Bulletin 55

The West Salt Creek Landslide: A Catastrophic Rockslide and Rock/Debris Avalanche in Mesa County, Colorado

By Jonathan L. White, Matthew L. Morgan, and Karen A. Berry

Colorado Geological Survey
COLORADO SCHOOL OF MINES

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This report is dedicated to the memory of the three men that perished in the landslide:
Wes Hawkins, Clancy Nichols, and Danny Nichols.

Cover Photo: Oblique aerial image of the May 25th, 2014 West Salt Creek landslide near Collbran, Colorado. The l andslide complex, which includes rock slide, rock avalanche, and debris-flow components, traveled approximately 3 miles down the West Salt Creek valley. The landslide covers almost one square mile. Aerial view is looking south toward the Grand Mesa. Image was taken on May 26th, 2014.

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Field mapping and geologic characterization by Jon White and Matt Morgan of the Colorado Geological Survey (CGS), with collaborative observations by Karen Berry (CGS). Geologists and hydrologists involved in emergency response activities in the two week period immediately after the landslide were Jon White and Karen Berry; Jeff Coe, Jason Kean, and David Brown with the U.S. Geological Survey (USGS), and Ben Stratton with the U.S. Forest Service (USFS). Jeff Coe, Rex Baum, and Matt Morgan completed detailed field mapping for the U.S. Geological Survey (USGS) and provided key observations and discussions. Rex Cole and Verner Johnson of Colorado Mesa University also conducted field reconnaissance of the landslide and provided information on the bedrock units. Tim Hayashi of the Mesa County Public Works Engineering section managed overall site coordination. He and Frank Kochevar also provided and installed instrumentation, as did Ben Stratton, Jeff Coe, and David Brown. The USFS provided and installed web-based camera stations. Immediate post-landslide UAV imagery was provided by Mesa County Sheriff's Office courtesy of Ben Miller. Frank Kochevar provided additional UAV imagery in the summer of 2014. The CGS acquired high-resolution LiDAR (Light Detection and Ranging) elevation data. Doug Bausch at FEMA supplied a pre-slide 4-m-resolution IfSAR (Interferometric Synthetic Aperature Radar) DEM. Other imagery was made available from Mesa County Public Works and GIS/IT departments. Seismograms are from the Colorado Mesa University Seismic Network, courtesy of David Wolny. Mesa County, USGS, and Colorado School of Mines (CSM) also shared other data sets. Kevin McCoy and Dr. Paul Santi, CSM Department of Geology and Geological Engineering, conducted a stability analysis of the landslide Upper Block. Deputies Jim Fogg and Terry Bridge wrote Mesa County Sheriff's emergency response/eyewitness reports. The West Salt Creek Emergency Action Plan was written by Andy Martsolf, Mesa County Emergency Manager. This paper greatly benefited from reviews by Rex Baum and Jeff Coe (USGS).

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INTRODUCTION

On May 25th, 2014 the longest landslide in Colorado's historical record occurred in west-central Colorado, 6 mi (10 km) southeast of the small town of Collbran in Mesa County. Three local men perished during the catastrophic event and subsequent recovery efforts failed to locate their remains or vehicles. The toe of the landslide came within 200 ft (61 m) of active gas-production wellheads. Loss of irrigation ditches and water impacted local ranches and residents. Continuing threats to nearby residents remain.

The landslide complex is referred to as the West Salt Creek landslide (WSCL) by local authorities (see frontpiece photo). The fast-moving, high-mobility landslide was caused by an initial rotational slide of a half-mile-wide block of Eocene Green River Formation. The resultant rock failures, rockmass disaggregation, and mostly valley-constrained rock avalanche, dropped approximately 2,100 ft (640 m) in elevation while extending 2.8 mi (4.5 km) from head scarp to toe, 2.2 mi (3.5 km) as a rapid series of cascading rock avalanche surges of chaotic rubble composed of fragmented to pulverized rock, vegetation, topsoil, and lesser amounts of colluvium and mud. Local seismometers recorded a magnitude 2.8 earthquake from the event with a seismic wave train duration of slightly less than 3 minutes. Within minutes, the WSCL covered almost a square mile of the West Salt Creek valley and the net volume displacement, calculated by digital elevation model (DEM) difference modeling, was 38 million yd^3 (29 million m^3). Though its very high mobility and surface morphology normally indicate a flow-like mechanism, the rock avalanche deposits were surprisingly dry with no visible mud or water seeps when examined 24 hours after the event.

Calculated thicknesses of the rock avalanche deposits were as high as 123 ft (~38 m) at the valley floor. Although precise pre-event conditions are largely unknown, geomorphic analyses of aerial photography, digital terrain models, and review of earlier landslide hazard mapping (Soule, 1988) indicate the WSCL occurred at the same location of a similar prehistoric landslide from the recent geologic past (Holocene, <11,700 years BP). Much of the surrounding area shows evidence of previous landslides. The failure was likely triggered by spring snowmelt in conjunction with two days of rainfall that infiltrated rock joints, fractures, and shear surfaces, increasing the pore pressure in the already disturbed and weakened marlstone and shale rock.

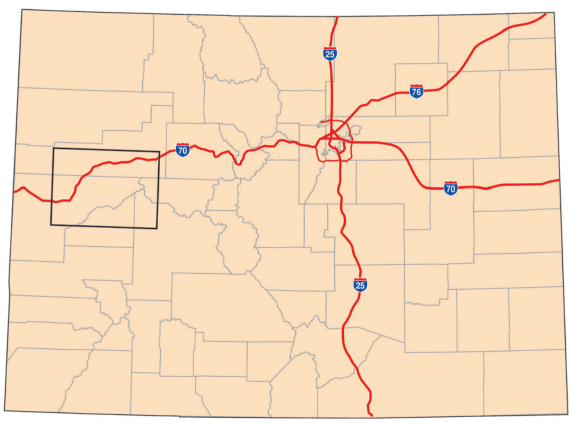
Currently, part of the prehistoric landslide block still looms above the valley floor. The oversteepened block remnant, with an estimated net volume of 65 million yd^3 (50 million m^3), is back rotated approximately 15°, forming a large depression at the base of the headscarp. Runoff from an extensive tributary area now flows into the depression, creating a sag pond that a year later (June 2015) reached almost the spill-over elevation. Water from the pond is also continuously percolating into the landslide mass. Many ponds formed in the rock avalanche debris field and a stream from these ponds began to flow from the landslide toe in early 2015. The increased pore pressure from this infiltration poses long-term threats for additional slope instability, and mud/debris flows caused by catastrophic release of the impounded water (similar to a dam embankment failure). In May 2015, as the pond was rising, a natural outflow pipe formed at the base of the landslide block that is flowing significant amounts of water.

Geologists from the CGS and USGS conducted a landslide investigation, including field mapping. The landslide and surrounding area is being actively monitored for additional movement and changes in surface water levels by Mesa County and the USGS. The purpose of this report is to describe the geologic setting, the ground conditions that existed prior to the WSCL event, the mechanisms of the landslide failure, descriptions of potential future hazards, and guidelines for future land use in the vicinity.

REGIONAL SETTING

The landslide lies in west-central Colorado within the west-fork valley of Salt Creek, which is a tributary stream within the greater Plateau Creek basin between Battlement Mesa to the north and the northern flank of Grand Mesa to the south. The closest town, Collbran (pop. 708, 2010 census) is 6 mi (10 km) downstream on Plateau Creek. County Road 330 and State Highway 65 follow Plateau Creek to its confluence with the Colorado River in DeBeque Canyon where State Highway 65 links with Interstate 70 (**see Figure 1**).

The bedrock in the upper Plateau Creek basin area is early Cenozoic in age. The units dip very gently and thicken to the north into the Piceance Basin, a syntectonic Laramide structural basin and an important oil and gas producer with one of the largest reserves of oil shale in the world. The Paleocene to Eocene Wasatch and Green River Formations underlie most of the Plateau Creek basin terrain. Above the Green River Formation at the rim of Grand Mesa are strata of the Uinta Formation, which is overlain by the Goodenough formation (informal name) of probable Miocene age (Cole and others, 2013). A geologic map, cross section, and list of map units adjacent to the WSCL are shown in **Map Plates 1 and 2**. The mudstones and sandstones of the Wasatch Formation occupy the Plateau River valley floor. The shales, marlstones, and minor oil shales of the Green River Formation and shale and sandstone beds of Uinta Formation at the top, form



Map area within Colorado (inset)

Figure 1. West Salt Creek Landslide (WSCL) map area shown in eastern Mesa County.

the upper 2000 ft (610 m) of slope and a low escarpment on the north flank of Grand Mesa where the landslide headscarp is located. Grand Mesa is a nearly flat-lying mesa that covers roughly 600 mi^2 (1,550 km^2) and is approximately 10,500 ft (3,200 m) above sea level. Directly upslope (southward) from this lower escarpment is the wide alpine plateau of Grand Mesa. Above the landslide area, at an elevation of about 10,000 ft (3,050 m), the plateau is locally named Sheep Flats on the 1:24,000-scale topographic map. The plateau and edge of the escarpment is underlain by the Goodenough formation. The topography of this plateau is hummocky and pockmarked with many sag ponds and lakes that reflect localized ground disturbances related to Pleistocene glacial morphology and till deposition, ground movements within the Goodenough formation, and colluvial sediment deposition. Further to the south and southwest, Grand Mesa is capped by 10-million-year-old basalt flows. The high point of the mesa is 6 mi (10 m) due south of the WSCL, at Leon Peak, where the elevation is 11,236 ft (3,425 m).

The climate of the area is considered semi-arid but varies considerably with elevation. The average high and low temperatures for the month of May in Collbran are 70° and 40° F (21° to 4° C), respectively, and the average monthly precipitation for May is 1.6 in (4.1 cm) (Western Regional Climate Center, 2014). Vegetation types within the West Salt Creek drainage basin include Gambel oak, spruce, and subalpine fir and aspen forests. Average annual precipitation at the valley floor at Collbran is only 15 in (38 cm). To the south on the mesa above the headscarp of the landslide, some 2,500 ft (762 m) higher in elevation, there is annual winter snowpack and the yearly precipitation average is over 30 in (76 cm). The landslide is on the south side of the greater Plateau Creek valley. The north-facing slopes in this area retain higher moisture and are more heavily vegetated compared to south-facing slopes on the opposite side of Plateau Creek valley.

EVIDENCE OF PAST LANDSLIDE ACTIVITY

Landslides have been mapped in this area by previous investigators and as part of this study (see geologic map of WSCL vicinity in Plate 1). Colton and others (1975) mapped landslides at a scale of 1:250,000 over the entire Sheep Flats plateau region (discussed previous chapter) and small portions of the lower escarpment where the WSCL headscarp is located. Ellis and Freeman (1984) described the colluvium (Qc) covering the plateau above as being formed by landslides, slumps, earthflow, mudflow, soil creep, and solifluction. Soule (1988), in his regional 1:24,000-scale landslide study of the Vega Reservoir area, mapped three landslides within the WSCL extent. For our study, an evaluation of pre-landslide topography and stereo aerial photography revealed an amphitheater at the head of the West Salt Creek valley below the plateau rim escarpment.

This "bowl" was the location of earlier significant, post-glacial landslide(s) (**Figure 2**) that will be referred to as the prehistoric landslide in subsequent discussions. Many subparallel intermediary scarps and ground-sag depressions above the amphitheater rim, shown in the Plate 1 geologic map, also indicate the potential for future retrogressive failures. The topographic bench shown in Figure 2b was formed from the prehistoric landslide and was the location of the landowner's down-valley hunting camp. The fatal May 25th event occurred at the same location of these earlier ground movements. Subsequent discussion will illustrate that the WSCL upper block failure surface approximated the prehistoric failure surface (**Figures 3a and 3b**). Recent shallow failures were also identified along the east flank of the prehistoric scarp. Post-event interviews with landowners revealed that this historic landslide occurred in 1984 when a cattle trail was lost.

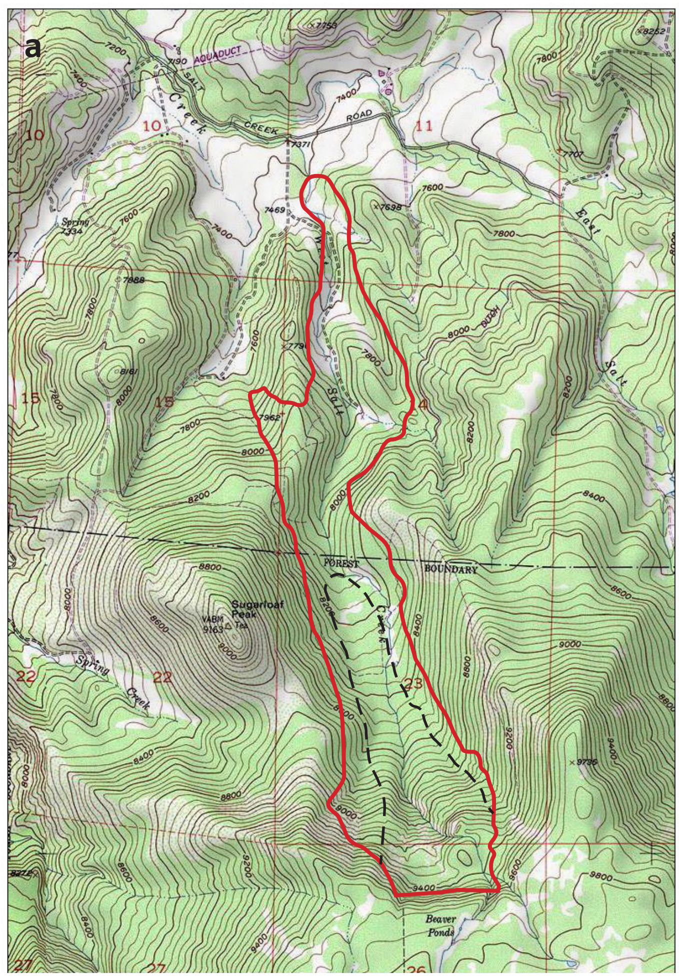


Figure 2. Outline of the WSCL is shown by solid red line. Section grid lines on USGS 1:24,000-scale topographic map are 1-mile square. Approximate boundary of pre-historic landslide is shown by black dashed line.

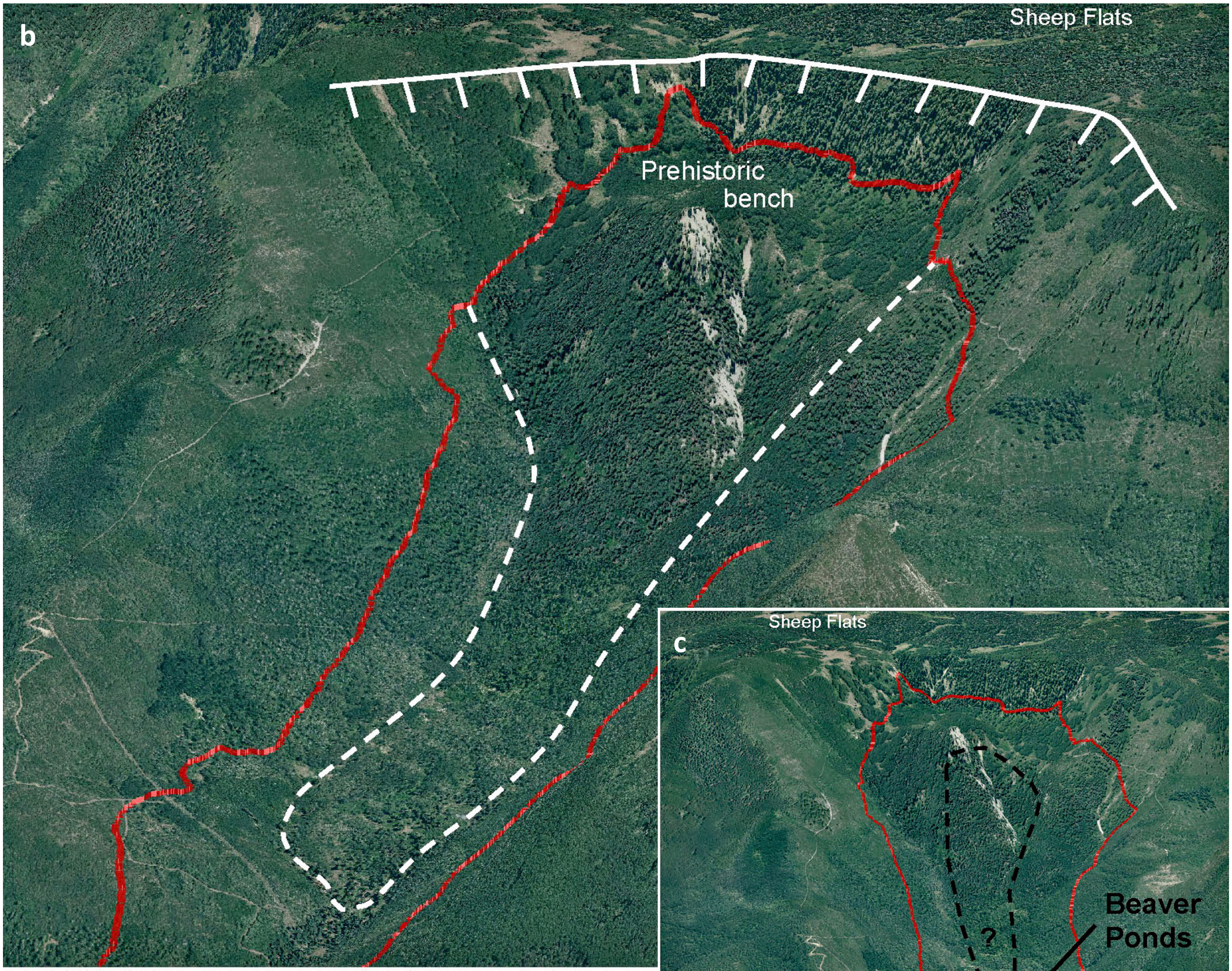


Figure 2(b). Approximate location of a prehistoric (Holocene) landslide (white dashed lines) and an ancient scarp (hachured solid white line) superimposed on a 2012 aerial photograph.

