presented in Table XV, the average block size was ~1,400 ft³ (40 m³) and the average distance from the base of the outcrop was 312.8 ft. In addition to minimum, maximum, and average rock fall volumes and runout distances, Table 15 includes the 90th percentile value for runout distance. The 90th percentile has been used in rock fall hazard analyses to exclude statistical outliers and represents the distance from the rock fall source at which there is a 10% probability of exceedance by future rock fall (Stock et al., 2012a).

<table>
<thead>
<tr>
<th>No. of Rock Fall Blocks (n)</th>
<th>Rock Fall Volume (ft³)</th>
<th>Distance from Source (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>32</td>
<td>130.7</td>
<td>6,326</td>
</tr>
</tbody>
</table>

*Average of internal measurement errors reported for each volumetric calculation in Pix4Dmapper.

Outlying boulders in the runout zone define the maximum extent of historic rock fall, and their location relative to the apex of the talus slope is used to calculate the rock fall shadow angle. The rock fall shadow angle is defined as the angle from horizontal formed between a
straight line connecting the apex of the talus slope with the distal extent of outlying rock fall in the runout zone (Evans and Hungr, 1993). The shadow angle concept is illustrated in Figure 22.

Figure 22: Shadow angle concept sketch (Stock et al., 2012).

The minimum shadow angle is a measurement that has been widely used in rock fall hazard assessments to estimate the maximum extent of potential rock fall impacts (Guzzetti et al., 2003; Stock et al., 2012a; Wyllie, 2014). The minimum rock fall shadow angle at Phipps Park is 20.9°. The 90th percentile shadow angle is 21.9°, which (incidentally) is associated with the largest boulder in the runout zone, a 6,326 ft³ (179 m³) strong, rectangular sandstone block. The minimum, maximum, average, and 10th percentile shadow angles calculated from outlying boulders in the Phipps Park spatial data set are presented in Table XVI. Figure 23 depicts the shadow angles of rock fall relative to its size; data points from the 2016 event are highlighted to illustrate how this rock fall compares to earlier failures.
Table XVI: Shadow Angle of Large Outlying Boulder Rock Fall in Phipps Park Runout Zone

<table>
<thead>
<tr>
<th>No. of Rock Fall Blocks (n)</th>
<th>Rock Fall Shadow Angle (degrees)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>32</td>
<td>20.9</td>
<td>29.1</td>
</tr>
</tbody>
</table>

![Figure 23: Shadow angle and size of large outlying rock fall boulders in Phipps Park runout zone.](image)

### 8.3. Evaluating the 2016 Rock Fall Event

Rock fall from the 2016 rock fall event at Phipps Park was differentiated from earlier slope failures by comparing UAV orthomosaic imagery from the 2019 photogrammetry flights with United States Department of Agriculture (USDA) National Agriculture Imagery Program (NAIP) imagery from 2005, 2009, 2011, 2013, 2015 and 2017 and historic Google Earth imagery from 1996, 2002, 2004, 2005, 2006, 2009, 2011, 2013, 2014, and 2015. The relatively low-resolution 2015 NAIP imagery in Figure 24 (as compared to the 2019 UAV imagery in Figure 25) depicts the site conditions at Phipps Park prior to the 2016 failure; note that each rock fall label in Figure 25 corresponds to a specific volume/distance/height measurement and shadow...
angle calculation in the attached rock fall inventory (Appendix A). UAV photogrammetry data were also used to estimate the size, areal extent, and percent fragmentation of the 2016 event. Approximately 80.4% of the large 45-foot tall, ~28,200 ft$^3$ (800 m$^3$) block disintegrated into angular boulders and cobbles less than 200 ft$^3$ (< 6 m$^3$) in size during impacts along its trajectory, depositing rock fall debris across a ~43,800 ft$^2$ zone that extends 322 feet horizontally from the base of the cliffs. Assuming that the size and fragmentation characteristics of earlier rock fall events at Phipps Park were comparable to those of the 2016 event, the outlying boulders in the runout zone were deposited by 6 – 7 large individual block falls.

Figure 24: 2015 NAIP imagery of Phipps Park study area prior to 2016 rock fall event.
Figure 25: 2019 UAV photogrammetry orthomosaic depicting rock fall deposition zone in Phipps Park after 2016 failure.
9. Rock Fall Modeling at Phipps Park

Numerical modeling is used to evaluate problems that require complex mathematical calculations performed over many iterations to solve. Two-dimensional (2D) dynamic rock fall modeling applications, such as the Colorado Rock Fall Simulation Program (CRSP) and Rocscience’s RocFall, are widely used for rock fall assessment and mitigation design (Wyllie, 2014). However, the ability for 2D modeling applications to define the lateral extent and spatial distribution of rock fall is limited, as simulated rock fall can only travel downhill along a linear, user-defined slope profile. In contrast, 3D slope geometries allow rock fall to follow multiple non-linear paths downslope, and 3D numerical modeling methods can be employed to evaluate not only the physical dynamics of rock fall, including velocity, kinetic energy, and bounce height, but also where rock fall is most likely to impact.