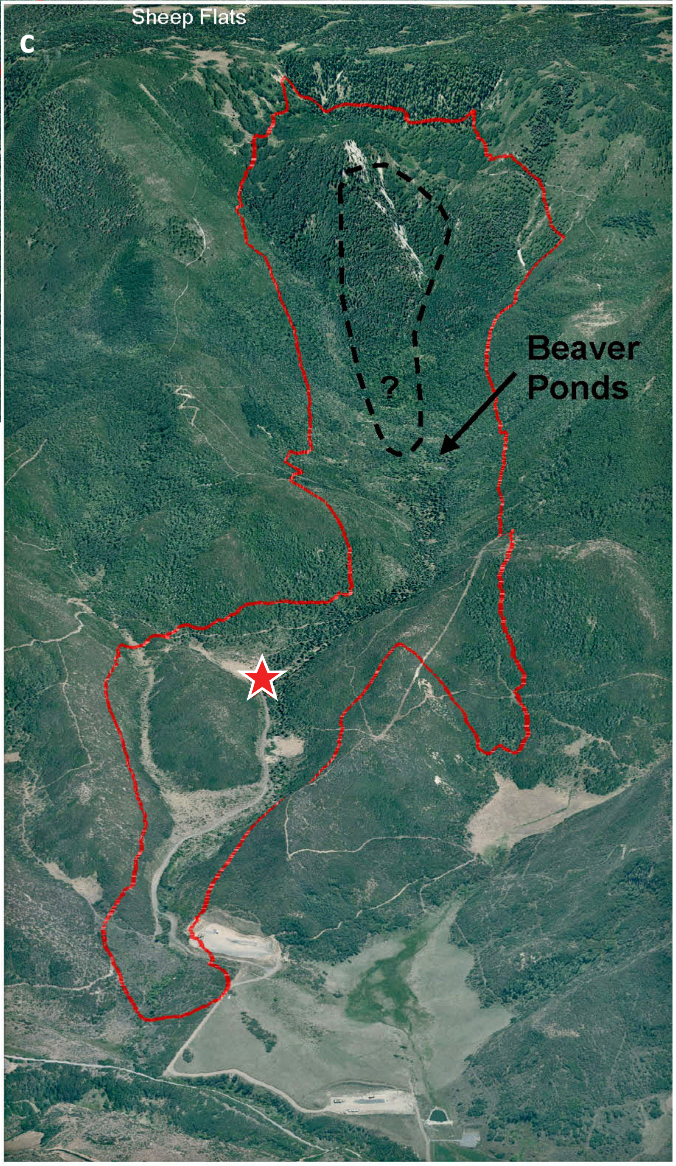
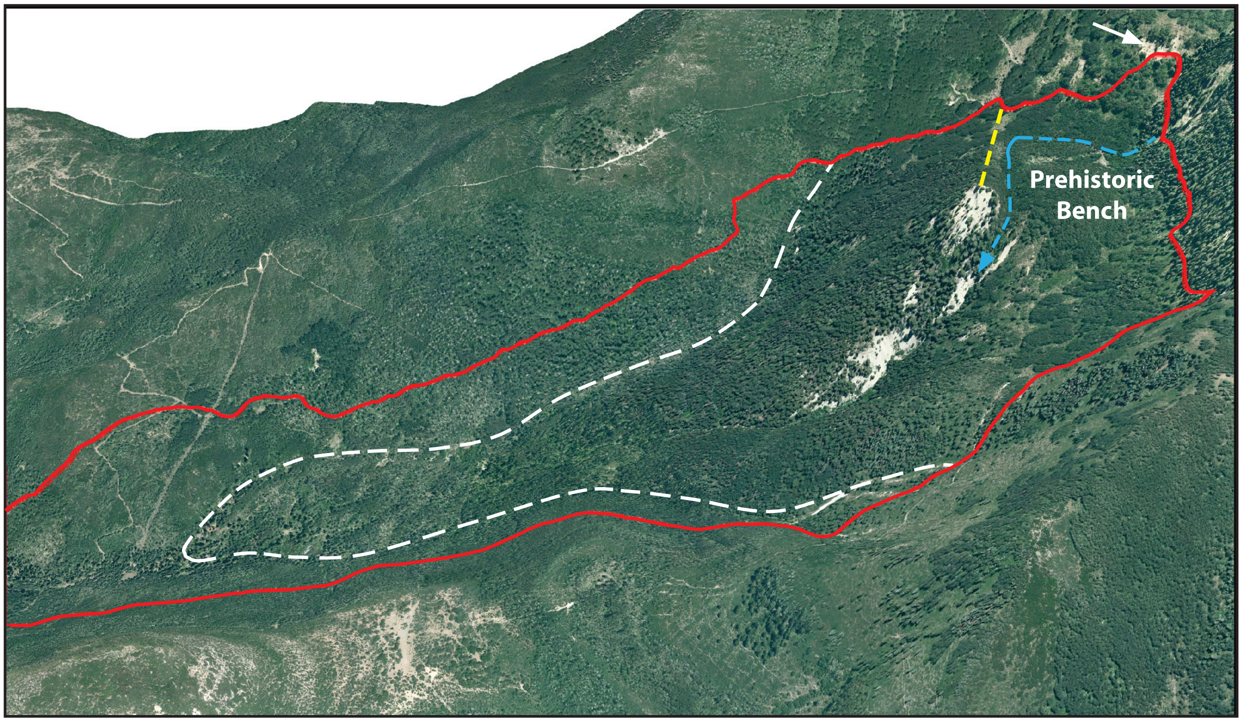


Figure 2(c). South-facing view of the WSCL with the approximate location of May 25th precursor landslides (black dashed line) that extended to the beaver ponds. The approximate extent of the precursor landslides were outlined by an eyewitness who saw them on morning of May 25th. Pre-event terrain models were created with ArcScene 10.2 using 2012, 9-in resolution color aerial photography from Mesa County GIS Department draped on a FEMA 4-m DEM. Red star is the assumed location of the missing pick-up truck at the end of the ranch road.



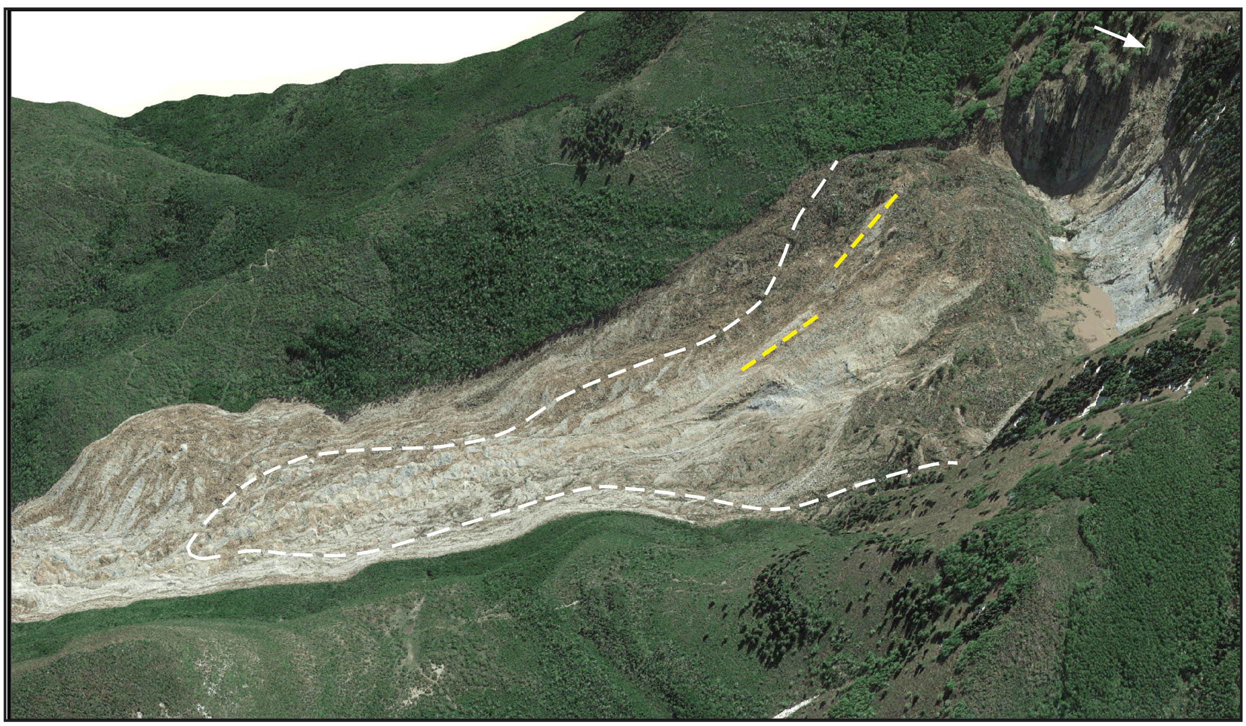


Figure 3. Pre- (top) and post-WSCL (bottom) images created from draping high resolution aerial photography onto DEMs. Top uses 2009 NAIP image and FEMA 4-m DEM as elevation base. Red line shows the WSCL extent. Dashed white line delineates runout of prehistoric landslide. Yellow dashed line shows prominent intermediate scarp block that has controlled the paleochannel of West Salt Creek (dashed blue line) that doglegs against it to follow a prominent shear zone on the paleo-bench before cascading down an earlier escarpment. Bottom image uses 1-m DEM from CGS LiDAR data and early post-WSCL aerial photo from Google Earth™ where the sag pond (showing as muddy water) was small and still filling. Prehistoric landslide is shown by dashed white line. Yellow dashed lines mark steep scars in block face that were likely avalanche detachment zones. White arrows show location of small 1984 landslide on both images.

LANDSLIDE MODES OF FAILURE

Data Used in Analysis

Geologists from the CGS and the USGS mapped the landslide in the summer and fall of 2014. The timeline and flow mechanisms of the landslide provided here are based on:

- Seismic records of the event;
- Eyewitness accounts;
- Comparing pre- and post-landslide surface elevations with high-resolution DEMs and stereo aerial photography;
- Evaluation of cross-cutting relationships of individual cascading surges preserved in the landslide morphology and the material characteristics of the landslide deposits;
- LiDAR elevation dataset of the landslide, acquired on June 1-3, 2014, and a 1-m DEM created from the dataset;
- IfSAR DEM (4 m) of the terrain prior to the landslide;
- High-resolution orthorectified and georeferenced aerial photography

According to provisional SNOTEL data, the spring 2014 snowpack was near to slightly above average on Grand Mesa (NRCS, 2014). However, residents reported significant rainfall prior to the landslide event. Coe and others (2014) reported the WSCL occurred 3.25 hours after a 30-minute rainfall event with an intensity of 21 mm/h (3/4 in/h). National Oceanic and Atmospheric Administration (NOAA) provisional data indicates that precipitation for the period of May 12th to June 10th was almost 200% of average (NOAA, 2014). This departure from average was in part due to a wet snowstorm the area experienced May 10-11, two weeks before the landslide occurred. Local residents reported over a foot of heavy wet snow fell on the plateau above the landslide scarp.

Timeline

The timing of the landslide activity on May 25th, 2014 is best constrained by two seismic events that were recorded on local seismometers. The first and smaller event occurred at 7:18 AM on May 25th and registered as a small seismic disturbance on the North Fork Valley Network (D. Wolny, Colorado Mesa University, written communication, 2014). The seismometer is located 20 mi southeast of the landslide. This seismograph may have recorded an initial precursor landslide that was noted by local ranch owner Melvin “Slug” Hawkins. Early that morning, he observed landslide activity at the prehistoric landslide on the east side of the head of West Salt Creek. Mr. Hawkins recalled that a second smaller precursor landslide also occurred on the west side of the creek later that morning. The approximate sizes of these morning precursor landslides are shown in Figure 2c. The traces are based on Mr. Hawkins’ recollections while examining oblique 3-D block diagrams with draped aerial photos of the terrain taken before May 25th, 2014.

Following these precursor landslides, water in irrigation ditches originating from West Salt Creek stopped flowing. Mr. Hawkins stated that he went up the valley and heard trees snapping and toppling, possibly as a result of a mud/debris flow occurring high on the valley floor in the area of the “beaver ponds” (Figure 2c). In the afternoon, Wes Hawkins, Clancy Nichols, and Danny Nichols drove up the West Salt Creek Road to assess damages to the irrigation diversion structure and whether there was a landslide risk to Salt Creek Road (CR 60 ½ Rd.). The assumed last location of their pick-up truck is shown in Figure 2c where the West Salt Creek ranch road ends.

On May 25th at 5:45 PM, a magnitude 2.8 earthquake was recorded approximately 8 mi southeast of Collbran (D. Wolny, Colorado Mesa University, written communication, 2014) with a duration of approximately 3 minutes (**Figure 4**). The overall appearance of the wave form was indicative of a surface event created by landslide-related movement in the West Salt Creek area (USGS, 2014).

The catastrophic failures of the prehistoric landslide block at the valley head manifested itself as a rock avalanche that buried the three men with over 123 ft (~38 m) of landslide debris. The rock avalanche “flowed” down the valley and the valley-constrained toe encroached upon an Occidental Petroleum Corporation well pad where three producing wells are located (**Figure 5**). The shut off valves at the wellheads were not impacted but there was slight

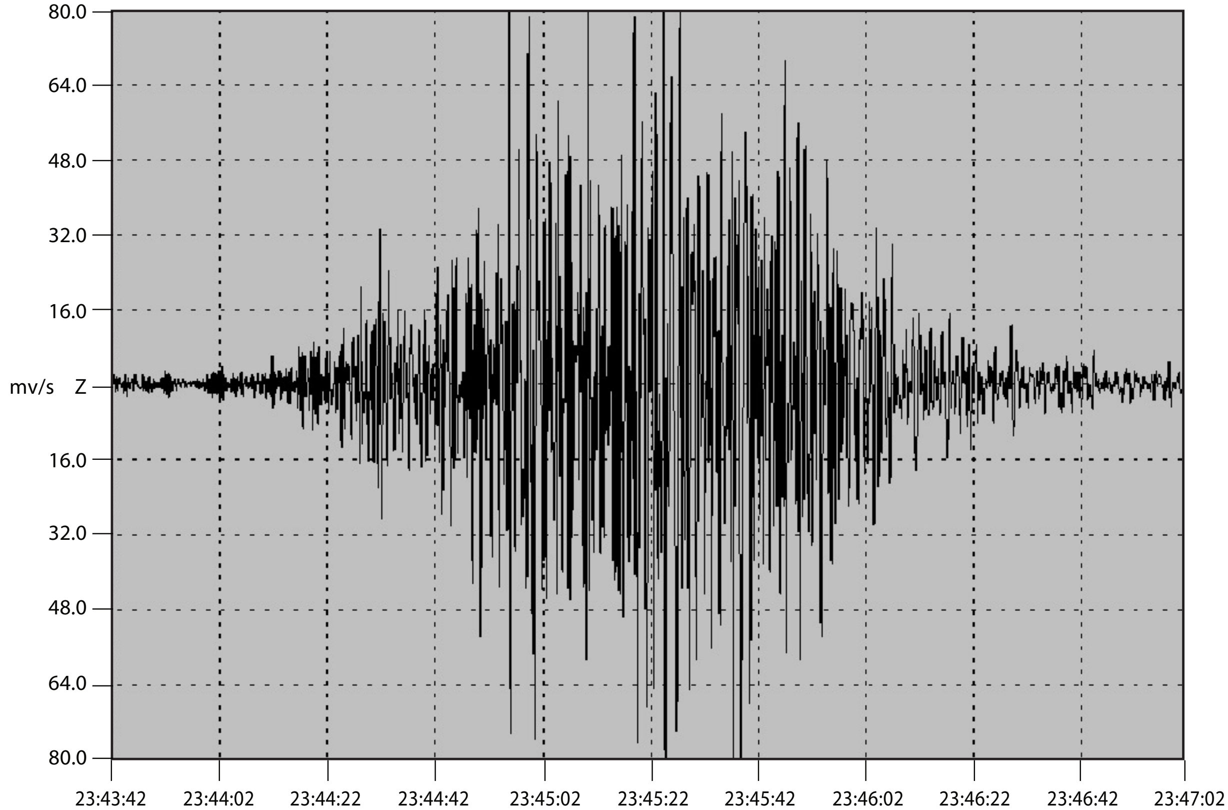


Figure 4. Colorado Mesa University Seismic Network seismogram of the WSCL event. Seismometer was 24.7 miles away at their Rapid Creek Station (courtesy of Dave Wolny, Colorado Mesa University). Note the spikes in the wave train that may indicate episodic failures of the rockmass.

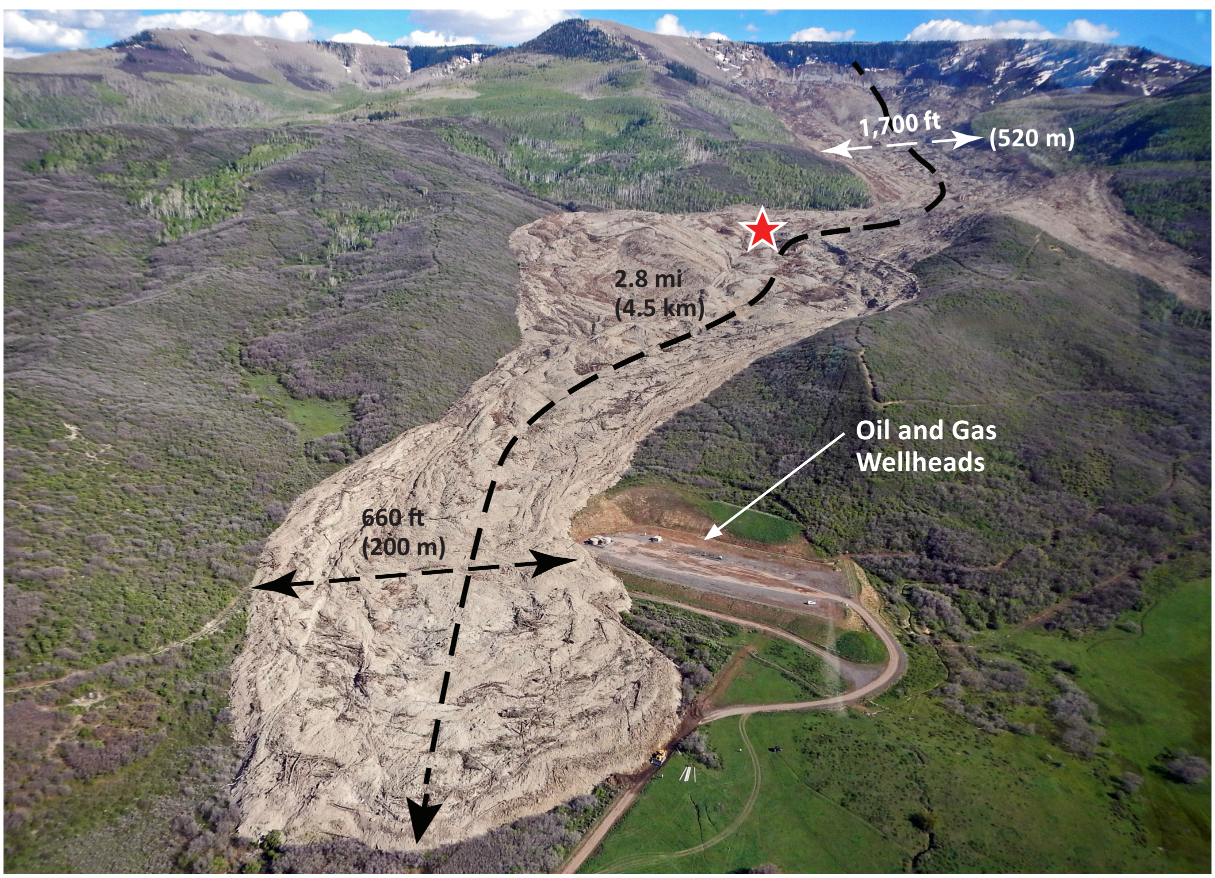


Figure 5. Oblique photo of the WSCL taken May 26th, 2014. The red star is the assumed truck location of the three men killed in the landslide. It is approximately located at the end of the West Salt Creek ranch road, which forks off at the front of the well pad.

damage to surrounding infrastructure. Soon after the event, Mesa County received 911 calls from local residents but there are no living eyewitnesses to the actual rock avalanche. According to sheriffs' reports (reproduced in their entirety in **Appendix A**), local residents first on the scene indicated that the landslide was essentially in place but material was creeping to a stop from the time the 911 call was made until the arrival of Sheriff's deputies about 1½ hours later.

Limited search and rescue efforts were made that evening. A helicopter was called on May 26th and rescue operations resumed that morning. Representatives of the Mesa County Road and Bridge Department, NOAA, and CGS made a cursory inspection and assessment of the landside by air later that day while search and rescue operations continued. Investigators noted that spring runoff was flowing at an estimated 50 cfs (1.4 m^3/s) into the landslide as waterfalls over the head scarp into the large depression formed by the rotated block and that a sag pond was beginning to form. Many seeps from the rock face exposed in the headscarp were also noted. The Mesa County Sheriff's office used UAV flights to search for the missing men and their vehicle, and acquire low-altitude aerial photography of the landslide. At 6:00 PM on May 26th, as the sag pond was enlarging and stability of the oversteepened face of the rotated block was questionable, search efforts by foot on the landslide were suspended for safety reasons.

Description

The entire landslide covers an area of 0.95 mi^2 (2.46 km^2). This includes the exposures of bedrock at the flanks and head scarps. The landslide is 2.80 mi (4.51 km) long (horizontal distance) and 2,200 ft (670 m) in height, from an elevation of 9,600 ft (2,926 m) at the landslide crown (undisplaced zone above the headscarp) to 7,400 ft (2,256 m) at the toe. The maximum width is 3,113 ft (949 m) at the surface of rupture. In the series of events, approximately 39 million yd^3 (30 million m^3) of rock and debris were mobilized at the WSCL, calculated using a comparative GIS analyses of a pre-slide, 4-m resolution DEM, and a 1-m resolution DEM created from post-event LiDAR. This volumetric estimate is based solely on changes in the surface topography and does not account for the geometry of the basal shear surface and overall thickness of the Upper Block since the depth to the failure plane is unknown. Using an assumed circular-slip failure plane shown in the map plate 1 cross section, the total displacement volume may be as high as 82 million yd^3 (63 million m^3).

The landslide includes two fundamental zones: a zone of depletion and a zone of accumulation (Varnes, 1978). These zones define the transition of the WSCL from a rotational rockslide to a rock avalanche. The zone of depletion is within the morphologic "bowl" or amphitheater where the landslide slid from, which includes the depression below the headscarp and the rotated, partially disaggregated, "Upper Block". The zone of accumulation is the resulting rock avalanche debris field that partially filled the West Salt Creek valley.

Headscarp

The near-linear headscarp is 2,070 ft (631 m) long, 450 ft (137 m) high, and exposes strata of the Parachute Member of the Green River Formation below interfingered sandstone beds of the Uinta Formation. The lateral side scarps curve outward to a point 1,500 horizontal ft (457 m) from the headscarp crown, where the maximum rupture width of the Upper Block is reached (see geologic map in Plate 1). A major slickenside of the landslide shear plane was observed on the headscarp rock face (**Figure 6a**). The headscarp extends upward and above the WSCL crown, to a heavily treed steep slope; this was also the location of the

Figure 6(a). View of the east flank of the WSCL headscarp from the Upper Block. Black arrow shows location of slickenside remnants of the landslide failure surface. This slip surface remnant has subsequently fallen into the sag pond. Note downed tree orientations toward the scarp on ruptured surface of the back tilted Upper Block.

prehistoric landslide scarp (Figure 2). Vegetation and glacial/colluvial sediments obscure the Goodenough formation but formational clay shale is exposed in the east ravine above the headscarp. Isolated zones of cherty limestone rocks from the formation are also poorly exposed near the plateau rim above the headscarp. The strata exposed in the wall of the headscarp show evidence of disturbance, including: localized tilted beds, structural offsets along subparallel intermediary scarps, and many sub-vertical to steeply-dipping to-the-south shear surfaces. These form an overall sheared fabric in the rock mass best seen in the exposed strata of the east flank of the headscarp (**see Figures 6b and 6c**). The exposed strata along the lateral scarps were very thinly bedded to laminated, brittle, and highly fractured with prominent blue-gray stained surfaces (**Figure 6d**). Active seeps in the rock faces of the head scarp and flank scarps continued for several days after the landslide.

Upper Block

The Upper Block is the remnant of the prehistoric landslide of the same area (Figure 3). On May 25th, 2014, the Upper Block rotationally slid down this pre-existing listric (concave upwards) surface of rupture related to the prehistoric landslide. The rotation and back tilt of the block disrupted the block surface into many fissured domains with varying declinations, typically between 12° and 15° toward the headscarp. Concurrently, the near vertical

Figure 6(b). Photo of the east side scarp. Disturbed rockmass is the Green River Formation. Note sheared rock fabric and landslide displacement at side scarp shown by red arrow. Colluvial red soil is also seen in the scarp along left edge of photo. Red dashed line approximates major near-vertical shear zone. Dashed oval marks tightly spaced, near vertical shearing in rockmass.

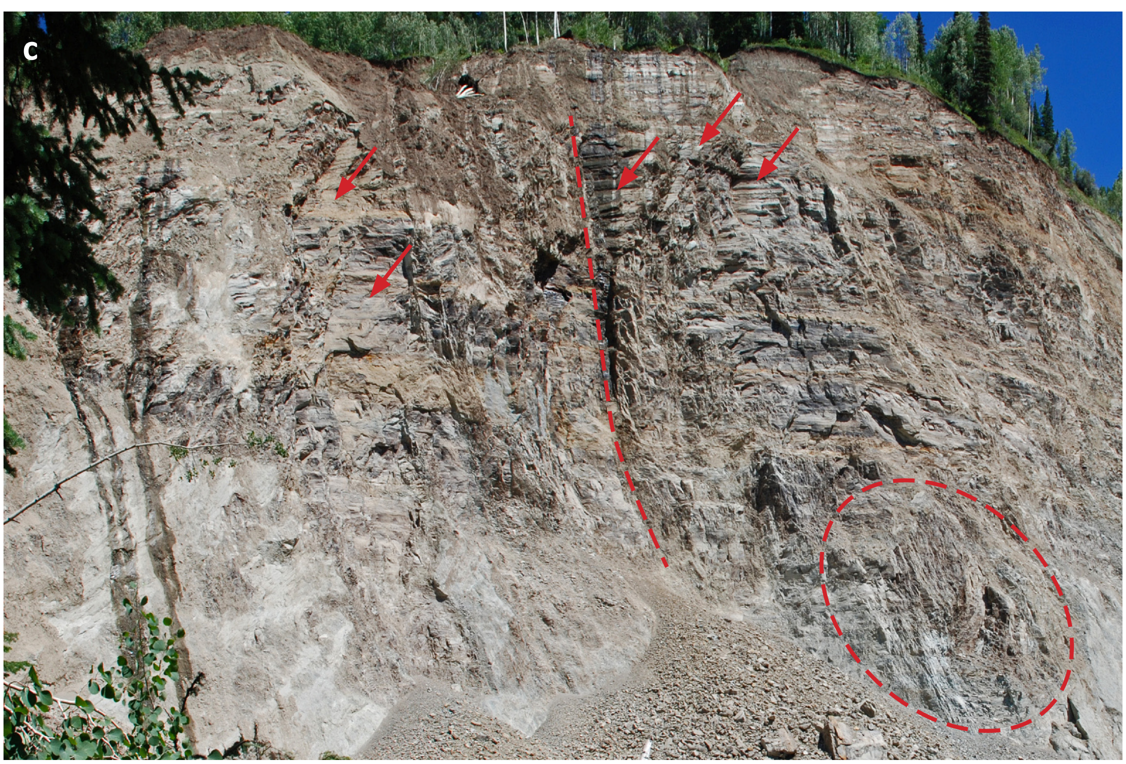


Figure 6(c). Photo is a close up of east side of headscarp (courtesy of Rex Cole, Colorado Mesa University). Note steep shear surfaces shown by arrows. Dashed red line and oval is in same location as shown in 6b. Seepage flow on rock face to left is occurring from another shear zone. The same location is shown by black arrow in 6b.

Figure 6(d). Exposed Green River Formation on west flank of scarp. Note blue-gray staining and degree of fracturing in the rockmass. Photos taken summer of 2014.

All Figure 6 photo locations are shown on Figure 9 map.

shear planes in the disturbed rock mass (Figure 3, top), which were dipping about 75° after the prehistoric landslide, were further rotated an additional 12° to 15° and estimated to be dipping steeply 55° to 70° to the north.

The large closed depression behind the Upper Block had a maximum depth of 110 ft (34 m) (**Figure 7**). The jolt and resultant ground disturbance from down dropping and back tilting, as the block slid down >450 vertical ft (137 m) along the scarp, caused extensive ground-surface ruptures, heaves, and subparallel fissures. Most of the trees were tilted or downed and thrown back towards the scarp face. Much of the broken ground on the eastern half of the block exposed reworked and transported reddish-orange colluvial/landslide soil with abundant Grand Mesa basalt boulders that were originally deposited along the east rim of the amphitheater (**Figure 8a**).

This ruddy-colored material became an important marker for distinguishing the different source areas and relative timing of the rock avalanche deposits. Heaved soil exposures also revealed alluvial sediments (**Figure 8b**) deposited on the original bench after the prehistoric landside occurred. The highly disturbed, steeply-sloping downslope face of the Upper Block, also known as the "area of evacuation" is where the rock avalanche originated. Several intermediary, steeply-dipping faces of the front of the Upper Block likely reflect deeper shear-slip or detachment surface remnants (see Figure 3 bottom) along this escarpment face. Some of the later slip failures were relatively thin, evidenced by shallow slumps of soil with fallen trees.

Rock Avalanche

The extent, approximate thickness, and morphology of the rock avalanche is shown in **Figure 9**. The volume of rock avalanche debris that filled West Salt Creek valley, calculated from the base of the Upper Block is approximately 17 million yds^3 (13 million m^3) using comparative analytical tools in Global Mapper™ GIS software. The GIS analysis also indicates rock avalanche deposit thicknesses up to 123 ft (~38 m) along the thalweg of the original stream channel. This event was extremely rapid, with eyewitness accounts indicating the majority of the rock avalanche deposit was in place over two miles down the valley in a matter of minutes (Melvin "Slug" Hawkins, oral communication, 2014). Based on the seismic data shown in Figure 4, the rock avalanche occurred from a 3-minute sequence of failure and rotation of the Upper Block and episodic rock mass failures from the zone of evacuation along the front of the Upper Block as it rotated, fragmented, and large blocks slipped down the very steep shear surfaces. Initial pulses of disaggregated and pulverized rock and related soil and vegetal debris had the volume and velocity to overtop and spillover two ridges of the West Salt Creek valley where the creek thalweg curves. These ridgelines, shown on the geologic map in Plate 1, are referred to as the West Ridge and the East Ridge.

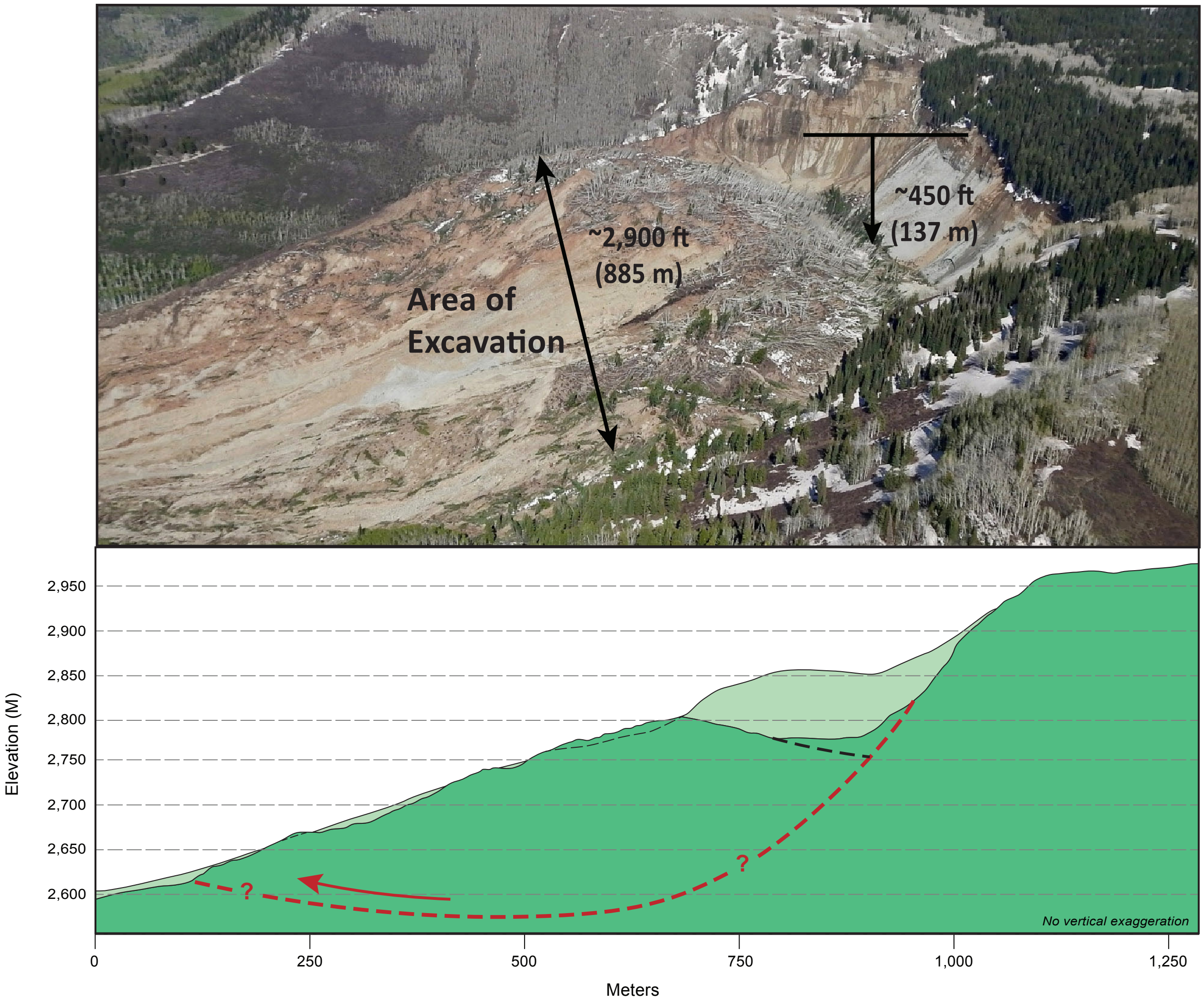


Figure 7. Photo at top is an oblique east-facing aerial photo of the Upper Block taken May 26th the day after the landslide before the sag pond began to fill. Lower image is a cross section at the center of the block at the approximate linear scale of the photo showing the assumed rotational failure surface as a dashed line. Dark green area is the post-failure surface after pond began to fill and material sloughed into depression from the scarp. Light green area is the pre-failure surface.

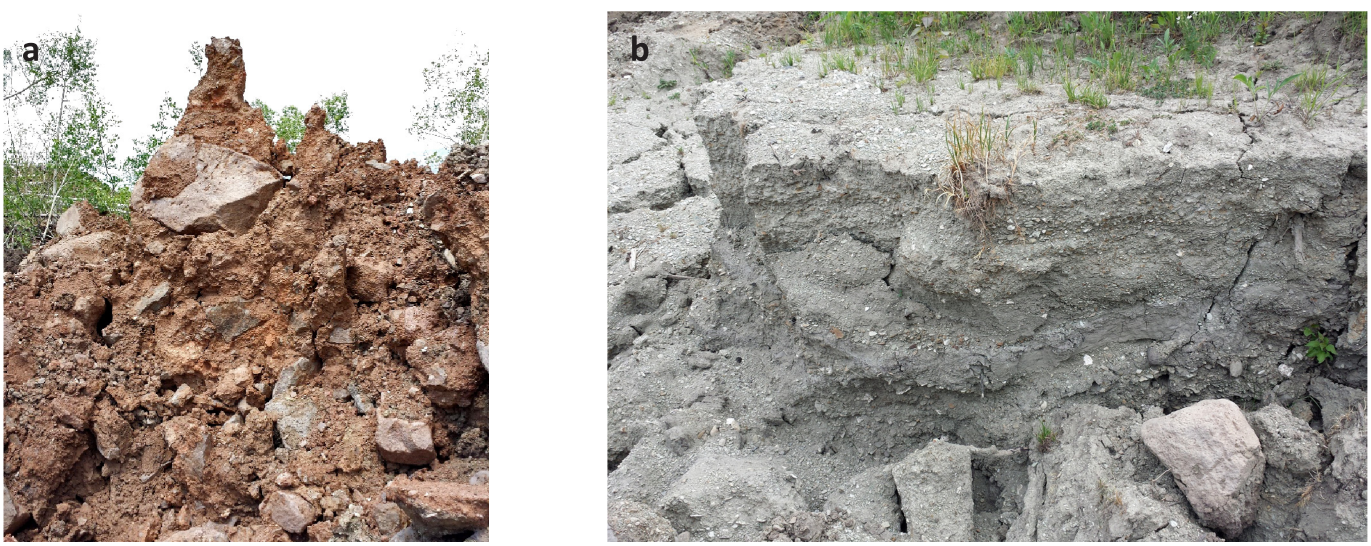


Figure 8. Upper Block sediments ruptured and heaved by May 2014 landslide movements. a) red colluvium with basalt clasts, b) Alluvium deposited on original Upper Block bench when prehistoric sag feature in-filled after failure in the recent geologic past. Photos taken summer of 2014. Photo locations are shown on Figure 9 map.

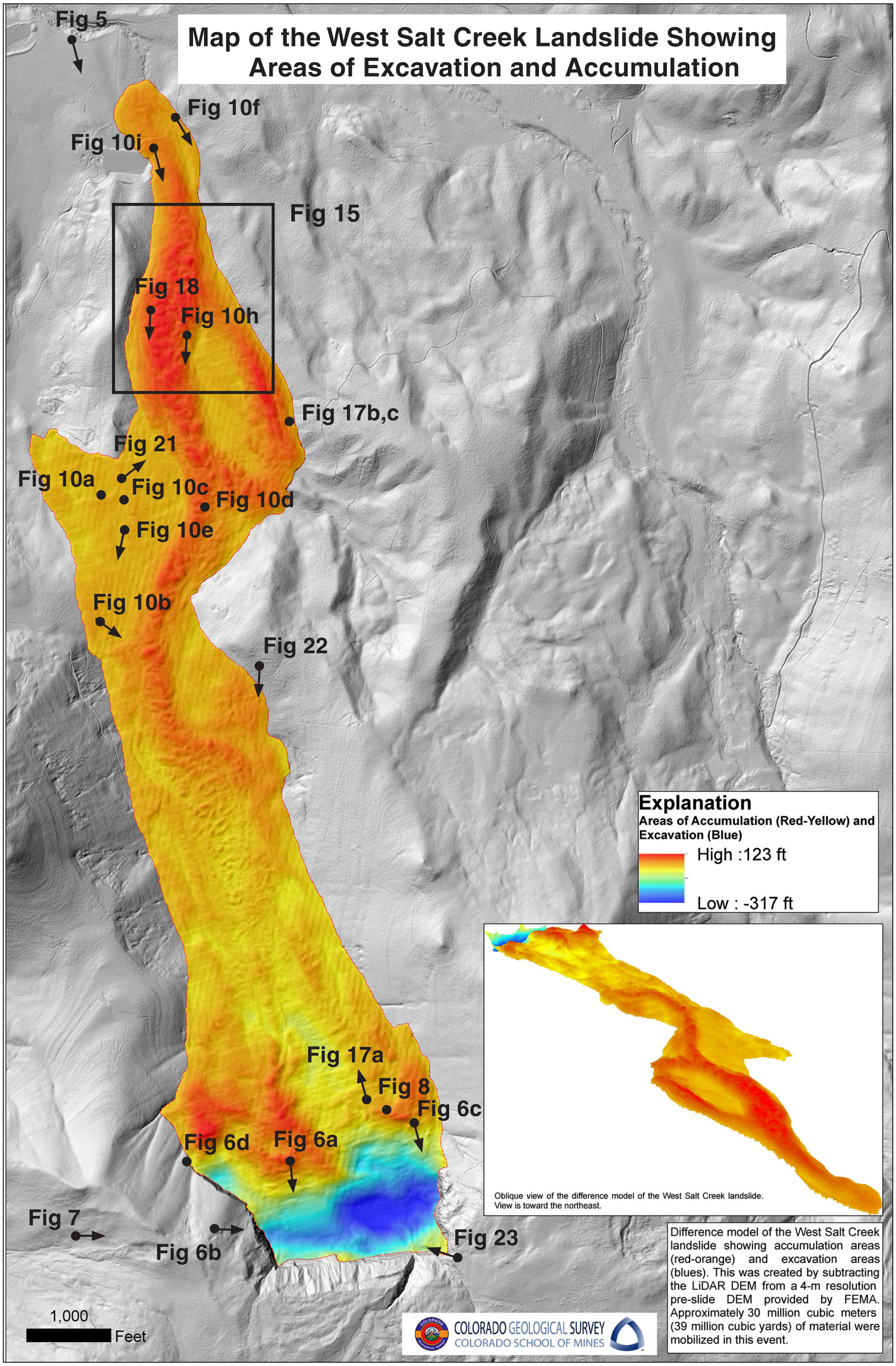


Figure 9. Material difference model. LiDAR hillshade is used as the basemap. Location of photo figures in this report are shown by points or view-direction arrows.