The first 3D numerical rock fall modeling codes were developed in the early-2000’s to aid in regional rock fall susceptibility mapping (Koning and Mansell, 2017). These DEM-based applications, such as STONE and its successor HY-STONE, employ a multi-scale stochastic approach to simulate rock fall trajectories and estimate rock fall frequency, bounce height, rotational and translational velocity, and kinetic energy for each cell of the input DEM (Acosta et al., 2002; Guzzetti et al., 2002; Agliardi and Crosta, 2003). STONE has been used with aerial LiDAR DEM data to develop regional rock fall susceptibility maps and to quantify and constrain rock fall hazard areas in sub-regional rock fall assessments, including in the Yosemite Valley, where STONE modeling was integrated with physical mapping data and statistical analyses to estimate the relative risk associated with rock fall hazard occurrence (Stock et al., 2012a).

While the availability of regional LiDAR data continues to improve, the coverage and quality of the data remains inconsistent in many parts of the country, including Montana (DNRC,
UAV photogrammetry has dramatically reduced the cost associated with acquiring high-resolution 3D topographic raster data and may provide a topographic data solution for some project-specific analyses where LiDAR data are unavailable (such as at the Phipps Park and Zimmerman Trail Road study area locations) or are of insufficient resolution for the required applications. The following analysis explores the feasibility of using UAV photogrammetry data for numerical rock fall modeling and provides an example of how UAV photogrammetry data can be integrated with 2D and 3D rock fall modeling software to identify and evaluate rock fall hazard areas.

9.1. Modeling Rock Fall with CRSP-3D

Early probabilistic codes such as STONE rely on a number of simplifying assumptions to reduce the computational intensity of the model, including treating rock fall as a “lumped mass,” that is, a dimensionless body with all mass concentrated at the center (Guzzetti et al., 2002). Ignoring the influence of rock fall size and shape on slope/rock fall interactions decreases the number of calculations required to approximate rock fall trajectories, but may also reduce the accuracy of the model, particularly predictions of bounce height and rock fall runout distance (Andrew et al., 2012). In an effort to develop more realistic rock fall modeling tools and improve the accuracy of rock fall simulations, the Federal Highway Administration (FHWA) supported the development of CRSP-3D, a rock fall modeling application by Yeh and Associates, Inc., Summit Peak Technologies L.L.C., and Advanced Numerical Modeling that was released in 2012.

CRSP-3D is the latest version of the venerable Colorado Rock fall Simulation Program (CRSP), which was originally developed as a rock fall engineering tool for the Colorado
Department of Transportation by Colorado School of Mines Geological Engineering graduate students in 1988 (Pfeiffer and Higgins, 1990). Four subsequent versions of CRSP were released between 1988 and 2000; CRSP-3D, which uses the discrete element method to directly model rock fall/slope interactions in 3D, represents a significant departure from these earlier codes. This numerical method provides a more accurate approximation of the interactions between the slope and rotational, non-spherical rock fall than could be achieved with the stochastic, semi-empirical approach employed in earlier software (Andrew et al., 2012). CRSP-3D software was obtained from the FHWA for 3D numerical rock fall modeling using UAV photogrammetry raster data from the Phipps Park study area. A discussion of the methods and results of this analysis are presented in the following sections.

9.1.1. \textbf{Slope Construction Methods}

Slope surface geometries were generated in CRSP-3D from X-Y-Z topographic slope coordinate data. Although there is no upper limit to the number of points allowed for constructing slope surfaces in CRSP-3D, the user manual recommends using no more than 2000 points, and the software performance was observed the degrade significantly when this number was exceeded by more than 500 - 1000 points. CRSP-3D uses fixed 12-foot center-to-center cells for modeling the slope surface; therefore, the maximum resolution that can be achieved for the slope surface is 12 ft x 12 ft pixels. Optimizing UAV photogrammetry DSMs for use in CRSP-3D required downsampling raster data in ArcGIS using the 3D Analyst and Spatial Analyst tools from 1.0 inch/pixel to 12 ft/pixel, which significantly reduced the resolution of the data.

12 ft x 12 ft resolution DEM grids were clipped and exported as delimited X-Y-Z coordinate data. These spatial coordinates were then corrected for offset to reduce the number of
digits stored in the geometry file (CRSP-3D does not support coordinates with more 5 digits), and a transformation matrix was applied to the coordinates to rotate the surface geometry so that the slope of interest was roughly perpendicular to the X-axis of the grid. This rotation was necessary to ensure that simulated rock fall would pass through each of the user-defined “Analysis Partitions,” which must be placed parallel to the X-axis. Analysis partitions are used in CRSP-3D to define the locations along the rock fall trajectory where physical data such as kinetic energy, velocity, and bounce height are calculated during the simulation. Although the software includes a LiDAR preprocessor tool for uploading slope surface coordinates and rotating the slope geometry, the ASCII and .txt files that were generated for use with this utility did not appear to contain the specific file contents required for its use. Therefore, all slope coordinate corrections were performed manually in Microsoft Excel, and corrected coordinate data were pasted directly into the software to generate the slope geometry.

9.1.2. 3D Rock Fall Model Calibration

In Section 6.2, UAV photogrammetric data were used to calculate the size and distribution of historic rock fall in the runout zone at Phipps Park, including the large May 18, 2016, event. These data were used to calibrate the CRSP-3D rock fall model for Phipps Park. CRSP-3D does not currently have the capability of modeling the effects of rock fall fragmentation during successive impacts, so an eight-element 10 ft x 20 ft x 15 ft (3,000 ft³) rectangular block was used for the calibration modeling. This theoretical rock fall block closely approximates the shape and dimensions of the largest outlying rock fall boulder from the 2016 event, a 3,063 ft³ (±29.8 ft³) rectangular block, and is roughly comparable to the 90th percentile for rock fall size in the Phipps Park run out zone rock fall of ~2,900 ft³. The average bulk unit
weight of strong Phipps Park Eagle Sandstone (144.7 lb/ft$^3$) was used for all Phipps Park rock fall simulations. Slope materials were manually assigned to regions of the CRSP-3D slope grid by selecting individual cells along each material boundary and selecting the applicable material type (talus, rock, etc.) from a drop-down list. The rock fall release area was assigned to the region of the slope grid representing the 2016 failure surface, and preliminary material parameters were assigned to each material type based on the recommended values for representative material types provided in the CRSP-3D user manual (Andrew et al., 2012). A total of four analysis partitions were placed at 100 ft (horizontal) intervals from the outcrop; the location of the analysis partitions is shown in 2D overlying the 2019 Phipps Park UAV photogrammetry orthomosaic in Figure 26.
The talus slope material parameters of slope roughness and slope hardness (which is akin to the coefficient of restitution described in Section 9.2) were calibrated by initially releasing 20 rectangular rock fall blocks from the 2016 failure surface and observing the rock fall runout during the simulation. Slope parameters were then adjusted for each subsequent simulation until the distribution of the simulated large rock fall runout closely approximated that of the 2016 event. This was evaluated by georeferencing images from the resulting the CRSP-3D models in

Figure 26: Analysis partitions from CRSP-3D rock fall simulations at Phipps Park; the location of the “overhanging corner block” is shown for reference.
ArcGIS ArcMap and visually comparing the distribution of rock fall in the model to the distribution of rock fall in the 2016 runout zone. Once the material parameters had been optimized, the simulation was repeated with 50 and then 100 rock fall releases to confirm the results. Figure 27 presents a semi-transparent, top-down view of the calibrated 20 release simulation relative to the talus and runout zone from the 2016 failure depicted in the 2019 UAV photogrammetric orthomosaic imagery. The color gradient represents rock fall velocity; a key is provided in the orthogonal view of the same CRSP-3D simulation shown in Figure 28.
Data from the final CRSP-3D calibration simulation at Phipps Parks, including the cumulative probability and maximum rock fall velocity, kinetic energy, and bounce height at the upper and middle analysis partitions, are presented in Table XVII. No rock fall reached the lower or bottom analysis partitions. Cumulative probability represents the likelihood (percent chance) that a given rock fall of the specified size will have a kinetic energies, velocity, or bounce height equal to or less than the specified value at the indicated analysis partition, while the maximum is the greatest raw data value recorded at the analysis partition. A total of 100 eight-element rectangular (10 ft x 20 ft x 15 ft), 434,100-pound equivalent blocks were released from the 2016 rock fall source area during the simulation. The “n” value reported in the analysis partition column is equivalent to the percentage of rocks passing each analysis partition, whose locations are shown in Figures 24 and 25. A roughness value of 2.0 ft and a hardness coefficient of 0.2

Figure 28: Orthogonal view of CRSP-3D Phipps Park calibration simulation rock fall velocity results.
were used for the talus slope material; bedrock was assigned a roughness of 2.0 ft and a hardness coefficient of 0.8.

<table>
<thead>
<tr>
<th>Analysis Partition</th>
<th>Kinetic Energy (ft-kips)</th>
<th>Velocity (ft/s)</th>
<th>Bounce Height (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cumulative Probability (%)</td>
<td>Max</td>
<td>Cumulative Probability (%)</td>
</tr>
<tr>
<td>Upper (n=89)</td>
<td>50</td>
<td>75</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>5,638</td>
<td>6,769</td>
<td>7,762</td>
</tr>
<tr>
<td>Middle (n=70)</td>
<td>1,290</td>
<td>1,938</td>
<td>2,926</td>
</tr>
</tbody>
</table>

9.1.3. Modeling Potential Future Rock Fall with CRSP-3D

The calibrated CRSP-3D model parameters were used to simulate potential future rock fall from the overhanging northeastern corner block at Phipps Park described in Section 2.1 (Figure 3) and shown in Figures 26, 27, and 29. Point cloud volumetric measurements in Pix4D indicate that the large suspended corner block is slightly larger than the block that failed in 2016, at 32,900 ft$^3$ (931.6 m$^3$) ±116.03 ft$^3$. A 10 ft x 20 ft x 15 ft rectangular rock block representing the size of rock fall in the 90$^{th}$ percentile of outlying boulders in the study area was again used for the rock fall simulation. The rock fall source area boundary was delineated in CRSP-3D around the overhanging corner block, and slope material parameters were held constant at the calibrated roughness and hardness coefficient values as 20, 50, and 100 rock falls were released over successive simulations. A semi-transparent, top-down view of rock fall simulation velocities from the 20-release simulation is shown overlying the 2019 UAV photogrammetry orthomosaic imagery in Figure 29, and orthogonal views of the same simulation are shown in Figure 30. Rock fall data collected at each of the four analysis partitions during the final rock fall simulation are summarized in Table XVIII.
Table XVIII: CRSP-3D Simulation Results – Phipps Park NE