The rock avalanche deposit is chaotically mixed, composed predominantly of disaggregated and pulverized mudstones and marlstones of the Green River Formation with clast sizes that grade from very large boulders, some in excess of 8 ft, down to rock flour. The much slower, later surge of the rock avalanche along the thalweg of the creek was much coarser, containing very large, disturbed blocks (car to cabin sizes) of Green River Formation that formed a hummocky topography that can be seen in the LiDAR hillshade base maps in Figures 9 and 11. There was no evidence of a dust cloud generated by the rock avalanche. A qualitative assessment of the surface exposures of the rock avalanche debris shown in **Figure 10** images seems to indicate the majority of the blocky, angular to subangular, rock clasts in the debris are generally less than small boulder size with a high percentage of the rock fragments falling within a fist to football size (3–10 in; 8–25 cm) range. However, there are many areas of the debris field that does have segregations of very large, boulder-sized clasts. Many clast surfaces have the original staining seen in outcrop near the headscarp (Figure 6d); while speculative, this range in clast size may be indicative of the fracture network and preferential gradation in the disaggregation of the rock mass. Accessory clasts types include rare sandstone and limestone, chert, and basalt boulders derived from alluvium, colluvium, and glacial till deposits that were originally deposited on the plateau above.

Depending on the original source area, the rock avalanche debris color may range from shades of light gray to gray to dark red and there may be compositional differences in accessory soils, forest duff, vegetation, trees, and mud. In many locations, there are segregations of downed trees and shattered woody material that may reflect a deposit rich in near-surface material. Other surface areas of the debris field are 100% Green River Formation clasts without a fine-grained matrix. Deposits from the early surges tend to be gray in color, more rich in rock fragments and contain much less clay in the matrix.

Figure 10. Rock avalanche debris locations: (a) typical matrix of avalanche deposit. Note pen for scale; (b) typical rocky debris field on west ridgeline. Note red-soil zebra-stripes related to spread of surficial soils on east flank; (c) subsidence fissures in deposit; (d) bouldery segregation within late-surge hummocky rock-debris flow; (e) debris on rise of west ridge spill over, red circle encloses person for scale; (f) east edge of debris field near toe. Photos taken summer of 2014. Photo locations are shown on Figure 9 map.

Figure 10 (con't). Rock avalanche debris locations: (g) debris field, photo taken from West Ridge towards East Ridge. Late surge hummocky rock-debris flow can be seen in center; (h) view up slope from flank of East Ridge, note spill over at West Ridge, dog-leg in East Elk Creek thalweg, and late surge hummocky rock-debris flow on floor; (i) con't on page 16.

Figure 10 (i) View up slope in toe area, note proximity to oil and gas well infrastructure.

In later surges derived from the east side of the amphitheater, the deposit contains remnants of the distinctive red-brown, basalt-rich colluvial soil. Also, late detachment and slips of large rock blocks, likely from deeper and lower in the excavation zone of the Upper Block, did not have the energy to completely disaggregate. These very large blocks of rock, some the size of small homes, while highly disturbed and broken, remained "intact" within the last slower surge of the rock avalanche flow and formed the hummocky topography along the valley floor.

Variations in velocity, deposit fabric, and soil remnant/clast composition can be assigned to differing surges of the rock avalanche. Those variations and the sequential timing of the discrete cascading pulses of rock avalanche and debris flows are discussed in the Rock Avalanche Morphology and Timing of Major Deposition Events sections.

Overall, the rock avalanche was a markedly dry deposit; during the field investigation, no water or mud was seen seeping or fanning out from the steeply sloped edge of the avalanche toe. The deposit did contain some moist muddy zones and pockets of damp, fine-grained matrix. Along the flanks, at shear ridges, and at the toe of the avalanche, the 20- to 35ft-thick rocky deposit was able to support slopes up to 45°, which gave the deposit a morphology similar to a lava flow at the toe. The toe of the rock avalanche remained dry until it was observed that ground water, percolating through the entire length of the deposit and forming a series of ponds in the debris field, finally reached the toe sometime in December 2014. During the spring 2015 run-off, a re-established stream now flows from these larger ponds, and is incising the landslide toe as the stream re-enters the original West Salt Creek bed below.

Estimated Velocity

The velocity estimates presented here are preliminary and are provided for discussion purposes with the hope they can be used to better refine future estimates. Early estimates, using the standard velocity equation v=d/t, were based upon a run-out distance of 2.8 mi (4.5 km) (the complete extent of the landslide from headscarp to toe) and duration of almost 3 minutes. However, after completion of mapping and field reconnaissance, the CGS reconsidered these variables, specifically the sources and extents of the mapped deposits. The precise area of origin, within the evacuation zone of the Upper Block, for the rock avalanche debris is unknown and the run-out distance for individual surges is complex. Thus, the CGS chose an initiation point, at the evacuation zone along the face of the rotated block (**Figure 11**), at the approximate location of a scarp of more intact rock relative to the majority of fragmented rock below the scarp.

Two end points in the rock avalanche debris field were considered (Figure 11). The first (labeled End Point 1) is the furthest mapped extent of the early surge deposit. The total travel distance from the initiation point to this End Point 1 is 2.36 mi (3.80 km) and the total vertical drop is 1,362 ft (415 m). The second possible end point (labeled End Point 2 on Figure 11) is where the gray breccia probably impacted the valley side as part of it came down the first surmounted hill and this is the approximate last occurrence of the middle surge red basaltic breccia. The travel distance to End Point 2 is 2.12 mi (3.41 km) and the total vertical drop is 1,267 ft (386 m).

The event as recorded on the seismograph, began at 17:43:45 with a duration of approximately 3 minutes. A rudimentary velocity calculation using v=d/t where d is distance and t is time, assuming the shortest distance of 2.12 mi (3.41 km), yields

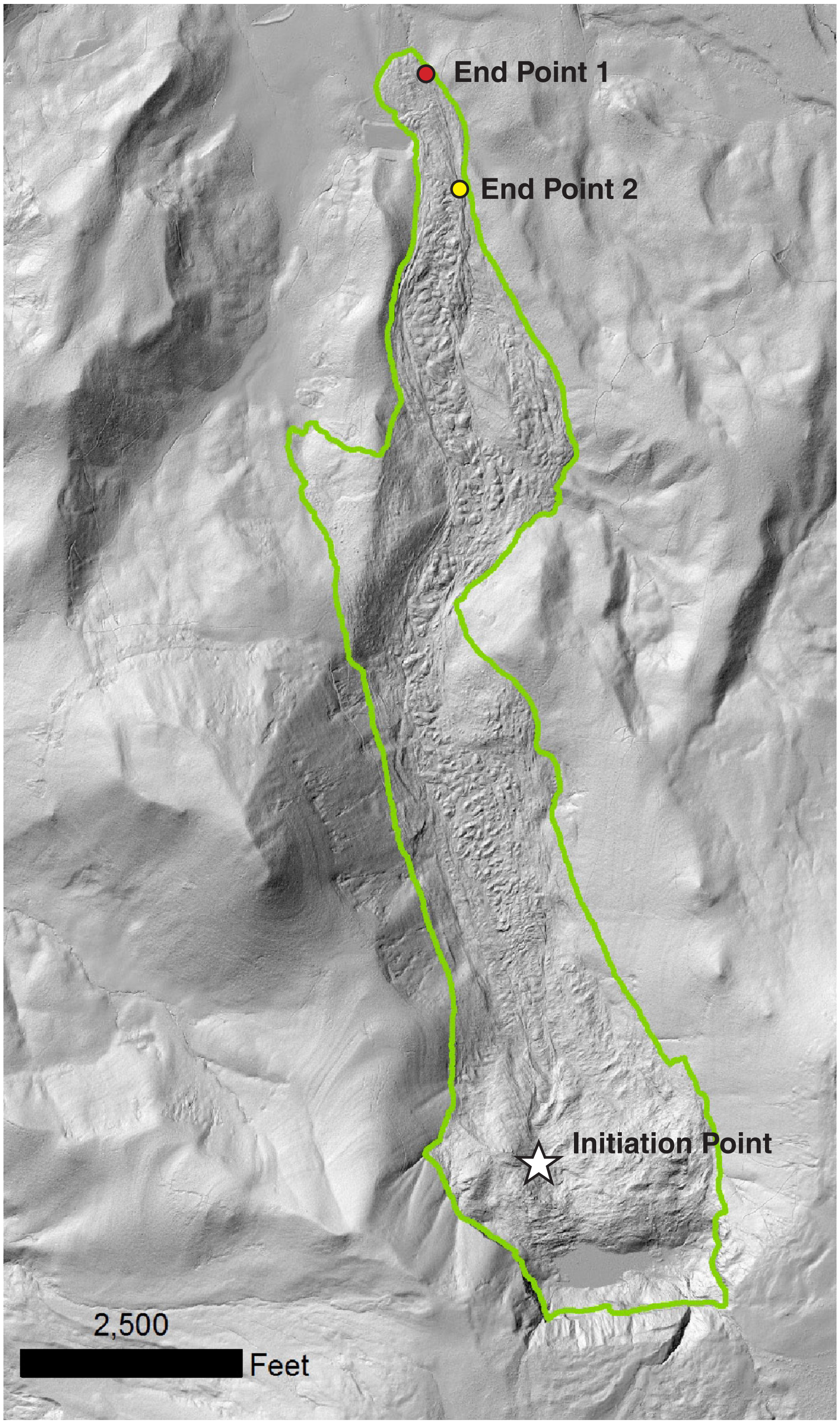


Figure 11. Hillshade of the WSCL with data points used in simplified estimated velocity calculations. The "Initiation Point" (white star) for the rock avalanche deposits is at the approximate location of a scarp consisting of more intact bedrock relative to the majority of brecciated debris below the scarp. End Point 1 (red circle) corresponds to furthest mapped deposit of a gray polymict breccia (part of early Surge) and End Point 2 (yellow circle) is where early surge may have impacted the valley side as it came off the spillover and where the red basalt-rich deposits end.

2.12 mi/0.05 hrs = 42.40 mph (18.95 m/s)

Alternatively, using the last known undisturbed location of the gray breccia at 2.36 mi (2.80 km) from the potential source area, yields

2.36 mi/0.05 hrs = 47.20 mph (21.10 m/s)

These velocity estimates should be considered minimum values for the early surge of rock material, based upon current knowledge of the seismic wave duration and beginning and end points of the debris discussed above.

Another velocity estimate can be calculated from the height of the first surmounted hill, which was measured to be approximately 280 ft (85 m) high, by using the velocity potential energy equation (Chow, 1959):

$$v = \sqrt{2gh}$$

where g is the acceleration due to gravity (9.8 m/s) and h is the height gained, giving:

$$v = \sqrt{2 \text{ x } 9.8 \text{ x } 85} = 40 \text{ m/s or } 89 \text{ mph}$$

A second hill with a height of 180 ft (55 m) was also surmounted:

$$v = \sqrt{2 \text{ x } 9.8 \text{ x } 55} = 33 \text{ m/s or } 74 \text{ mph}$$

However, this equation assumes that energy was completely kinetic and converted to potential energy and the surmounted object must be perpendicular to the flow (Jakob, 2005). It should be noted that if the surge approaches the hill obliquely, the estimate of the velocity to top the hill is a strict minimum, because the velocity measured by the velocity potential energy equation is only the component perpendicular to the hill. Furthermore, it could also have a component of undetermined size parallel to the hill crest, so the flow velocity must be even higher, which is necessary to supply the gravitational energy to overtop it. Because the calculation does not take into account bends in the stream or the trim lines of correlative deposits, the estimated velocities are approximate and only give the velocity needed to run up the given height.

The preferred method to account for the channel bends and the banking angle of the deposit at the channel bend is

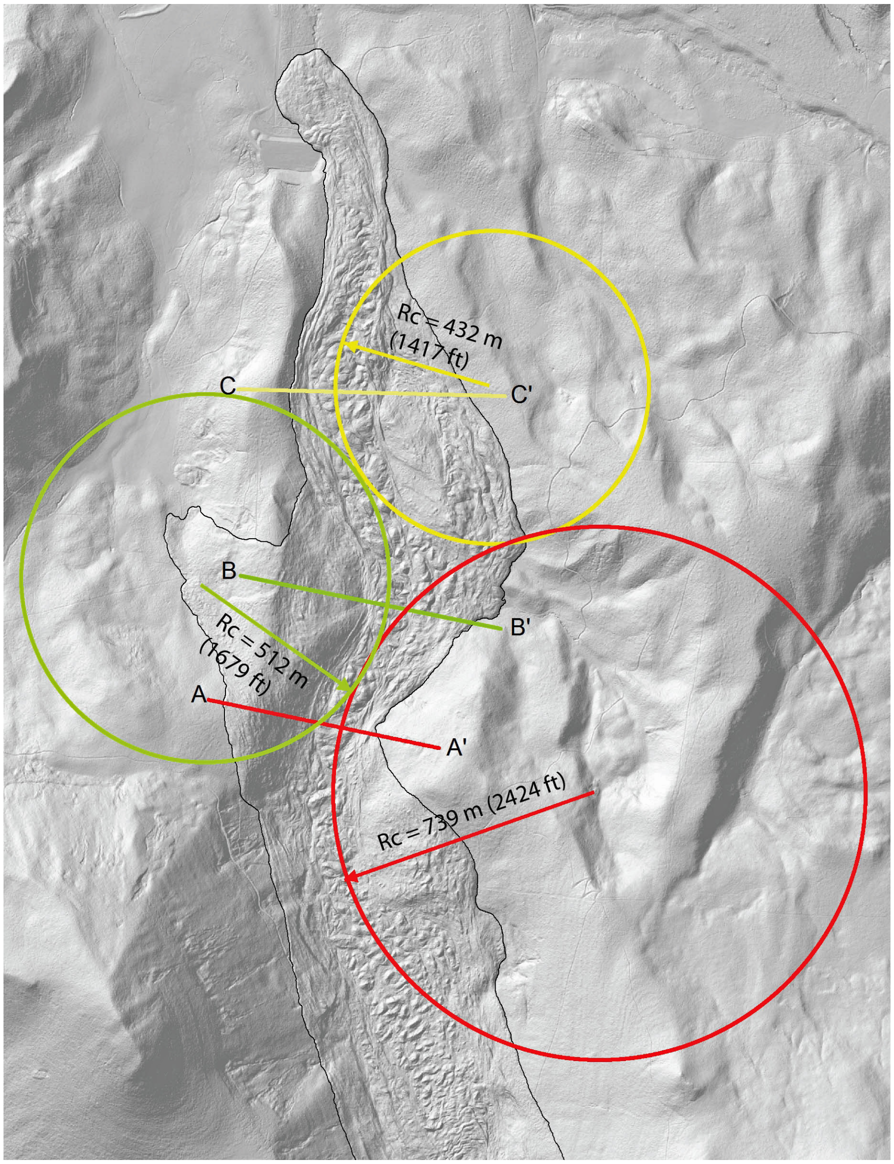


Figure 12. Hillshaded LiDAR DEM of the area of the WSCL analyzed for velocity estimates. "Best-fit" circles were used to determine the radius of curvature (Rc) for channel beds. Alignment of cross-section profiles are labeled A-A', B-B', and C-C'.

the forced vortex equation (Chow, 1959; Henderson, 1966; Hungr and others, 1984; and Johnson, 1984). Discussion of this method is provided in Prochaska and others (2008) and it has been used to back calculate rock avalanche velocities if these factors are known (Plafker and Erikson, 1975; Evans and others, 1989, 2001; Boultbee and others, 2004). This equation is as follows:

$$v = R_c g \tan\beta$$

Where R_c is the channel's radius of curvature, g is the acceleration due to gravity and β is the banking angle of the deposit from horizontal.

The radius of curvature (*Rc*) was determined by drawing circles that approximated the channel curvature through at least 3 points along the stream course using 1:24,000-scale topographic maps and a pre-slide 4-m DEM (**Figure 12**). Three cross-section profiles (locations also shown in Figure 11) were placed perpendicular to the channel bend and were plotted for each analyzed bend using the pre-slide 4-m DEM and the post-slide 1-m LiDAR DEM. The three generated cross sections are shown in **Figure 13**. The banking angle (β) was determined by approximating the trimline of correlative deposits and measuring the angle from horizontal.

Table 1 summarizes the measured variables. The calculated velocity of 89 mph for the first surmounted hill using the velocity potential energy equation compares favorably with the velocity of 83 mph for the same hill using the forced vortex equation. However, the forced vortex calculation for cross section A-A' likely underestimates the velocity because the inner trimline of the Early Surge is either lower in the valley or obliterated by later surges that were higher than the first surge. Similarly, the lower trimline of the first rock avalanche in cross section B-B'

Table 1.

Section	*Rc* (m)	Banking angle (β) (degrees from horizontal)	tan β	Maximum velocity in m/s (mph)
A-A'	739	11 (?)	0.19	37 (83)
B-B'	512	4 to 9.5 (?)	0.07	19 (42) to 29 (65)
C-C'	432	1	0.02	9 (21)

(**Figure 13**) is also unknown and the calculated velocities can vary widely based on the banking angle.

The calculated velocities from the velocity potential energy equation (based on run-up height) and forced vortex equation (based on channel bend and trimlines) fall in the range of velocities given for other rock/debris avalanches: 105 mph (47 m/s) at Nevados Huascaran in 1962 (Plafker and others, 1971), 86 mph (38 m/s) at Huancavelica, Peru (Kojan and Hutchinson, 1978), 77 mph (34 m/s) at Mt. St. Helens (Schuster, 1983; Voight and others, 1983), and 76 mph (33 m/s) at Zymoetz River (Boultbee and others, 2004). While it is likely that the velocity of the material would have varied within the flow zone and the physical characteristics of each surge differ, velocities between 40 mph (18 m/s) and 85 mph (38 m/s) are plausible for the rock avalanche.

We acknowledge that velocity estimations are variable and additional details about this event may refine the velocities provided here. Factors such as the precise point of origin for the measured surges, variations in channel bed

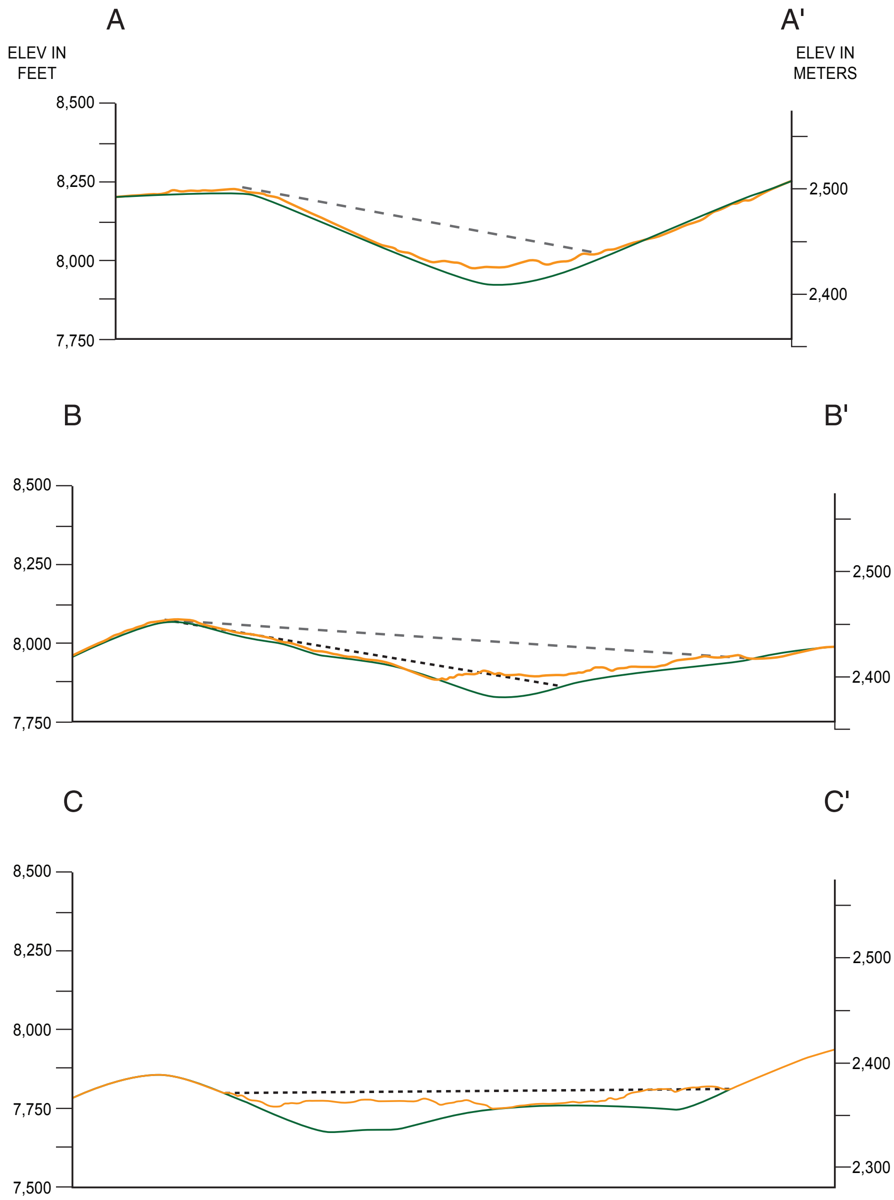


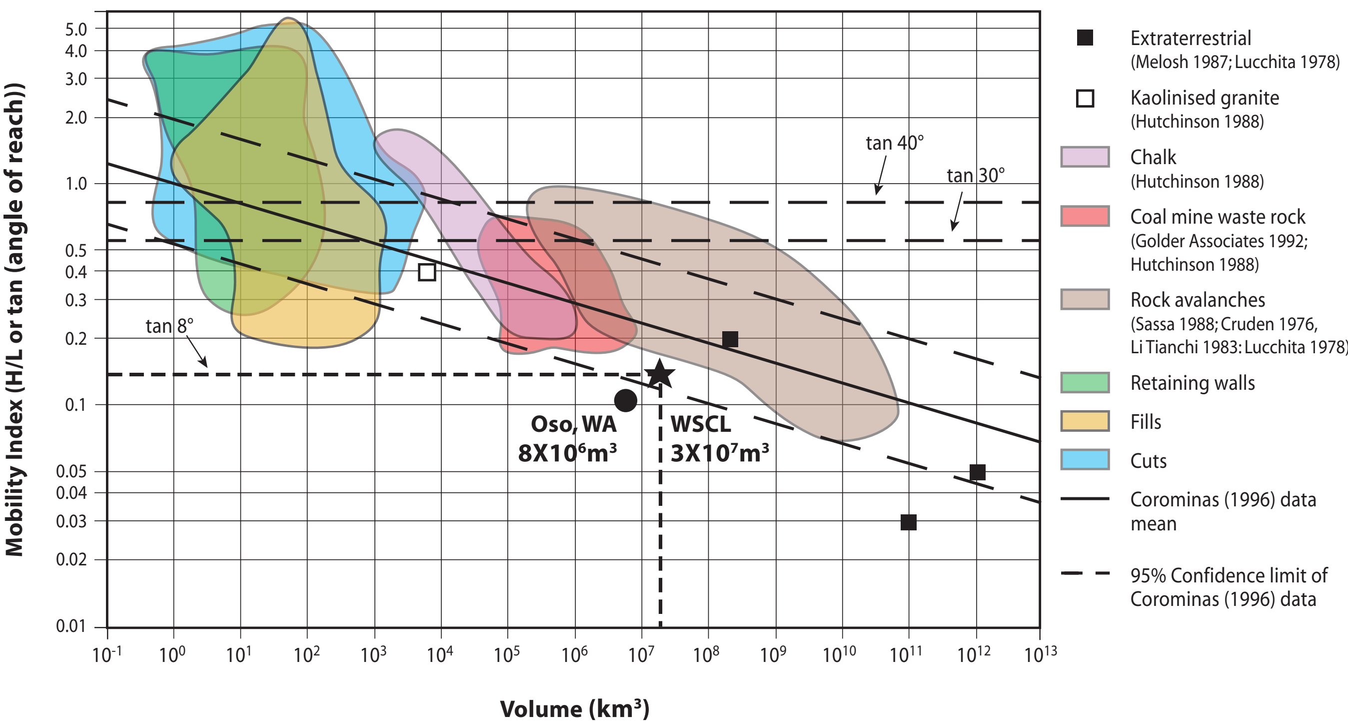
Figure 13. Cross-section profiles created from pre- and post-event DEMs. Location of the cross-section alignments are shown on Figure 12. The original topography is indicated by the green line and the landslide debris topography is shown by the red line. Dotted black line is the banking angle as determined from trim lines of probable correlative deposits. Two banking angles were proposed for cross section B-B'. The dashed black line is a very conservative estimate from hilltop to the widest extent of deposits. The dotted line was determined from the angle of the first surmounted hill and the approximate location where a parallel line would have intersected the valley below.

sinuosity, channel depth, precise superelevation of correlative deposits, and deposit engineering properties all factor into the velocity calculations and with more investigation will help determine a more precise velocity value.

Landslide Mobility

While the actual range of velocities is not precisely known, the WSCL was catastrophic in nature and was well above the minimum speed for the highest, extremely rapid, classification (>5 m/sec or about 11 mph, the approximate speed of a person running) (Cruden and Varnes (1996). The run-out extent (2.8 mi, 4.5 km) of the deposit also reflects an extremely high mobility. A simple mobility index is the H/L ratio: the height of the landslide by the length of the landslide, also referred to as the friction coefficient. This value is also the tangent of the run-out angle of reach from the crown to the toe of the landslide. Coe and others (2014), in an early preliminary approximation, stated an H/L ratio of 0.10.

Based on detailed GIS-based measurements, using a height of 2,100 ft (640 m) and length of 14,750 ft (4,496 m) along the thalweg of the stream, the H/L ratio is now calculated at 0.14 and the run-out angle of reach (fahrböschung) at 8°. **Figure 14** contains two graphs with points plotted of the WSCL data. In these graphs, we used



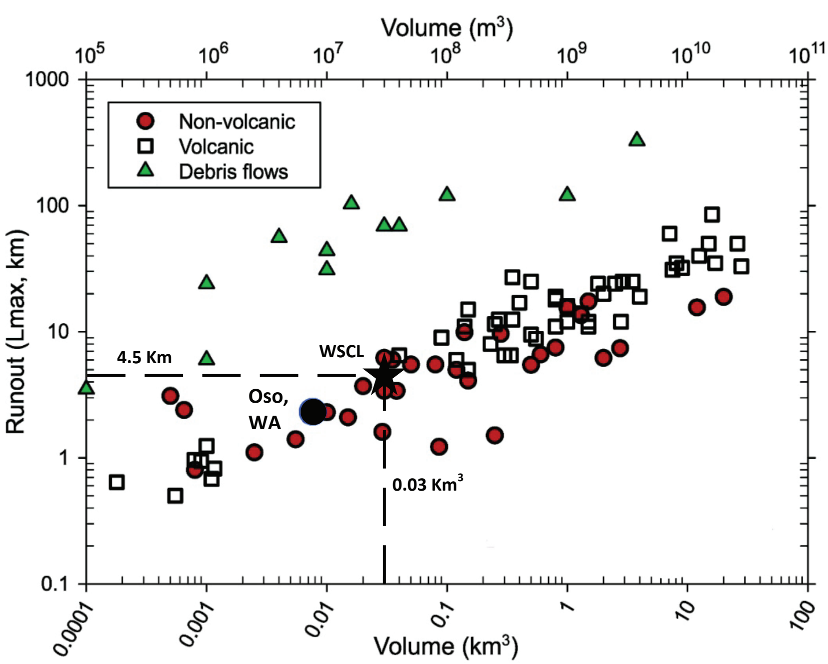


Figure 14. Graphic representation of volume, angle of reach, and runout lengths of large catastrophic landslides and rock/debris avalanches. Top graph is a Log mobility index vs. Volume (V) graph modified from Finlay and other's (1999) compilation. Lower graph is a runout length versus volume chart from the GEER Association report (Keaton and others, 2014) of the Oso landslide that shows rock avalanches and debris flows compiled by Legros (2002). WSCL point is the star. For comparison, the Oso landslide point (Iverson, 2014) is shown as black circle.

the volume of the landslide deposit calculated from volume differences between a pre- and post-landslide DEM - 39 million yd^3 (30 million m^3). However, using the rock avalanche deposit alone, approximately 17 million yds^3 (13 million m^3), would result in a slight shift of the plotted points on the logarithmic scale.

The top graph, with compiled data from Finlay and others (1999), illustrates the low mobility index and the flat angle of reach of the WSCL. Conversely, this indicates an extremely high mobility; one of the highest for its comparative volume of material when plotted within Finlay and other's (1999) compilation. The second lower graph of Figure 14 contains a compilation of data from Legros (2002) that shows the relationship between volume and runout length. This graph does not take into account landslide height and the WSCL plots within the general trend of rock avalanches. Also included in Figure 14 is a comparison point from the March 22, 2014 Oso landslide that caused 43 fatalities. This smaller but extremely rapid, high mobility, catastrophic mud and debris flow occurred in Washington State (Iverson and George, 2014; Keaton and others, 2014).

ROCK AVALANCHE MORPHOLOGY

Mapping by the CGS and USGS using hillshaded LiDAR data, and both oblique and orthorectified aerial photography, documented many different landslide forms that indicate overlapping, crosscutting, and episodic deposition. These features include:

- discrete thrust and overlap features where subsequent flows surged over earlier deposits or the velocity allowed later surges to overtake earlier ones while they were still moving;
- discrete run-up and surge overlaps onto and over existing topographic ridgelines;
- "zebra-striped" soil deposits of alternating red and gray material from the surface spreading of mobilized material;
- v-shaped depositional ridges that point uphill on the east, overtopped ridgeline, which mark where later middle-surge flows stopped on the ridgetop but continued to flow around and down the ridgeline;
- parallel-to-flow depositional lateral levees where flow edges slowed and stopped;
- steep parallel-to-flow-direction furrows and ridge lines at lateral shears along cross-cutting surge boundaries (**Figure 15**); and
- pressure-ridge flow banding at the toe.

The morphology of the rock avalanche deposits indicate that the event occurred as a series of cascading surges that reflect rapid, but episodic failures of the rock mass within the evacuation zone of the lower Upper Block. These episodic failures resulted in detachment and disaggregation of the rock mass, causing stacked surges of rock and debris material to course down the West Salt Creek valley. The episodic spikes within the 3-minute seismic wave train in Figure 4 support this conclusion. It was also apparent that there are zones in the rock avalanche debris field that were modified immediately afterwards by slumping and settlement. We observed slumps and steep scarps where oversteepened debris had slid, as well as settlement fissures and depressions (Figure 10c) that we attribute to consolidation or packing of the loose, lower-density debris once movement of the rock avalanche ceased. Again, we found no evidence that the rock avalanche created a dust cloud. There was also no evidence of high heat or fused rock (frictionite) that is reported to occur with high-velocity sturzstrom-type deposits (Erismann, 1979; Legros and others, 2000; Lin and others, 2001).

During the summer and fall of 2014, CGS observed that clasts of the Green River Formation, which comprise almost all of the landslide deposit, are highly susceptible to slaking when exposed to physical weathering. The clasts on the surface of the debris field rapidly disintegrated into finer and finer material (**Figure 16**) that will be easier for future debris flows to entrain and may increase their bulking factor.

Timing of Major Depositional Events

The precursor movements and failure mechanisms of the Upper Block formed the conditions for the rock mass failure, disaggregation, pulverization, and cascading flow of rock, soil, and forest cover. These latter catastrophic movements at 5:45 PM completely obliterated and/or buried the precursor landslides earlier that morning so we must rely on eyewitnesses and the early seismic record of 7:18 AM (D. Wolny, Colorado Mesa University, written communication, 2014). We also have no account of any precursor activity at the main landslide scarp.

We have subdivided the run out of the rock avalanche into three surge periods (see the geologic map in Figure 2). Deposits consistent with smaller sub-events within these major surges were observed and mapped but discussion of complex sub-events is beyond the scope of this report. The three major surges are based on the morphology, clast, and matrix variations of the rock avalanche deposits.

In addition, peaks in the seismic wave train (Figure 4) may indicate larger rock mass failures that correspond to the discrete surge episodes. Of significant importance is the pocket of red-clay colluvium with abundant basalt rocks that occurs on the east flank of the valley above the Upper Block, and as disturbed prehistoric landslide deposits on the eastern side of the Upper Block bench in the original pre-May 25th landscape (see Figures 2, 3, and 6b). The first two surges were the result of high-velocity rock avalanches, while the last deposit occupies only the valley floor. This last surge was lower velocity and has morphological characteristics of a rocky earth flow.

Figure 15. Aerial photograph at low sun angle showing complex crosscutting relationship of discrete surges in the avalanche debris field. Note parallel to-flow linear shears and ridgelines at the boundary of the late hummocky surge. Photo was stitched from UAV images courtesy of Ben Miller, Mesa County Sheriff's Office taken 24 hours after the landslide occurred. Red dot shows approximate location of photo in Figure 18. Extent of photo is shown by boxed area in Figure 9.

Early Surge

The early surge had the velocity to surmount the West Ridge, overwhelm and cover the East Ridge, and flow down close to the existing WSCL toe. This first widespread rock avalanche deposit was light-gray, yellowish-gray, and brownish-gray, poorly sorted, matrix supported, rocky debris derived from the Green River Formation. The rocky deposit consists of angular to sub-angular granule-, cobble- and boulder-sized clasts of similar composition to the matrix. Also present are rounded basalt clasts, tree fragments, forest duff, and dark-gray to brownish-gray organic-rich soil remnants. The fine-grained matrix consists of sand- to rock flour-sized pulverized rock fragments and wood particles, duff, and dark-gray to brownish-gray organic-rich soil remnants; some is charred by previous forest fires. The deposit was derived from the disintegration and pulverization of disturbed rock mass of the Upper Block and probably previously existing landslide deposits along with wet forest slope colluvium, topsoil, and woody debris.

This surge is believed to reflect an initial failure of the face of the Upper Block where there was little red soil, and had the volume and velocity to surge over the ridgelines where the stream thalweg doglegs down the valley. Most of this deposit was subsequently buried or incorporated into later surges. However, there are remnants of this first surge along the east margin in the lower parts of the landslide, the toe, and where it overtopped the west and east ridgelines.

Middle Surge

The middle surge is more complex and included disaggregation and rock avalanche flows along the entire width of the evacuation zone of the Upper Block. It reflects failure(s) of the entire width of the block because it includes surges similar to the early surge from the west side that is gray in color and almost entirely derived from the Green River Formation, but also includes deposits from the east side that consist of significant percentages of red-clay soil with abundant basalt clasts. This episode also attained substantial velocity to surge over the two

Figure 16. Rapid slaking of Green River Formation claystone and marlstone clasts in the WSCL debris field. Note surface staining of clasts and progression, clockwise from upper left, of rock disintegration in less than 4 months.

ridgelines. In the debris field, there is a rough segregation of rock avalanche deposits from the east side with red soil and west side without.

Middle surge deposits with the red soil can range compositionally. They can be the typical gray rock avalanche breccia composed predominantly of Green River clasts described above but with scattered surface clumps of red soil and basalt clasts. Where the surge source included higher percentages of the original red colluvial soil, the deposit can be a reddish-brown to red, clay-matrix supported, and basalt-rich debris; with lesser percentages of shale and marlstone, rare sandstone, and scattered Miocene (?) Goodenough formation chert. Basalt boulders can exceed 8 ft in diameter but they are rare. Where there are high percentages of the red-clay soil, there are corresponding increases in forest cover material typically incorporated into the deposit, such as tree debris, shrubs, duff and organic-rich soil remnants, and fragments of matrix-supported rock and soil debris that resemble prior landslide deposits (**Figure 17**).

Late Surge

The late surge deposit is a narrower unit (from 400 to 500 ft wide) that approximately follows the original thalweg of West Salt Creek from below the Upper Block to nearly the same level as the oil and gas well pad up valley from the toe. Its channelized landslide morphology is typical of rapid-moving earth flows or debris flows and is characterized by chaotic hummocky topography that is visible in the LiDAR hillshade image in Figures 9, 11 and in Figure 15 aerial photo. The flow is comprised of a mixture of the brecciated units described above, smaller localized muddy debris flows, plant and tree debris, red soils with basalt boulders, and most importantly, many very large disturbed blocks of Green River Formation that have rafted on and within the hummocky rock-debris flow. The localized debris flows are reddish-brown in color and appear to have moved as a thin (less than 3 ft thick) viscous slurry of surface soil, rock and plant debris deposited in and around the large disturbed blocks.

The rock blocks vary in size, approximating the size of cars to small houses. The blocks are in various stages of fragmentation, from nearly intact with only minor disruption of bedding planes to highly disturbed, almost disintegrated, where the original bedding is only slightly apparent. The blocks commonly form hummocks in the center of the landslide mass and appear to have "bulldozed" the underlying deposits into low ridges at the front and sides of the blocks. Remains of the original forest floor, with living trees (predominantly coniferous pines) and plants in growth position, is preserved on some of the surfaces of the hummock-forming blocks. This degree of block preservation in conjunction with the great distances the blocks traveled from the evacuation zone source indicates that near the end of its rotational movements, the Upper Block was detaching blocks of Green River Formation from the evacuation-zone without sufficient momentum or speed to completely disaggregate the rock mass as what occurred in the earlier surges. It is clear this was the last significant movement of the landslide because the lateral boundaries of its entire length is marked by sharp furrows (**Figure 18**) that define shear zones as this material flowed through, over, or past the pre-existing early to middle surge deposit runouts. The late surge rock-debris flow ground to a halt as it bulldozed earlier surges at the toe near and below the oil and gas well pad. The late surge boundary was discerned near the toe by the formation of pressure-ridges and flow bands normal to the flow direction and the down-slope cessation of red-soil remnants.