<table>
<thead>
<tr>
<th>Analysis Partition</th>
<th>Kinetic Energy (ft-kips)</th>
<th>Velocity (ft/s)</th>
<th>Bounce Height (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cumulative Probability (%)</td>
<td>Max</td>
<td>Cumulative Probability (%)</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>75</td>
<td>90</td>
</tr>
<tr>
<td>Upper (n=100)</td>
<td>4.622</td>
<td>7.515</td>
<td>8.614</td>
</tr>
<tr>
<td>Middle (n=91)</td>
<td>4.759</td>
<td>6.621</td>
<td>8.014</td>
</tr>
<tr>
<td>Lower (n=83)</td>
<td>1.844</td>
<td>2.525</td>
<td>3.196</td>
</tr>
<tr>
<td>Bottom (n=2)*</td>
<td>587</td>
<td>916</td>
<td>947</td>
</tr>
</tbody>
</table>

*Cumulative probabilities may exceed maximum values of raw data due to small sample size for distribution.
Figure 30: Rock fall velocity (a) and kinetic energy (b) from initial Phipps Park NE CRSP-3D simulation (n=20).
9.2. Comparison with 2D Modeling Results

The CRSP-3D analysis of potential rock fall from the Phipps Park NE outcrop segment indicated that 2 of the 100 rocks released during the simulation reached the BNSF railway or railroad right of way at the bottom analysis partition shown in Figure 27. These results were confirmed by performing a 2D rigid body rock fall analysis using the statistical analysis software application RocFall 6.0 by geotechnical software developer Rocscience. Topographic profile graphs for the rock fall simulation were created from a 1 m (3.28 ft) raster DEM of the Phipps Park study area using ArcGIS Spatial Analyst and 3D Analyst, which was downsampled from the original DSM. For the 2D rock fall calibration simulation, the profile graph was drawn to align roughly with the largest outlying rock fall boulder from the 2016 event (A – A’ in Figure 31). The profile graph for the 2D rock fall analysis of potential rock fall from the Phipps Park NE source area (B – B’ in Figure 31) was drawn to approximate the trajectory of the furthest outlying rockfall from the CRSP-3D model presented in Section 9.1.3. As shown in Figure 31, both topographic profiles cross two or more of the analysis partitions used in the CRSP-3D analysis, allowing a direct comparison of rock fall parameters between the models. Topographic profiles were exported as X-Y coordinate data, which were pasted directly into RocFall 6.0 after manually correcting elevations for offset.
9.2.1. 2D Rock Fall Model Calibration

A rigid-body rock fall analysis was performed in RocFall 6.0 to calibrate the input parameters for the simulation based on the 2016 rock fall event. A point seeder was added to the upper corner of the 2016 failure surface to delineate the rock fall release area, and the rock type was defined as a rectangular block with a length to width (L x W) ratio of 1 x 0.7 and a mass of 434,100 pounds to approximate the size and shape of the 3,000 ft³ rectangular rock fall blocks.
specified in the CRSP-3D simulations. Slope material parameters in RocFall 6.0 include dynamic friction coefficient, rolling resistance coefficient, normal coefficient of restitution (Rn) and tangential coefficient of restitution (Rt), and slope roughness. The dynamic friction coefficient, which is the tangent of the friction angle at the rock/slope interface (tan\(\phi\)), is applied during impacts and when the rock is sliding. The rolling resistance coefficient, which accounts for loss of energy due to other rock/slope interactions, is applied when the rock is rolling. Each slope material is also assigned a normal coefficient of restitution (Rn) and a tangential coefficient of restitution (Rt). The normal coefficient of restitution, which is the same as Newton's coefficient of restitution in rigid-body mechanics, is a measure of the normal component of velocity lost during each rock fall impact with the slope surface, expressed as:

\[ Rn = -\frac{v_{fN}}{v_{iN}} \]

Where \(v_{fN}\) is the normal component of the velocity immediately after impact and \(v_{iN}\) is the normal component of velocity immediately before impact (Wyllie, 2014). The tangential coefficient of restitution (Rt) is a measure of the tangential component of velocity lost during each rock fall impact with the slope surface, expressed as:

\[ Rt = \frac{v_{fT}}{v_{iT}} \]

Where \(v_{fT}\) is the tangential component of the velocity immediately after impact and \(v_{iT}\) is the normal component of velocity immediately before impact (Wyllie, 2014). Empirically derived dynamic friction coefficient and rolling resistance coefficient parameters for rock and soil were used for all RocFall simulations (Chau, 1998).

Data collectors, which are analogous to the analysis partitions used in CRSP-3D, were placed at each location along the slope profile where the slope crossed an analysis partition. Just
as with the CRSP-3D simulation, the Rn and Tn parameters were calibrated by initially releasing 20 - 50 rectangular rock fall blocks from the 2016 failure surface and observing the rock fall runout during each simulation. Slope parameters were then adjusted for each subsequent simulation until the distribution of the simulated large rock fall runout closely approximated that of the 2016 event, and the number of rocks released from the seeder was increased to 100. The results of this simulation are shown in Figure 33, which depicts the slope topographic profile A-A’ and the trajectories of 100 simulated rockfalls.

Figure 32: RocFall 2D calibration simulation slope profile (A-A’). The shadow angle at the middle data collector is 26.2°.

The final talus slope material Rn and Tn parameters used for the calibration simulation and subsequent RocFall modeling were 0.37 and 0.87, respectively, which reflect the firmness of the rocky talus slope and the relative hardness of the large boulder rock fall at Phipps Park. The dynamic and rolling friction coefficients used were 0.6 and 0.5, respectively, which were
empirical values adapted from experimental results presented in (Chau et al., 1998). A slope roughness spacing of 3.28 ft and amplitude of 1.0 ft were also used to simulate the effects of rock debris on the talus slope. These parameters are summarized in Table XIX.