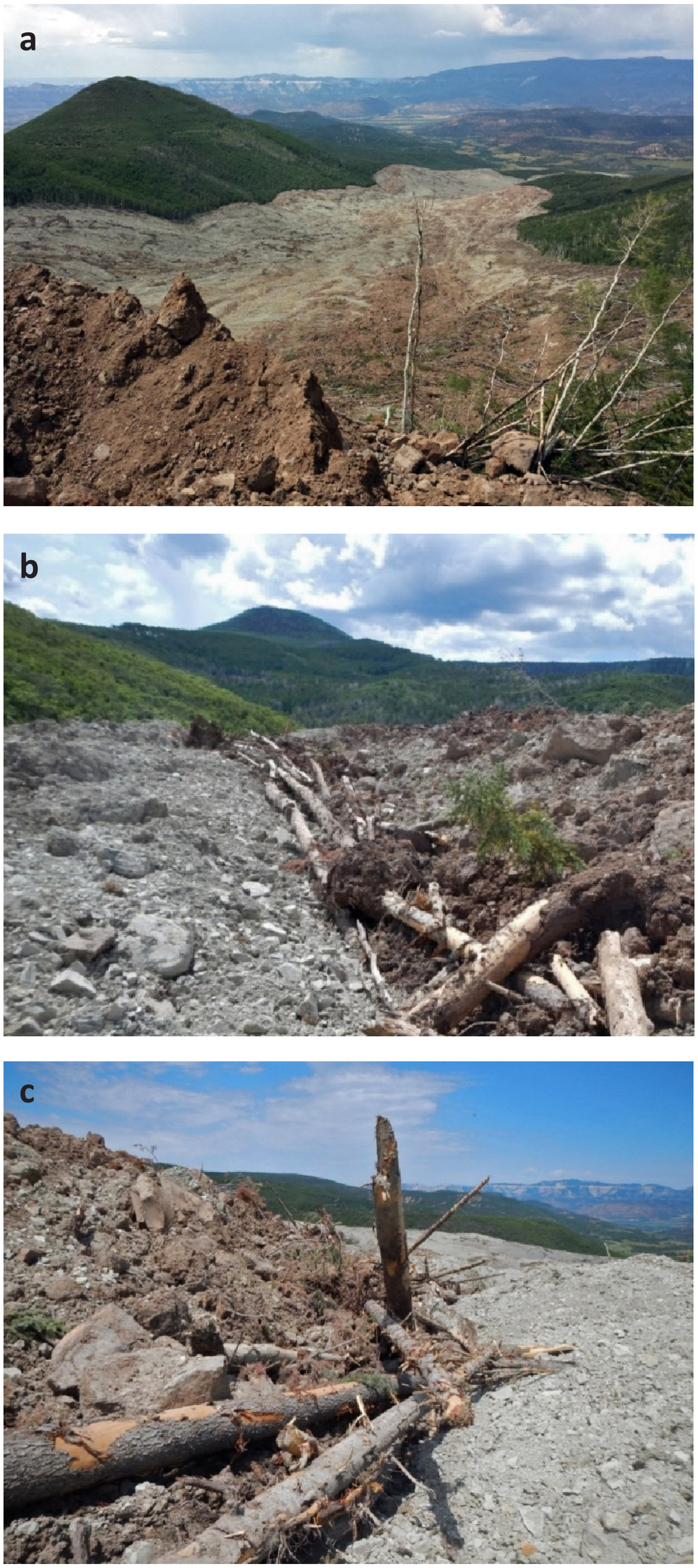


Figure 17. Red bouldery deposits: a) photo taken from the east side of the disturbed bench of the Upper Block at red soil deposit; b and c) photos on boundary, upslope and downslope, where middle surge material (with red soil remnants, basalt boulders, and tree fragments) has overrun light gray early surge deposit that is nearly completely composed of finer Green River Formation clasts. Photos taken summer of 2014. Photo locations are shown on Figure 9 map.

Figure 18. Well-defined side furrow (dashed line) on west side of debris field marks a lateral shear of subsequent movements of a later, lower level, debris surge. West edge of late, hummocky surge along stream thalweg is shown by dotted white line. Photo taken summer of 2014. This photo location is also on the aerial photo in Figure 15 and is shown on Figure 9 map.

TRIGGERING MECHANISMS

The triggering mechanisms for the WSCL includes the driving forces for two modes of failure: 1) the rotational failure of the Upper Block, and 2) the mechanics that allowed the disturbed Green River Formation rock mass to rapidly disaggregate and create a condition where a valley-constrained flow of rock and debris could run out over two miles on a relatively low gradient.

Rotational Failure

The rotational movement of the Upper Block is the more easily understood failure at the WSCL from a limit-equilibrium and kinematic framework. As discussed earlier, the Upper Block was the remnant of a pre-existing prehistoric landslide and the WSCL movement appears to have occurred along the same, pre-existing, deeply-curved shear surface (Figures 2 and 3). Prior to the May 25th WSCL failure, a prehistoric shear plane had already experienced over 270 ft (82 m) of vertical movement in the geologic past and was at a much weakened, residual-shear strength condition.

Three drainage networks also converge onto the Upper Block from the plateau above, insuring that ground water levels are high in the spring. The plateau escarpment receives a precipitation average of about 30 in per year. Data from the NOAA regional climate center indicates that average precipitation was over 200% of normal for the period from 5/12/2014 to 6/10/2014. According to local residents, significant heavy wet snow fell during a Mother's Day weekend storm. High ground water was also indicated by seeps in the scarp seen for several weeks after the landslide. While the precise triggering threshold is not known, there were precursor failures and slumps along the front of the Upper Block recorded by both a seismic station and eyewitness account (Figure 2), and muddy debris flows were occurring at the toe of the block where beaver ponds existed. High ground-water levels in the disturbed rock mass, an already weakened shear strength of the slip plane material, high pore pressure reducing the effective normal stress, and loss of lateral support of the Upper Block front by precursor landslides earlier that morning all contributed to triggering the slip along the pre-existing, deeply-curved, shear surface and causing the rotational failure of the Upper Block. This 3-minute-duration rotational failure occurred at 5:45 PM and was the source of materials that formed the rock avalanche/debris flow(s) down the valley.

Rock Avalanche and Debris-Flow Failure(s)

The failure and run out of the rock avalanche is complex, and detailed discussion of the mechanical transition of a rock slide to a rock avalanche is beyond the scope of this report. However, based on field observations, the CGS believes a number of conclusions and assumptions can be stated:

1. The disturbed rock mass was thrust out from the toe of the Upper Block along an assumed rotational slip plane shown in Figure 7.

2. The rock mass was composed of brittle, fractured, and thinly bedded shale and marlstone that was already disturbed by shearing and earlier landsliding The original near-vertical joints and shears, now tilted by rotation of the Upper Block by both the prehistoric landslide and the WSCL, dip steeply (55°–70°) toward the valley below.

3. Very large segments of mobilized rock mass, with a lateral velocity component, sheared off the face of the Upper Block along these high-angle shear zones. While speculative, the seismic waves (Figure 4) seem to indicate that there was a time-relative spacing of the failure of the rock mass segments and development of the cascade of rock avalanche debris surges over the 3-minute period. The crosscutting morphology of the rock avalanche deposits supports the theory of discrete avalanche surges.

4. The sliding disturbed rock mass very rapidly disaggregated into the granular material seen in the debris field.

5. This material, including soil and forest cover, had the ability to mobilize from the evacuation zone of the face of the Upper Block and "flow" approximately 2.2 mi (3.5 km) at an extremely high velocity. Figure 13 contains superimposed cross sections that were cut normal to the flow direction of the rock avalanche using pre- and post-landslide topography.

The sections show the comparative elevation differences of the opposing lateral deposit trim lines at bends of the stream thalweg. The extremely high velocity of the rock avalanche front caused the debris to surge up and overtop both ridgelines; the west ridge trim line has a differential rise of a minimum 206 ft (63 m), compared to the inside-curve trimline elevation on the opposing east side.

6. No mud or water flowed from the steep-walled toe of the landslide. The dry nature of the deposit would imply that, while ground water and pore pressure likely played a major contributing triggering factor for the rotational failure of the Upper Block, it likely played a lesser role in the flow of the granular rock avalanche deposit and did not provide the uplifting stress (i.e., friction reduction) to allow the avalanche to achieve such high mobility.

MONITORING

Initial monitoring of the landslide included water level gages of the sag pond and the floor of West Salt Creek 750 ft (228 m) below the landslide toe, 5 GPS stations, and 2 web-based cameras. The locations of these tools are shown in **Figure 19** which also shows property ownership in the WSCL area. Following peak runoff (late June 2014) the pond level remained relatively consistent, indicating the lower summer inflow rate into the sag pond was about the same as the infiltration rate of water percolating into the landslide mass and rock avalanche debris field. During spring 2015, sag-pond levels rapidly rose 13 ft (4 m) before slowly dropping in mid June.

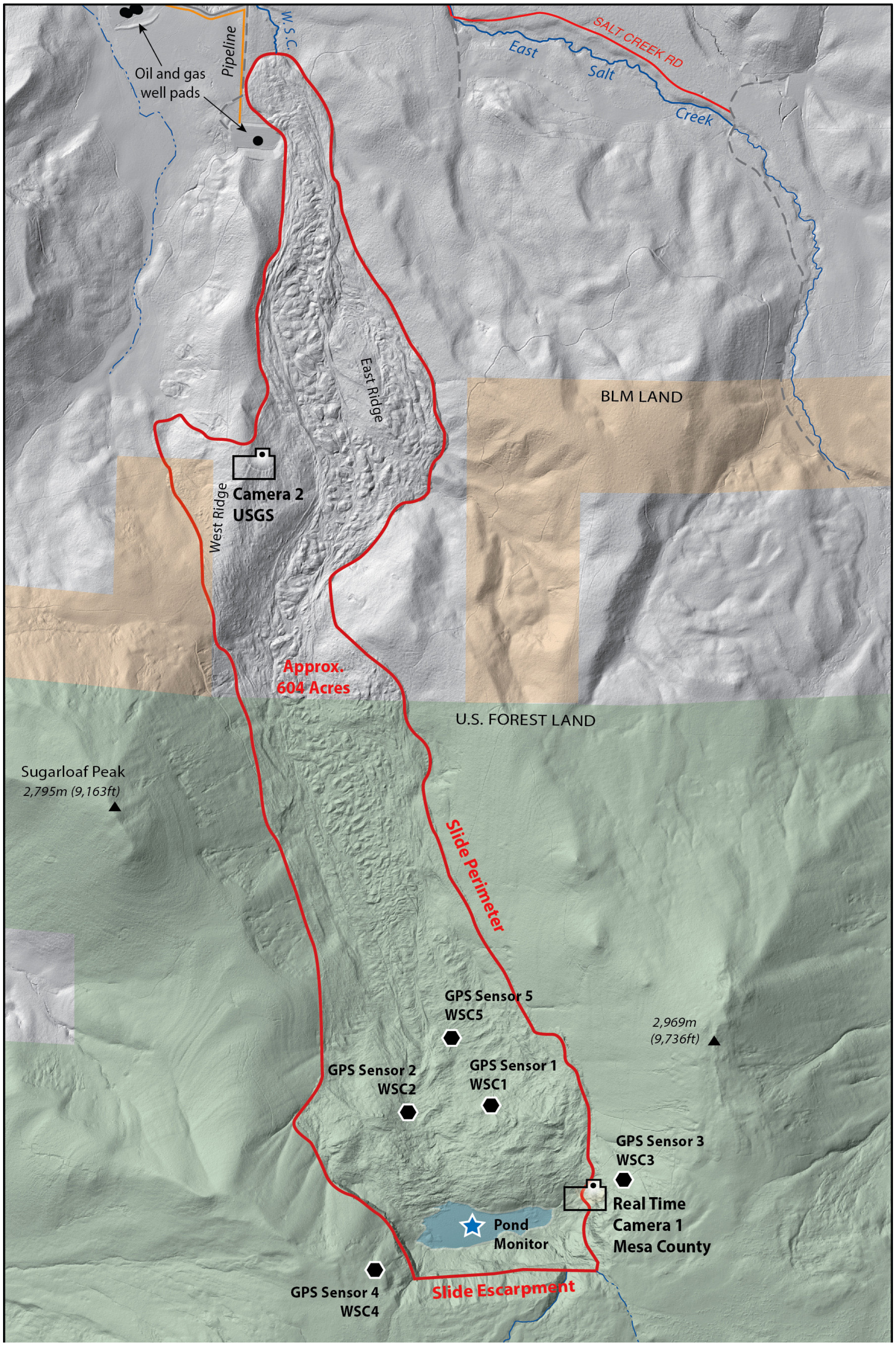


Figure 19. WSCL instrumentation and property ownership map. Map courtesy of the Mesa County GIS/IT Department.

GPS stations were installed by Mesa County at five locations; three are on the Upper Block within the landslide while two are located on the flanks above the headscarp. Vectors of movements through October 1, 2014 are shown on **Figure 20** (B. F. Kochevar, written communication, 2014). Most of the movements outside the landslide appear to be within instrument tolerances. Vertical movement is occurring in the center of the Upper Block, which are attributed to settlement of the dilated and disturbed rock mass. As of early June 2015, no discernible movements of the Upper Block have occurred.

The USGS and Mesa County replaced wireless-based camera stations in early spring 2015 to conduct remote visual inspections of the sag-pond and evacuation zone of the Upper Block where the new piping outlet flows water. In videos created by Jeff Coe (USGS), other than minor localized sloughing of material in very steep areas of the Upper Block face, no gross movements of the Upper Bock have been visually detected.

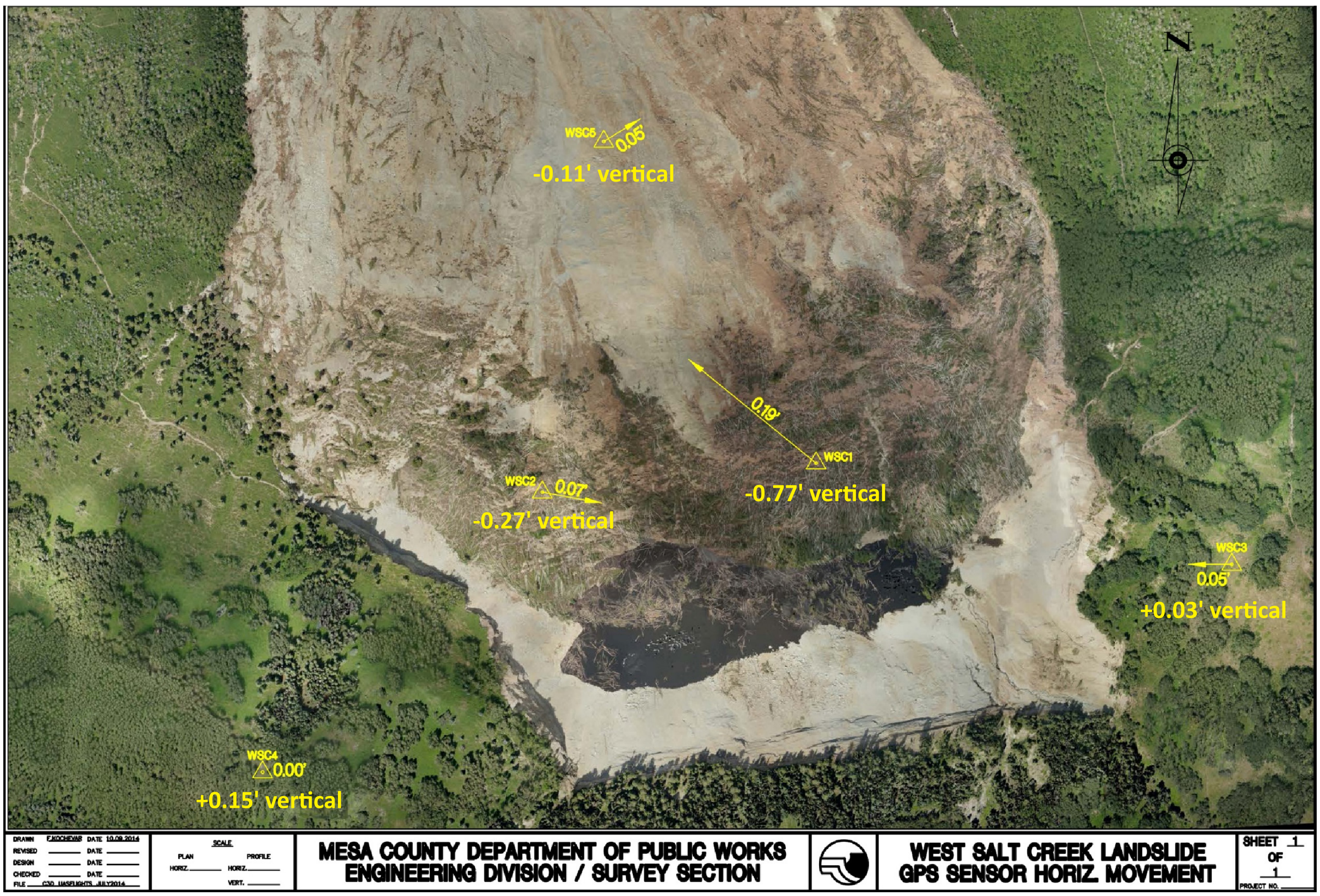


Figure 20. GPS sensor locations with horizontal vectors through October 1, 2014. Vertical displacements are also shown in yellow text. Lengths are in feet. Image courtesy of Frank Kochevar, Mesa County.

FUTURE CONCERNS and LONG-TERM HAZARD ASSESSMENT

Fortunately, the WSCL occurred in a rural setting and did not directly damage the town of Collbran or destroy nearby residences. However, the community, and local businesses were affected personally and economically. The loss of life, pasture, access to grazing land, irrigation water, revenues from reduced tourism, and living with the threat of additional flooding and landslides were devastating to the local community. Oil and gas operations had to be halted and mitigation measures were completed to help prevent future damage to the well pad.

Throughout the summer and fall of 2014, staff from the CGS, USGS, and Mesa County observed ponds forming below the sag pond and along the length of the landslide, indicating saturation of the rock avalanche deposit. However, no water was seen seeping from, or flowing over, the toe of the landslide until December 2014. The landowner reported that surface flow from the debris-field ponds had extended to a 4-wheeler track Mesa County built across the landslide toe just above the oil and gas well pad (T. Hayashi, Mesa County Road and Bridge Dept., written communication. 2014). In January 2015, 7 months after the landslide event, surface waters began to flow over the landslide toe into the original channel of West Salt Creek. However, this surface flow is still an accumulation of ground-water seepage in the rock avalanche deposit. In spring 2015, debris-field ponds on the hummocky floor have increased in size, some up to 300 ft (91.5 m) across (**Figure 21**), which have further fed the new creek that flows down the lower half of the debris field to the landslide toe where the debris material has slumped and gullied to create a small 50-ft (15.2 m) long alluvial fan near the original West Salt Creek bed.

Figure 21. A year after the WSCL, large ponds formed on the hummocky late-surge rock/debris avalanche deposits. View is to the northeast from the West Ridge at the same location of Figure 11g. Note finer-grained debris field in foreground compared to Figure 11(g), as a result of year-long slaking of Green River Formation clasts. Photo date: June 5, 2015. Photo location is shown on Figure 9 map.

In April 2015, as this report was being completed, Mesa County Office of Emergency Management prepared a West Salt Creek Landslide Emergency Action Plan. This plan includes an emergency action plan, inundation study, sensor location map, a trail map, and communication directory. The emergency manager also prepared a notification system so the appropriate response personnel would be automatically called if any of the threat scenarios discussed below were to occur. In late May and early June 2015, the sag-pond water level rapidly rose 13 ft (4 m) and, more ominously, a flowing spring had begun to pipe from the base of the Upper Block (**Figure 22**). Safety concerns caused the Emergency Manager of Mesa County to issue Level I and II alerts. West Salt Creek still flows into the sag pond at the landslide scarp. In early June of 2015, the sag pond level is approximately 2–3 ft (0.6–0.9 m) below spill-over elevation. By mid-June the pond level began to slowly drop.

Long-term Stability of the Upper Block

The disturbed and rotated Upper Block is now resting at a temporary equilibrium and the existing driving and resisting forces are at parity. Colorado School of Mines Department of Geology and Geological Engineering conducted limit-equilibrium slope stability analyses of the Upper Block. Since it wasn't feasible to complete investigative borings, failure models were back-calculated from before and after topography.