<table>
<thead>
<tr>
<th>Normal coefficient of restitution (Rn)</th>
<th>Tangential coefficient of restitution (Rt)</th>
<th>Dynamic Friction Coefficient</th>
<th>Rolling Friction Coefficient</th>
<th>Slope Roughness Spacing (ft)</th>
<th>Amplitude (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.37</td>
<td>0.87</td>
<td>0.6</td>
<td>0.5</td>
<td>3.28</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Rock fall data in RocFall 6.0 are not subjected to any statistical analysis at the conclusion of each simulation. In order to facilitate the comparison with the CRSP-3D simulations, which reports rock fall data as maximum values and cumulative probabilities, the statistical analysis software @RISK™ 8.0 (Palisade Inc.) was used to calculate cumulative probability based on the best fit distribution function for a given data set. This was performed using raw data values for total kinetic energy, translational velocity, and bounce height, which were exported in spreadsheet format at each data collector location. This cumulative probability data is presented in Table XX along with the maximum values recorded at each data collector. The locations of the data collectors, as well as the trajectories of individual rock fall along the A-A’ slope profile, are depicted in Figure 32. Bar graphs comparing the results of the CRSP-3D and RocFall 6.0 calibration simulation data are presented in Figure 33.

<table>
<thead>
<tr>
<th>Data Collector</th>
<th>Kinetic Energy (ft-kips)</th>
<th>Velocity (ft/s)</th>
<th>Bounce Height (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cumulative Probability (%)</td>
<td>Max</td>
<td>Cumulative Probability (%)</td>
</tr>
<tr>
<td>Upper (n=62)</td>
<td>5.083 9.090 13.601 22.577</td>
<td>25.3</td>
<td>34.1</td>
</tr>
<tr>
<td>Middle (n=6)</td>
<td>1.396 3.060 5.259 6.608</td>
<td>14.5</td>
<td>21.4</td>
</tr>
</tbody>
</table>
Figure 33: Bar chart comparison of RocFall 6.0 and CRSP-3D calibration simulation data at upper and middle analysis partition/data collector locations.
9.2.2. **Modeling Potential Future Rock Fall with RocFall 6.0**

The calibrated RocFall 6.0 model parameters were used to simulate potential future rock fall from the overhanging northeastern corner block at Phipps Park to facilitate comparison with the CRSP-3D modeling results presented in Section 9.1.3. A slope topographic profile (B-B’) was imported into RocFall based on the approximate maximum runout trajectory observed during the CRSP-3D simulations, and data collectors were assigned to locations on the slope corresponding to the analysis partitions used in the CRSP-3D simulations. 100 rocks were released from the point seeder at the crest of the Phipps Park NE outcrop segment during each simulation. Cumulative probability data and maximum values recorded at each data collector during the final 100 rock fall release simulation are presented in Table XXI. The locations of each data collector, as well as the trajectories of individual rock fall along the B-B’ slope profile, are shown in Figure 34.

<table>
<thead>
<tr>
<th>Data Collector</th>
<th>Kinetic Energy (ft-kips)</th>
<th>Velocity (ft/s)</th>
<th>Bounce Height (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cumulative Probability (%)</td>
<td>Max</td>
<td>Cumulative Probability (%)</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>75</td>
<td>90</td>
</tr>
<tr>
<td>Upper (n=81)</td>
<td>5,757</td>
<td>9,473</td>
<td>12,770</td>
</tr>
<tr>
<td>Middle (n=39)</td>
<td>7,267</td>
<td>11,413</td>
<td>15,093</td>
</tr>
<tr>
<td>Lower (n=18)</td>
<td>4,162</td>
<td>8,352</td>
<td>13,890</td>
</tr>
<tr>
<td>Bottom (n=2)*</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Insufficient data to generate distribution.
Figure 34: RocFall 2D Phipps Park NE potential rock fall simulation slope profile (B-B’). The shadow angle at the bottom data collector is 25.6°.
10. Summary of Findings

The methods of analysis employed during this investigation demonstrate how UAV photogrammetry can augment and enhance four critical aspects of quantitative rock fall hazard assessment. After summarizing the geologic conditions that contribute to rock fall hazards at Phipps Park and Zimmerman Trail Road (Section 2) and describing the geomechanical characteristics of Eagle Sandstone samples collected from the study area locations using new data obtained from laboratory testing (Section 3), I explain how nadir and oblique images of rock fall source areas and runout zones were acquired using a DJI Phantom 4 Pro UAV (Section 4) and how those images were processed into high-resolution 3D digital reconstructions of the study areas (Section 5). UAV photogrammetry data were used to map the orientation of discontinuities in rock fall source areas (Section 6), evaluate relative rock fall risk along Zimmerman Trail Road using the Rock Fall Hazard Rating System (Pierson, 1991) (Section 7), measure the volume, runout distance, and shadow angle (Evans and Hungr, 1993) of historic rock fall at Phipps Park (Section 8), and model past and potential future rock fall at Phipps Park (Section 9). Conclusions regarding the capabilities and limitations of UAV photogrammetry for each of these aspects of rock fall assessment are presented in Sections 10.1 - 10.5 alongside a summary of the results from the investigation and recommendations for future work.