Sensitivity analyses were completed by varying cross sections through the block, failure surfaces, and ground water levels in the model. Their executive summary suggests the global stability of the rotated block is good, with a 26-53% higher safety factor (SF) than the pre-May 25th condition. However, they caution that there is strong sensitivity to water levels, and as the sag pond fills to overtop, the SF could drop as much as 30%, and slope failures could breach the pond (McCoy and Santi, 2014). This became a significant concern in the spring of 2015 as the sag pond filled to almost the spill-over elevation and the active pipe began to flow water from the base of the block. At present, the global stability of the Upper Block is unknown, as well as whether any potential failure would be the entire block, or only a portion as an embankment-type failure.

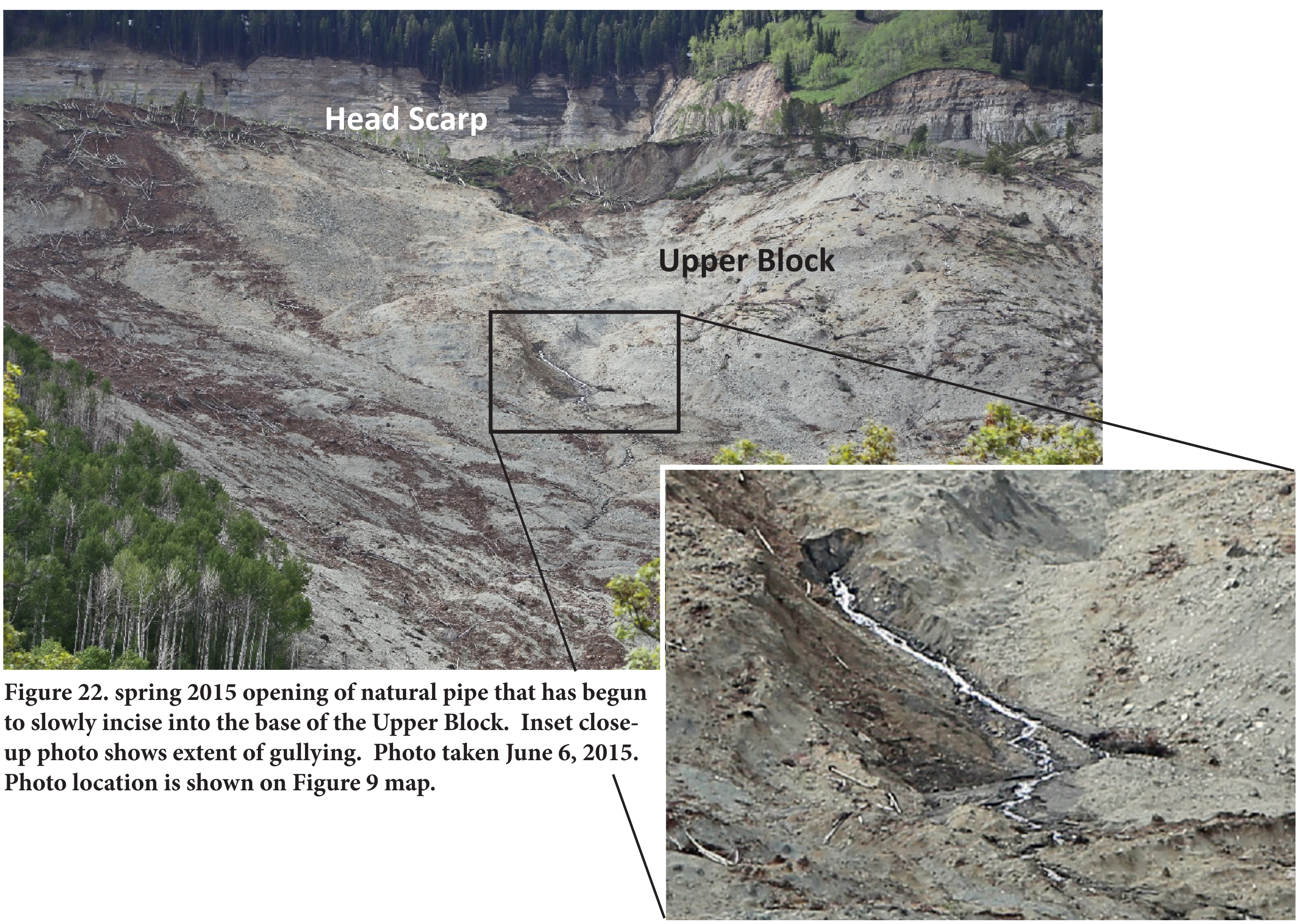


Figure 22. spring 2015 opening of natural pipe that has begun to slowly incise into the base of the Upper Block. Inset close-up photo shows extent of gullying. Photo taken June 6, 2015. Photo location is shown on Figure 9 map.

Reactivation and Retrogressive Failure from above the Landslide Headscarp

There is a level of uncertainty in the extent of disturbance and overall stability of the bedrock exposed above the escarpment of the May 25th landslide. Considerable evidence suggests that an extensive disturbed bedrock zone lies around the perimeter of the headscarp where many geologically recent subparallel escarpments of varying steepness and vertical slip extent were mapped (see Map Plates 1 and 2). Some are prominent: a narrow remnant of one prehistoric intermediary block that slid down 110 ft (33.5 m) remains above the east end of the May 2014 headscarp, portions of pre-existing eastern flank landslide scarps were further ruptured by the May 25th event, and the newly exposed rock shows evidence of shear in the downhill direction (Figures 6b and 6c). These secondary scarps that outline the perimeter of the current head- and lateral-scarps have had the most recent movement prior to the May 25th event. At these locations, exposed bedrock is disturbed and should be considered unstable. During inspections in June 2015, new small scarps and widening of existing tension cracks were observed at or near the headscarp. One would expect some dilation of the rock mass at the scarp cliff with the loss of lateral support from the 450-ft (137-m) downward slip of the Upper Block. While there has been small shallow slips from the scarp into the sag pond, other than visual inspections, there is currently no instrumented monitoring of the rock mass exposed along the 2014 scarp.

It is also unknown whether old scarps above the escarpment, with slips less than 10 ft (~3 m), reflect precursor deep-seated shear zones within the Uinta and Green River Formations, or are only near-surface failures within soft claystones of the Goodenough formation. Because of the orientation of the subparallel scarps to the perimeter of the valley landslide "amphitheater" shown on Plate 1, it is our judgment that these smaller features are tied to disturbance (rock dilation and shear) within the deeper bedrock. The CGS considers those areas of the mapped disturbed bedrock zone to be potentially unstable. If portions of the head scarp were to fail and slide into the sag pond, the rapidly displaced water would create a mini-tsunami and slosh over the spill-over rim. Further loading of the Upper Block would also occur, increasing the driving forces and lower overall global stability.

Threat of Mud/Debris Flows

Below the headscarp, mudflows and debris flows are additional threats with risks likely higher during spring runoff. When water in the sag pond rises and overtops the depression rim, it may flow uncontrollably down the steep slope of the shattered lower face of the Upper Block. Slaking of the rock avalanche debris at the surface (Figure 16) is also increasing both erodability and potential bulking factor of any flow. Four major scenarios are possible when the sag pond "fills and spills" (**Figure 23**):

1. Embankment-failure type slump of a portion of the Upper Block and catastrophic release of the pond,

Figure 23. Image of the sag pond taken June 6th, 2015. The pond level is estimated to be 2–4 ft (0.6–1.2 m) below spill over (red arrow).Photo location is shown on Figure 9 map.

flooding through the debris field, and likely extending a debris-laden flood surge to the floor of the Salt Creek valley. This scenario raises the highest concern because of the potential catastrophic nature of the failure, and the piping flow that began from the base of the Upper Block in spring 2015 (Figure 22).

2. Overtopping flow becoming turbulent and erosive, quickly downcutting, and causing a rapid release of water down the steep gradient that would entrain landslide material to form a debris flow. The flow would likely remain within the hummocky landslide debris field but it is unclear whether the extent of downcutting would ultimately extend to the pond floor elevation and empty it.

3. The mini-tsunami displacement of sag-pond water would top the spill-over rim and potentially wash out the Upper Block rim, rapidly lowering the causeway while simultaneously entraining material into the debris flow.

4. West Salt Creek re-establishes a channel through gradual downcutting and ravine widening at the front of the Upper Block. Part of the pond remains and a stable pond outlet is created. In time, the broken ground will smooth out and the pond will fill with alluvium and colluvium (talus) from the scarp so that a pronounced topographic bench is formed in the slope, similar to the original pre-May 25th condition shown in Figures 2 and 3.

Creeping Earth-flow Spread and Sediment Loading

As was mentioned earlier, the WSCL rock avalanche debris field was relatively dry with no water or mud seeping from the toe immediately following the event. However, runoff from the West Salt Creek basin continues to flow into the sag pond and percolate into the landslide mass. One year after the landslide, many ponds have formed from groundwater upwelling into the debris field (Figure 21), as well as water flowing over the toe into the existing West Salt Creek bed.

As the debris becomes fully saturated, and disintegration from slaking continues to increase the percentage of clay and silt in the deposit, we expect a certain amount of creep at the toe of the rock avalanche that will move towards the confluence of the East and West Salt creeks. However, the valley widens and the gradient flattens considerably below the landslide toe; thus, the likelihood of a creep scenario that could possibly impact 60 ½ Road about 670 ft (204 m) below the rock avalanche toe is very low and would likely span many years. A year after the WSCL, the current stream flowing from the 2014-2015 pond network is incising into the avalanche toe and deposited a small alluvial fan below. However, earth-flow creep has not been detected.

Until West Salt Creek re-establishes a stable channel through the landslide, and the debris field is revegetated, increased sediment will continue to be transported downstream to Plateau Creek. It is not yet known how the increased sediment load will affect stream dynamics and water quality. The Colorado Water Conservation Board (CWCB) will conduct a pilot study on sections of Plateau Creek downstream of the landslide. The study will contrast two channel migration zone mapping methods and assess the effectiveness of each method. They will provide recommendations to the local community on how to use the mapping for planning and zoning purposes. The final erosion hazard maps will be used to understand how predictions of erosion hazard vary spatially, and the differences will be assessed to understand how the methodological approaches led to these differences. In completing the study, CWCB may evaluate how increased loading from landslides affects stream capacity, velocity, gradients, erosion, and deposition.

Burial and Shearing of Oil and Gas Well Heads

Immediately after the May 25th event, there was much discussion on what might have happened if the landslide toe had flowed over oil and gas well heads. The shut-in valves (Christmas tree) were above ground and may have sheared off if the landslide toe had flowed over them. This would have resulted in one or more open well bores with uncontrolled release of gas. To seal the wellbores, the operator would have likely needed to directional drill a new well from a safe distance from the well pad, intercept the venting well bores, and plug them (C. Clark, Occidental Petroleum Corp., personal communication, 2014)

Once the landslide toe was considered stable enough to study, the oil and gas company reduced debris flow hazards for their site. Produced fluid tanks and well pipelines were moved to the west side of the oil and gas pad, away from the rock avalanche toe, and diversion berms and ditches were constructed to both direct future flows to either remain within the landslide mass or be conveyed away from the well heads. This mitigation would likely be ineffectual if another large landslide or catastrophic breach of the sag pond, were to occur. The oil and gas operator elected to shut in the three wells near the WSCL rock avalanche toe during the spring 2015 runoff as the sag pond level was rapidly rising.

LAND-USE RECOMMENDATIONS and FUTURE STUDY CONSIDERATIONS

While the WSCL was extraordinary in its size and mobility, landslides in the Plateau Creek valley area are common, and the geologic evidence strongly suggests that similar-sized prehistoric landslides and earthflows have occurred in other drainage subbasins that flow into the greater Plateau Creek valley from the same geologic bedrock units. However, the available geologic maps of the area (Ellis and Freeman, 1984; Donnell and others, 1985) do not map any landslides in the vicinity; they are entirely omitted or included in colluvium or glacial till units.

Due to the abundance of landslide activity in the 1970s and 1980s, CGS completed two landslide studies near Vega Reservoir and vicinity (Soule, 1986; 1988). These previous studies concluded that landslides and earthflows can be extensive. However, the risk of massive catastrophic failures, like the WSCL that could extend a rock avalanche debris field miles down a valley, were not considered. The work of Soule (1986, 1988) is included in the online CGS landslide inventory.

However, with the benefit of LiDAR data and generated bare-earth hillshade imagery, and much higher resolution stereo aerial photography, there are many more discernible, mappable landslides than were originally mapped by Soule (1986, 1988), and several reflect movements of rock avalanche or rocky debris flows of similar magnitude. In conclusion, the existing CGS inventory of landslides from published map sources does not presently reflect true ground conditions and the actual landslide density and the risk of catastrophic failure, is higher, both for the study area and more regionally in the Plateau Creek basin.

The catastrophic, high mobility, lethal nature of the WSCL rock avalanche cannot be mitigated in any appreciable way so avoidance of potential susceptible areas or monitoring of at-risk areas as part of an emergency action plan are the only reasonable course of actions. On the basis of the available data and the mapping efforts at the WSCL, this report offers the following recommendations, observations, and suggestions for future studies.

Public Use of U.S. Forest Service (USFS) Lands within the Landslide Area

The USFS has implemented an area of closure of Forest Service lands that includes the landslide debris field and a 984 ft-wide (300 m) perimeter on the plateau above the headscarp. Because of the stability and hazard concerns raised above, we generally concur with the closure set back until further notice.

Future Development and Land Usage of the Landslide Vicinity

The CGS recommends that no development or land use that includes human occupancy should be allowed within the landslide debris field, the alluvial fan from the landslide toe to the confluence of the West and East Salt Creeks, or along the flood plain of Salt Creek. Because of the threat that an earth flow could dam East Salt Creek, CGS also recommends that development not be placed in the flood plain immediately above the confluence.

Additional Instrumentation

One of the biggest unknowns for the landslide complex is the stability of the headscarp. The area above the headscarp is not included in the existing array of GPS stations because of the heavy tree cover and inability of acquire cell service. The current cameras and GPS tools will not detect small displacements of the rock mass exposed along the head scarp or within the disturbed bedrock zone above the escarpment. We recommend either GPS stations be placed atop, prisms anchored for EDM surveys, or either terrestrial or aerial (QL1 resolution) LiDAR or InSAR surveys be conducted at least yearly to monitor any deformation such as bulging of the rock mass at the headscarp cliff or displacement behind it.

Regional Recommendations

As stated earlier, there are abundant landslides in the greater Plateau Creek basin, many of which have not been mapped. Fortunately, this is predominantly a rural area and the Mesa County Master Plan recommends keeping the land in large parcel sizes and avoiding the conversion of agricultural lands to residential or nonagricultural commercial uses (Mesa County, 2013).

However, it is also part of the Plateau Field, a regional oil and gas producing area, with over 80 active facilities (COGIS, 2015), some of which are located in potentially hazardous areas and at risk of being impacted by landslides, earth flows, and/or debris flows. **Figure 24** is an image of the Plateau Creek basin that shows the locations of mapped landslides and oil and gas wells. As previously stated, there are many more landslides not in the current landslide inventory shown in this figure. For new development, including oil and gas facilities, we offer the following recommendations:

1. Development should not be constructed along a valley/drainageway bottom or the alluvial fan that outlets the valley mouth without a detailed geologic hazard investigation. Hill slopes immediately above proposed development locations should also be carefully examined for evidence of movement or landslide morphology.
2. Completion of a comprehensive landslide risk assessment of the greater Plateau Creek basin and other landslide-prone areas in the county. The assessment should include both field mapping and mapping using high-resolution LiDAR.
3. The geologic conditions above existing development should be examined for potential landslide risk.

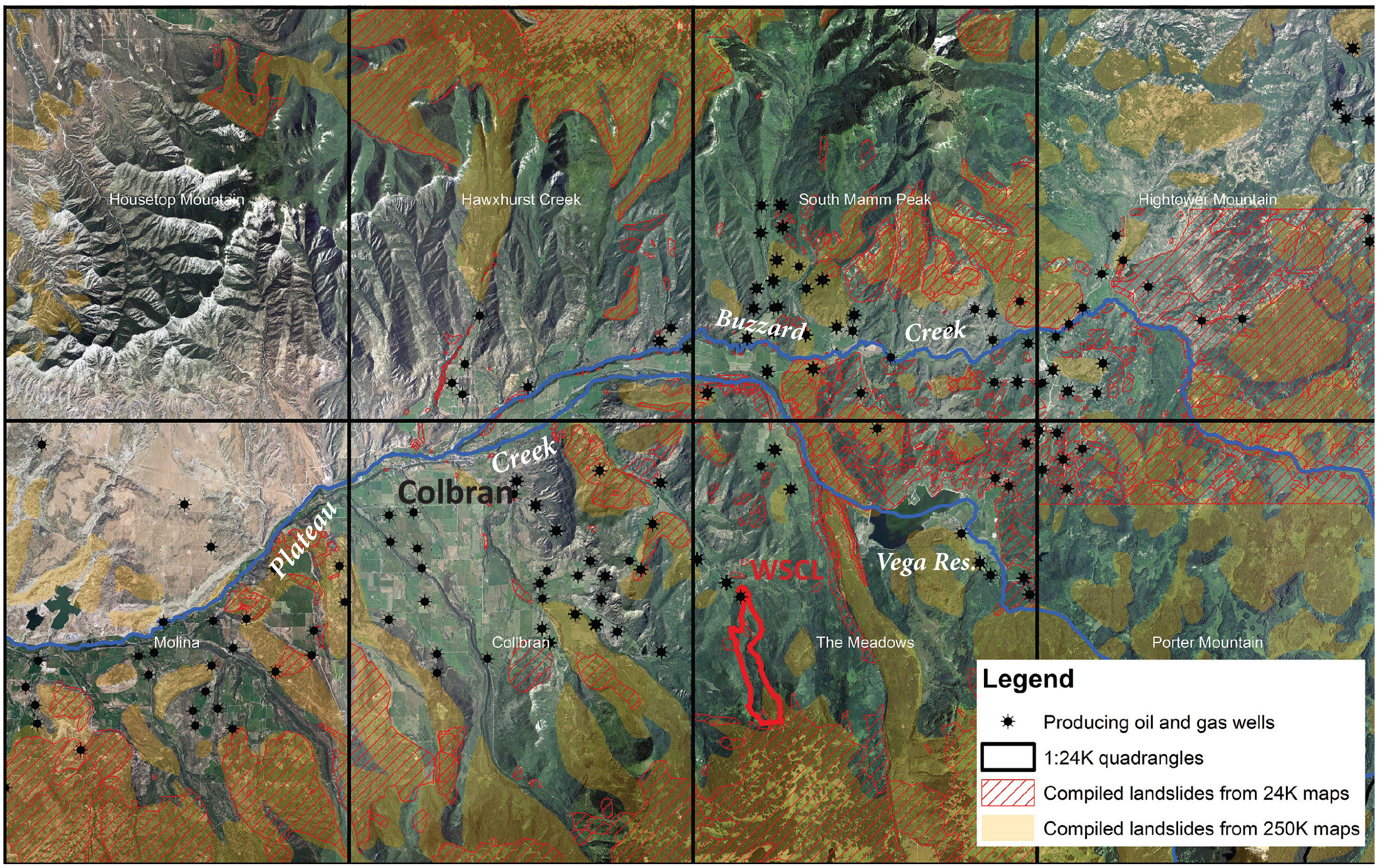
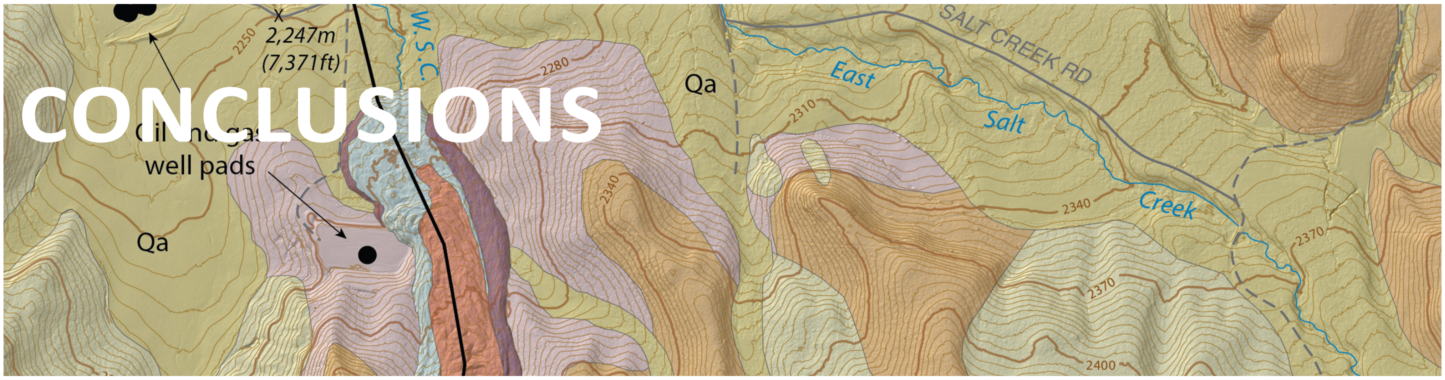


Figure 24. . Map of greater Plateau Creek basin showing location of oil and gas well pads and landslide inventory. The WSCL boundary is shown by solid red line. Basemap is a NAIP 2009 orthorectified aerial photograph. Note lack of mapped landslides near the WSCL in inventory compared to landslides mapped from LiDAR data on geologic map.