10.1. Geomechanical Characteristics

Differential cementation in the Eagle Sandstone manifests as pronounced variability in intact rock strength. The dramatic reduction in strength observed when the sandstone is wetted coupled with the increase in total vertical stress associated with moisture retention supports anecdotal evidence of an association between rock fall events in the Rimrocks and heavy
seasonal precipitation. The four Eagle Sandstone rock samples tested during this investigation, which represent a small selective sample from the unique sandstone stratigraphy encountered at each of the respective study areas, ranged in strength from weak to indurated (McNally and McQueen, 2000).

- The Phipps Park sandstone rock specimens had a dry UCS of ranging from 3,933 psi (n=1) to 8,562 (n=1) with an associated tensile strength of 261 psi (n = 5) and 533 psi (n = 5), respectively.

- The Zimmerman Trail Road specimens had a dry UCS ranging from 2,183 psi (n = 2) to 8,971 psi (n = 2) with an associated tensile strength of 152 psi (n = 5) and 431 psi (n = 5), respectively.

- The bulk unit weight of weak sandstone was approximately 124 lb/ft³, while the bulk unit weight of strong to indurated sandstone ranged from 145 - 152 lb/ft³.

A comparison of the UCS of dry and wet sandstone samples from Phipps Park and Zimmerman Trail Road shows a reduction in the UCS of the weak sandstone at each location by approximately 40% when wet and a reduction in the strength of the strong to indurated sandstone at each location by approximately 30% when wet. The weak sandstone from both locations also absorbed significantly more water during the 24-hour soaking period prior to UCS testing. At the completion of the test, the moisture content of the weak sandstone ranged from 7.5 - 9%, which was 2 - 4 times greater than that of the strong to indurated sandstone.
10.2. Remote Discontinuity Mapping

Despite the relatively rudimentary methods employed to scale and orient the UAV photogrammetric data used in this investigation, point clouds were successfully used to accurately measure the orientation of discontinuities in active rock fall source areas. A significantly greater number of measurements were obtained remotely than could be acquired in the field, as the remote data set included measurements at locations that were inaccessible by foot due to steep slopes and/or traffic hazards.

The potential for fracture networks caused by tectonic uplift and other large-scale geologic processes to occur in the Rimrocks is pertinent given the complex tectonic history of the region and should be considered when evaluating discontinuities at the local scale. However, the orientation of recurring joint sets in the study areas largely appears to reflect the contemporary in-situ stress conditions, which are defined by the accumulation of tensile stress in the cliff face due to undercutting erosion and debuttressing. Structurally controlled instabilities in the study areas may be identified by the presence of two intersecting high-angle master joints oriented roughly parallel and perpendicular or sub-perpendicular to the rock slope face, which was sometimes concordant with bedding strike. Many these of these joints appear to intersect with low-angle bedding plane discontinuities to form rectangular or wedge-shaped blocks in the cliff face, whose size varies with joint spacing and persistence.

Remote point cloud measurements of the orientation of discontinuities at and around the overhanging northeastern Phipps Park outcrop segment (n = 18) compared favorably with measurements made in the field (n = 7), varying on average less than ± 3° with respect to strike and ± 4° with respect to dip. Remote point cloud measurements were used at this location to obtain the mean orientation of the bedding (291°, 10°) and the mean orientation of tensile joints
parallel (and perpendicular to the cliff face $249^\circ$, $82^\circ$ and $153^\circ$, $86^\circ$, respectively). The orientation of Eagle Sandstone bedding was also measured remotely across the entire Phipps Park and Zimmerman Trail Road study areas; the mean bedding strike and dip is $308^\circ$, $05^\circ$ ($n = 37$) at Phipps Park and $296^\circ$, $02^\circ$ ($n = 57$) at Zimmerman Trail Road.

Although the frequent recurrence of intersecting joint sets in the rock mass suggests that there may be a structural component to at least some of the large block failures in the Rimrocks, most of the large structural instabilities observed in the study areas could not be effectively evaluated using kinematic stability analysis methods due to undercutting erosion, which removes support from the base of joint-bounded blocks and allows them to hinge away from the cliff face during toppling failures. Further analysis and long-term monitoring of structurally controlled instabilities, which may be accomplished remotely with change detection analysis from repeat UAV photogrammetry or LiDAR surveys or in the field with the implementation of a strain monitoring, is recommended wherever potential rock fall could threaten public safety or infrastructure.

10.3. Zimmerman Trail Road

Merged nadir and oblique UAV photogrammetry was used to perform a detailed Rock Fall Hazard Rating (Pierson and Van Vickle, 1993) at Zimmerman Trail Road, the site of a significant rock slope mitigation project that was completed in 2014. Each of the 12 rating categories were evaluated and scored remotely using the high-resolution 3D photogrammetric reconstruction and associated data products. Most significantly, components of the RHRS that have traditionally required exposure to traffic hazards, such measuring the minimum visible sight distance at points of curvature on the road using a measuring wheel, were completed remotely.
Spatial measurement tools in Pix4D also made the application of rating criteria related to block size, slope height, and roadway width highly consistent and replicable, and the ability to quickly navigate in the immersive 3D mesh environment allowed features of geologic interest, such as tension cracks and erosional features, to be evaluated from multiple viewing perspectives.

Using merged oblique and nadir UAV photogrammetry to perform detailed RHRS rating remotely is a new application of the technology, and any attempt to implement this method of remote assessment for rock slope asset management should first be thoroughly validated with field measurements in a controlled experimental setting. However, with further validation remote RHRS rating using merged nadir and oblique UAV photogrammetry may prove to be a cost-effective alternative to field-based assessment, particularly for transportation agencies that have already developed UAV photogrammetry programs for other mappings and surveying applications. UAV photogrammetry also offers the added benefit of allowing site conditions to be compared over time, which could increase the accuracy with which time-dependent rating criteria (such as estimating erosion rates and rock fall frequency) are applied.

It should also be noted that while the continued use of the RHRS and variations thereof speaks to the durability and effectiveness of the system, it is not without detractors. Some critics contest that by weighting all parameters equally, the system underestimates the importance of geologic conditions on slope stability (Swanger and Admassu, 2018). Others have noted that the system fails to show significant changes in risk when repeat surveys are conducted after rock fall mitigation measures have been implemented, as large changes in a single rating category often have only a minor effect on the overall RHRS score (Strouth et al., 2016).

While it was not possible to compare the results of the remote RHRS rating at Zimmerman Trail Road to any prior ratings which may have been performed, the exponential
rating system effectively drew attention to two regions within the study area, identified as Zone 1 and Zone 3 in Section 7.2, where the difference in erosion rates and presence of major erosional features resulted in a high RHRS score. Both locations have experienced rock fall in the past and were evaluated in detail prior to the 2014 stabilization project (Terracon Consultants Inc., 2014). Despite the apparent success of these mitigation measures, continued observation and long-term monitoring of the slope conditions at Zimmerman Trail Road are recommended due to the unavoidable progression of differential erosion at the site and likely recurrence of instability in the future.

10.4. Phipps Park

Predicting exactly when and where rock fall will occur is inherently difficult, and conventional wisdom suggests that hazard avoidance is more effective at reducing the risk associated with geological hazards than widespread monitoring and engineered mitigation (Cruden and Varnes, 1996). Quantitative methods for determining appropriate setbacks in sub-regional rock fall hazard areas, such as the “shadow angle” approach first presented in Evans and Hungr (1989) and used by the USGS to map rock fall hazard areas in the Yosemite Valley (Stock et al., 2012a), provide more consistent, reproducible, and defensible results than could be obtained by relying solely on geomorphic evidence of past rock fall to delineate hazard areas. UAV photogrammetry allows this type of quantitative approach to be implemented in areas lacking high-resolution aerial LiDAR coverage or other comparable spatial data set.

UAV photogrammetric data were used in this investigation to calculate the volume of 32 large outlying rock fall boulders at Phipps Park and to measure the distance traveled and resulting change in elevation of these large high energy rock fall blocks along their trajectory.
The maximum runout distance of the large outlying rock fall at Phipps Park is 427 ft, while the 90th percentile runout distance is 397.7 ft. The minimum rock fall shadow angle at Phipps Park, which was calculated from UAV photogrammetric data, is 20.9°. The 90th percentile rock fall shadow angle is 21.9°, and the average rock fall shadow angle is 24.2°. The average size of outlying rock fall boulders is 1,433 ft³, the 90th percentile is 2,877 ft³, and the largest boulder measured was 6,326 ft³ ± 64.4 ft³. The average measurement error for these volume calculations was ± 29.4 ft³.

Where structures or infrastructure are identified within the zone of potential rock fall, numerical rock fall modeling can be employed to assess the probability and potential consequences of rock fall impacts. This information may be used to implement an appropriate risk management strategy based on the risk tolerance of the land user. UAV photogrammetric elevation data were used to construct the 2D and 3D slope geometries needed for numerical rock fall modeling during this investigation. The 3D discrete element method rock fall modeling software CRSP-3D was employed to simulate a potential rock fall release from the large overhanging block at the northeast corner of Phipps Park. Two out of the one-hundred 3,000 ft³ rectangular block falls simulated at the location reached the BNSF railroad and/or right of way, which is at a shadow angle of approximately 26.2°. This analysis was repeated using the 2D dynamic rock fall modeling software RocFall 6.0 (Rocscience Inc.), in which three out of the one-hundred simulated block falls reached the BNSF right of way. Upon reaching the right of way, the simulated large boulder rock fall was traveling at a velocity of 13 ft/s (CRSP-3D) to 13.8 ft/s (RocFall 6.0) and still carried considerable kinetic energy (up to 916 ft-kips in CRSP-3D and 1,497 ft-kips in RocFall 6.0). The maximum bounce heights observed in the right of way were 7.6 ft (RocFall 6.0) and 9.0 ft (CRSP-3D).
The longitudinal distribution of simulated rock fall along the respective 2D and 3D slope profiles, as well its kinetic energy, translational velocity, and bounce height of individual rock fall, were observed to differ between the two modeling software applications used in this investigation. However, the differences between these software applications, including (but not limited to) different user-defined slope material parameters and data outputs, made it impossible to isolate analytical differences from estimates in parameterization. An ideal comparison would include field trials with controlled rock falls to measure the ability of the respective applications to replicate real-world rock fall dynamics and the corresponding parameters required to achieve representative results (Wyllie, 2014).

10.5. Limitations

The research performed during this investigation was undertaken in good faith as an academic exercise to explore how UAV photogrammetry may be applied to evaluate rock fall. Geologic conditions can change both spatially and temporally, and the methods, results, and conclusions presented here should not be construed as definitive or comprehensive. Recommendations presented here for reducing geologic risk may be used to guide future research but should not be misconstrued as an endorsement for their application to any specific geologic hazard or condition, including those described in this investigation.

No LiDAR or topographic survey data were available at the study areas to validate the accuracy of elevation data products derived from the scaled and oriented photogrammetry. The accuracy of elevation measurements of the ground surface using UAV photogrammetry data decreases with increased vegetative cover, and ground surface measurements are wholly unreliable in wherever trees, shrubs, or dense groundcover completely obscures the ground.
surface. The accuracy of the methods used in this investigation could be evaluated by replicating on one or more of the analyses with the addition of surveyed ground control points and quality aerial or terrestrial LiDAR coverage in the area of interest.

The inability to filter vegetation in digital surface models, which undoubtedly affected surface elevations in the resulting DEMs, is also a potential source of error in the numerical modeling, as was relying on post-2016 rock fall topography to calibrate the model parameters to the 2016 failure conditions. While the extensive downsampling required to generate elevation data for CRSP-3D may have reduced some of these effects, the loss of resolution resulting from this downsampling should itself be regarded limitation, albeit one related to the software. Due to the limited resolution, outdated system requirements, and overall poor technical performance of CRSP-3D, which has not been updated since its release in 2012, future researchers seeking to replicate this analysis may wish to consider investing in one of the several commercial 3D rock fall modeling software products currently available.

10.6. The Future of UAV Photogrammetry in the Geosciences

Even as the use of UAV photogrammetry in the geosciences appears to be increasing, engineering geologists have only just begun to explore the full potential of the technology, and there are real and perceived barriers to more widespread implementation. Despite burgeoning demand for experienced UAV pilots in the private sector, UAV photogrammetry has not been widely integrated into undergraduate geoscience curricula, and in most universities the use of UAVs is limited to graduate research and development (Al-tahir, 2015). Even at the graduate level, UAV-related research programs are more likely to be found in mechanical engineering, aerospace engineering, or robotics departments, where the emphasis is often on building UAVs
rather than using them for spatial data acquisition (Al-tahir, 2015; Fombuena, 2017). While there are many certificate programs, short courses, and workshops available for individuals seeking to develop their UAV photogrammetry skill set, a cursory online search of these options suggests that there are few educational alternatives that serve the specific needs of engineering geology professionals. Finally, the evolving regulatory environment concerning the commercial use of UAVs, which culminated in the introduction of certification requirements for remote pilots in 2016 under 14 Code of Federal Regulation (CFR) Part 107, may have the unintended consequence of deterring academic research and further entrenching the division of labor between specialists who provide UAV photogrammetry services and those that perform the post-processing analysis of discretized, formatted data products.

It is imperative that the geoscience community remains involved with UAV photogrammetry education and research to ensure that geoscience graduates emerge with an understanding of the capabilities and limitation of the technology for geological investigations and are prepared to take advantage of the technology upon entering the workforce. Active participation in the development of UAV photogrammetry platforms and related software technology will also encourage the industry to grow in directions that can further the image acquisition and post-processing objectives of geoscientists. Significant recent developments in flight planning software applications, confined space inspection UAV platforms, and image capture technology have already expanded the role of UAVs in geological engineering, and innovations in machine learning and autonomous flight promise to further revolutionize the technology in the years to come. Incorporating new and emerging UAV photogrammetry technology into the geoscience curriculum today will ensure that geoscientists are equipped to
apply the technology of tomorrow to the evaluation of complex geologic conditions and natural hazards.
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## 12. Appendix A: Phipps Park Rock Fall Inventory

### Table XXII: Phipps Park Large Outlying Rock Fall (Pre-2016 Event)

<table>
<thead>
<tr>
<th>Rock Fall ID</th>
<th>Volume (ft³)</th>
<th>Measurement Accuracy (± ft³)</th>
<th>Weight (lb) @ 144.7 lb/ft³</th>
<th>Δ Horizontal (talus slope apex to rock fall) (ft)</th>
<th>Δ Vertical (talus slope apex to rock fall) (ft)</th>
<th>Shadow Angle (°)</th>
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<td>Rock Fall ID</td>
<td>Volume (ft³)</td>
<td>Measurement Accuracy (± ft³)</td>
<td>Weight (lb) @ 144.7 lb/ft³</td>
<td>∆ Horizontal (talus slope apex to rock fall) (ft)</td>
<td>∆ Vertical (talus slope apex to rock fall) (ft)</td>
<td>Shadow Angle (°)</td>
</tr>
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Note: Rock fall ID #'s 3, 9, 21, and 36 – 40 excluded from data set due to vegetative cover and/or insufficient relief at base surface.

Table XXIII: Phipps Park Large Outlying Rock Fall (2016 Rock Fall Event)

<table>
<thead>
<tr>
<th>Rock Fall ID</th>
<th>Volume (ft³)</th>
<th>Measurement Accuracy (± ft³)</th>
<th>Weight (lb) @ 144.7 lb/ft³</th>
<th>∆ Horizontal (talus slope apex to rock fall) (ft)</th>
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SIGNATURE PAGE

This is to certify that the thesis prepared by Micah Gregory-Lederer entitled “Nadir and Oblique UAV Photogrammetry Techniques for Quantitative Rock Fall Evaluation in the Rimrocks of South-Central Montana” has been examined and approved for acceptance by the Department of Geological Engineering, Montana Technological University, on this 24th day of April, 2020.

Larry N. Smith, PhD, Professor and Department Head
Department of Geological Engineering, Montana Tech
Chair, Examination Committee

Mary MacLaughlin, PhD, Professor
Department of Geological Engineering, Montana Tech
Member, Examination Committee

Phillip Curtiss, PhD, Assistant Professor
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