CONCLUSIONS

The WSCL and resultant rock avalanche on May 25th, 2014 was the largest mass-movement slope failure in the historical record of Colorado. The catastrophic failure occurred on the northern margin of Grand Mesa where smaller landslides existed previously. Late springtime runoff likely lubricated the already weakened shale bedrock causing it to slip, disaggregate, and mobilize down the West Salt Creek valley at relatively high velocity. The failure created a series of cascading rock and debris avalanches that were deposited in a matter of minutes and registered a small earthquake on local seismometers. A large block of disturbed bedrock still looms below the landslide headscarp that has dammed local streams and formed a sizable sag pond. Concerns with the stability of the WSCL continue a year later with rising sag pond levels, emergent springs, and piping outlets of flowing water. The failure has raised concerns in the geologic and emergency response community about the potential similar large-volume, high-velocity catastrophic landslides. It has prompted a re-examination of ancient landslides as to whether their morphology and modes of failure were similar in magnitude and mobility to the WSCL. Mesa County, and especially Grand Mesa, contains hundreds of active and inactive landslides. Fortunately, many of these features are in remote or undeveloped areas and have caused little damage. LiDAR technology and its ability to record ground surface elevations below the forest canopy greatly improves mapping of landslides in these areas. Collaborations of county, state, and federal agencies and private industry to complete a state-wide LiDAR survey will be important to Colorado, especially where landslide conditions exist. As more detailed mapping becomes available, a better understanding of landslide susceptibility will be forthcoming.

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Appendix A - Police Reports

Case No. – 2014-15096
Deputy – Lt. Jim Fogg
Date – 06/12/2014
Time – 1800 hrs.

On May 25, 2012 at approximately 18:17 hrs. Tiffany M. Bracco (born 12/28/76) made a 911 call to Grand Junction Regional Communications Center (GJRCC) reporting three people possibly caught in a large mud slide in the West Salt Creek Drainage. Mrs. Bracco was calling from 63444 60 ½ (Salt Creek) Road., the home of Melvin Clyde Hawkins (born 03/29/42). Mrs. Bracco identified two of the three subjects possibly trapped in the slide as Melvin "Wes" Hawkins and Clarence "Clancy" Nichols. It was later learned that the third subject was Clancy's son, Daniel Nichols. This incident occurred after a day of heavy rain in the area, and at the height of the spring run-off. The lower end (toe) of the slide was located on property associated with 63511 60 ½ (Salt Creek) Road.

Plateau Valley Fire Department (PVFD) and the Mesa County Sheriff's Office (MCSO) were dispatched to the incident. Some of the first members of the PVFD was Eric Bruton (born 07/09/1964), his wife, Monica Bruton (born 12/30/66) and her son, Mathew Nichols (born 12/18/94). Monica Bruton is Daniel Nichols' mother, and ex-wife to Clancy Nichols. Matthew is brother to Daniel and the son of Clancy Nichols. Upon their arrival, Eric Bruton began simultaneously coordinating resources, gathering information, and performing a hasty visual search on the lower part of the slide. At the time of their arrival, the slide was still actively moving.

MCSO Sgt. Terry Bridge and Lt. Phil Stratton were notified and began the process of gathering search and rescue resources and responding. When they arrived about 1 ½ hours after the 911 call the slide was still active. At that time members of PVFD were attempting to search the lower portion of the slide. However, because there was little day-light left, the slide still being active, and the unknown threats presented by this type of event, the decision was made to wait until the next morning to perform any additional searching. However, several people were left in strategic and safe locations around the slide overnight to monitor any movement of the slide or the victims.

It was learned that that the three men (Clancy Nichols, Wes Hawkins, and Danny Nichols) had gone into the area of the West Salt Creek drainage to investigate a smaller slide reported by Wes' father, Melvin Hawkins. Wes Hawkins was acting in his capacity as the District Water Manager for the Collbran Conservancy District. Clancy Nichols was there acting in his capacity as the Mesa County Road and Bridge Supervisor for the area and had taken his son Danny along. They were believed to have been in slide area when the larger slide began. Wes Hawkins was riding a 2009 blue Yamaha Grizzly 400 (model YFM450FWAN, VIN #5Y4AJZ6YX9A007529) owned by his father, Melvin Hawkins. Daniel and Clancy were in Clancy's personal vehicle a gray 2012 Chevy Silverado 2500 4x4 truck with a gas engine and the stock tires bearing a Colorado license plate of 486WDC. Based on the location where Melvin Hawkins believed they would have driven to, the search would be focused on the lower third of the slide.

On the morning of 05/26/2014 a more comprehensive search was conducted. A helicopter, approximately 20 ground searchers, and an unmanned aerial vehicle were used throughout the day. At the same time, an assessment of the stability of the upper part of the slide was being conducted.

By the end of the day, 05/26/2014 ground searches had searched the edges of the lower third of the slide twice, with no success. At the same time, a more thorough assessment of the size of the slide had been made. It was determined that the slide was as much as 200 feet deep in some areas, and averaged about 30 to 60 feet deep in the lower section. It was 2.4 miles long (south to north) and about ½ mile wide at its widest (east to west) with an elevation drop of about 2800 feet. Later calculations determined that there was 30 million cubic meters of material that had moved, filling the lower part of West Salt Creek drainage. It was estimated to have taken less than a minute to cover the distance from the top to the bottom, and therefor was not a survivable event for anyone caught in its path. Geologists on scene on 05/26/2014 determined that the slide area was still very unstable and therefore unsafe for anyone to be searching. At about 1800 hrs. on 05/26/2014 the decision was made to cease all search efforts due to safety concerns. No evidence of any of the men was found to that point.

On 05/27/2014 I returned to the scene with Eric Bruton. Eric pointed out to me tire tracks leading into the slide area that he was confident were the tire tracks of Clancy's truck and Wes's ATV. The tracks were on a dirt road that goes across land belonging to the Hawkins's family. The primary use of the road is for two gas wells. The section with the tire tracks was a short branch of the road between the two well pads, and directly below the higher well pad. The road was only used to access the West Salt Creek drainage, but all that was remaining was about 100 yards directly off the main well pad road. The remaining ½ mile to 1 mile of the road was covered by the slide.

I noted that there was only one set of car/truck tires, and one set of ATV tracks on the road. It was evident that the tracks had been made when the ground was wet based on the depth of the tire impressions compared to the firmness of the now dry ground. The tire tracks disappeared into the slide debris field, which was about sixty feet high at that point. Eric Bruton told me that he had noticed the tracks when he first arrived on the scene on 05/25/14 and that they had been unchanged since that time.

Eric Bruton also told me he and several other people had searched both the east and west sides of the lower portion of the slide during the 24 hours after the slide. He said he continually watched for any foot or tire tracks coming out of the slide area, but never found any.

On 05/27/14 I also interviewed Matthew Nichols. Matthew told me that he had spent part of the early part of the day on 05/25/14 with his brother, Daniel Nichols, and father, Clancy Nichols. At about 1445 hrs. on 05/25/14 Matthew said Clancy discovered he had a voice mail related to the report of a slide on Salt Creek. Matthew said his father called his supervisor with Mesa County Road and Bridge to get details. Clancy invited both Matt and Daniel to go with him to investigate the slide. Matt declined, but Daniel agreed. Matthew said he left his father's home at about 1530 hrs. He said his father and brother were just getting ready to leave. Matthew said he believed the two headed toward Salt Creek within minutes of him leaving the house.

Matt told me that he believed Daniel was wearing brown leather work boots, blue fire retardant (FR) work pants, and a long sleeve tan FR work shirt. He said Daniel would have also been wearing a camouflage Under Armor hoodie and a hat with a logo representing a pipe line. He said his father, Clancy, was wearing brown leather work boots, blue jeans, a forest green long sleeve shirt, a dark colored Mesa County hat. He said his father had his reflective safety vest in hand and a pair of binoculars hanging around his neck when he was preparing to leave. Matt said his father would probably have had a camouflage jacket with a hood in the truck.

I also asked Matthew about the tracks that Eric Bruton had shown me. Matthew said he was fairly confident the truck tire tracks we had seen were consistent with his father's truck tires. Matthew said his father's truck was a 2012 Chevy Silverado 2500 with the stock tires.

On 05/27/14 I spoke with Melvin "Slug" Hawkins, Wes Hawkins' father, who resides directly across the Salt Creek valley from the West Salt Creek Drainage. He has a clear view of the top of the West Salt Creek drainage from his home. Mr. Hawkins told me that events on the West Salt Creek drainage started early in the morning. He said he heard a strange "hissing" noise coming from that direction between 0600 hrs. and 0700 hrs. He suspected there might be a problem with one of the well pads in the area. He drove to the well pads, but found no problem.

Mr. Hawkins told me that between 0930 hrs. and 1000 hrs. on 05/25/2014 he looked out his window towards the top of the West Salt Creek drainage and realized something didn't look right. At about that time, Danny Walk (who farms some of the fields in the area) stopped by and told him the he (Danny) wasn't getting enough water down the irrigation ditch. Realizing the water issue and what he had seen on the West Salt Creek drainage might be related, he and Mr. Walk went to investigate.

Mr. Hawkins said he drove up a trail on a high ridge towards the Forest Service Boundary on West Salt Creek drainage. As soon as he was close enough, he noticed trees moving high up in the drainage and on the east side. He realized the ground was already slowly sliding, but to a much smaller degree than what would come later, and had already blocked West Salt Creek. Concerned about potential damage the slide might cause, he returned home to call his son, Wes Hawkins. He estimated the time of the call to his son to be about 1350 hrs. Wes mentioned to him that he was going to call someone from County government since the slide could end up affecting the road.

While I spoke with Melvin Hawkins', Kyla Hawkins, Wes' wife was also present. She told me that she had gotten a call from Wes about 1400 hrs.. She said she had been in Collbran when she got the call, but arrived home before Wes left to go to Salt Creek to investigate. She said she believed it was about 1500 hrs. when Wes left his home to go to his father's home on Salt Creek.

Mr. Hawkins went on to tell me that Wes, Clancy, and Danny all met at his house before going up the West Salt Creek Drainage. He said Wes decided to borrow one of his ATVs, a blue 2009 Yamaha Grizzly 400, while Clancy and Danny took Clancy's truck. Mr. Hawkins believed they would drive to near the Forest Service boundary on West Salt Creek, then walk up farther to investigate. Mr. Hawkins estimated that the three left his home at about 1530 hrs. (It was likely later given the time that Clancy and Wes left their respective homes and given driving time. Throughout Mr. Hawkins' statement I noted that his estimation of the time of day was often off from what other evidence showed).

Mr. Hawkins told me that at about 1700 hrs. he noticed something on the ridge line running down the west side of West Salt Creek. He then looked closer and realized the entire drainage had released and created the massive slide. He quickly called his neighbors Tiffany and Melvin Bracco and told them to "come quick."

I later spoke with Tiffany and Melvin Bracco who reside at 64277 Salt Creek Rd. Their residence was the closest to the slide of any of the homes in the area. They told me that they heard a loud rumbling that got their attention. Tiffany described it as sounding like a low flying, large, military helicopter. Melvin described it as a very long clap of thunder that actually rattled the windows of their house. They said their children had been outside at the time and came running into the house. The children described the noise as sounding like a freight train coming. They said they all looked around outside, but didn't notice the slide because their view was blocked until they got farther down the driveway.

Both Bracco's report that it was between 10 and 30 minutes after hearing the noise, they got the call from Mr. Hawkins. They said he was panicked and asked them to come to his house. He told them the entire West Salt Creek had slid, and that Wes, Clancy and his son were up there. They immediately responded to his home that is only about ½ mile away. As they drove out of the driveway they saw the slide for the first time. (Mr. Hawkins mistakenly believed that it was Matthew Nichols, not Daniel Nichols that had been with Clancy.)

Once at Mr. Hawkins' residence, Tiffany called 911 while Melvin Bracco and Mr. Hawkins drove to the area of the slide to try and find the three men. They drove up a trail that goes to the top of the ridge on the west side. By the time they came back down, Eric Bruton was at the well pad.

On 05/28/2014 Dave Wolney, an Adjunct Faculty Member for Colorado Mesa University (CMU) advised the Mesa County Sheriff's Office that on 05/25/14 two of CMU's seismic stations detective a seismic events consistent with a landslide. That event occurred at 1743 hrs. and lasted about two minutes. This time frame would be consistent with witness statements in relationship to the 911 call. Mr. Wolney qualified that the actual landslide most likely only lasted about one minute, but that the energy waves detected lasted longer. Another seismic detector identified a smaller event at about 0719 hrs. This time would be consistent with Mr. Hawkins's hearing the strange noise while out irrigating.

Since 05/25/14 there has been a significant amount of human activity in and around the slide area. However, there has been no evidence that any of the three decedents.

On 05/30/2014 Colorado Governor John Hickenlooper issued Executive Order D 2014-009 declaring a disaster emergency due to the West Salt Creek Landslide in Mesa County. That order was issued pursuant to C.R.S. 24-33.5-701 and portions of C.R.S. 28-3-104.

End Report

JSF, L2193

06/09/2014 - ACTIVITY REPORT

CASE NO - 2014-15096

DEPUTY - TERRY BRIDGE #2222

TIME - 1700HRS

On 05/25/2014, at approximately 1845hrs, Lt. Phil Stratton contacted me by telephone. He informed me he received a message of a mudslide in the Salt Creek area on Grand Mesa, Mesa County, Colorado. He further informed me Plateau Valley Fire Department was en route as there were three people believed to be missing. Plateau Valley had requested SAR response.

I paged SAR volunteers, requesting ground, communications, and ATV's respond to an unknown staging area near the location. Once resources were paged, I responded to the area, with Lt. Stratton behind me.

Once we arrived on scene, we located the staging area, which was just off of Salt Creek Road, near the slide, at the entrance to Sugar Loaf Ranch. I contacted fire personnel, who told me three local people had been in the area where the slide occurred, and they had not been located. I was told the three had gone up to check on irrigation water and the road condition and had not returned. I was told the three people were Wes Hawkins, Clancy Nichols, and Clancy's son, Danny Nichols. Wes was reported to be riding an ATV. Clancy and Danny were reported to be in Clancy's pickup, a grey Chevrolet pickup.

Lt. Stratton and I wanted to take a better look at the slide so we could determine resource needs, so we drove up nearer the slide in my patrol vehicle. We drove up a gas well access road, looking for the slide. We saw what appeared to be a slide coming down through a saddle, thinking this was the major slide area. As we drove through one well site and started up to another well site, we discovered we were driving alongside the slide, which was at least twenty (20) foot above the level of the road. Partway up the road we discovered the slide had pushed out into the road. We had to drive out into a field to go around the slide and up to the upper gas well pad.

When we arrived at the upper gas well pad, we could see the slide had almost overrun the pad area, and was pushing against some of the equipment on the well pad. There was also an unoccupied UTV sitting at the end of the pad. While we were looking around the area, Eric Bruton and Cory (last name unknown) came walking down the hill to the south of where we were. Eric stated the slide was still moving and unstable. He pointed out a tree that was sticking out of the slide near the northeast corner of the slide. Eric said the tree had moved close to 40 feet since they arrived to walk up the hill approximately 1 hour prior.

We left the gas pad and drove back to the staging area. Com. 1 was positioned near the area and began setting up. It was decided that all other SAR resources would be staged in Collbran and the Plateau Valley Fire Department and would be deployed from there. This was mainly due to the small amount of room at the staging area and the fact the staging area was indirectly in the path of the slide if it continued down the valley.

As it began to get dark, it was decided the light plant would be needed, so Deputy Coleman was contacted and asked to pull the light plant up. Captain Callow and Undersheriff Spiess also responded to the scene. Captain Callow took over as Incident Commander. He appointed Lt. Stratton as Operations Chief. I was assigned as the liaison between SAR Resources and operations. Deputy Derek Johnson was contacted in reference to the availability of our UAV assets. Deputy Johnson responded to the scene.

By the time resources were available, the sun had gone down and it was dark. It was decided that there would be no search attempts due to the instability and low light. Helicopter assets were contacted, however the weather in the Grand Junction area was not conducive to flying. When the UAV arrived on scene, it was determined its usefulness would be very limited, also due to the low light. I did make arrangements to have a helicopter available the next morning. Century Link was contacted and agreed to help.

During this time, I spoke with "Slug" Hawkins, who lived across the road from the staging area. He told me the house directly to the south of the staging area belonged to his brother, Gerald, who advised Slug to open it up to be used.

As the house was available, which had a larger yard area, and was up the hill a little more out of the path of the slide, it was decided to move the staging area to the yard of the house. Once the staging area was moved, the personnel staying on scene for the night settled in for the night. This consisted of Captain Callow, Lt. Stratton, myself, and three SAR communications personnel. We contacted the rest of the SAR volunteers who were staged at Plateau Valley Fire Department and advised them to go home and return the next morning. Most Plateau Valley Fire Department personnel also left the scene.

Shortly after daybreak on 05/26/2014, SAR personnel started arriving at the Plateau Valley Fire Department staging area. While waiting for operations to start, I was asked to take a representative from the energy company up to where the slide was across the access road as arrangements were being made to clear the road so the upper well pad could be accessed and production water removed.

At approximately 0910hrs, we received information that the Century Link helicopter was on it's way to the scene.

Once it arrived on scene, the pilot was briefed on what was being asked of his helicopter. An initial flight was taken of the perimeter, with myself on board. We flew the perimeter from the northwest corner, south along the west perimeter, to the beginning of the slide, across the top of the slide, then back down the east side. We were looking for any signs of Clancy's vehicle or Wes' ATV. We flew the area for about 20 minutes, but did not locate any signs to direct searchers to.

Once I was back on the ground, the decision was made to put ground team searchers on the edge of the slide, in the lower third portion of the slide. It had been determined that Clancy and Wes would have gone into the area on an access road that was in the lower third area of the slide.

Throughout the day, numerous other flights were conducted over the slide area, and search operations were conducted within the lower 1/2 of the slide area. Subject matter experts were contacted and some responded to look at the slide area.

Due to recommendations from some of the subject matter experts about the stability of the slide area, search operations were suspended before dark. All personnel were demobilized and sent home. I left the scene at approximately 2000hrs.

END OF ACTIVITY REPORT

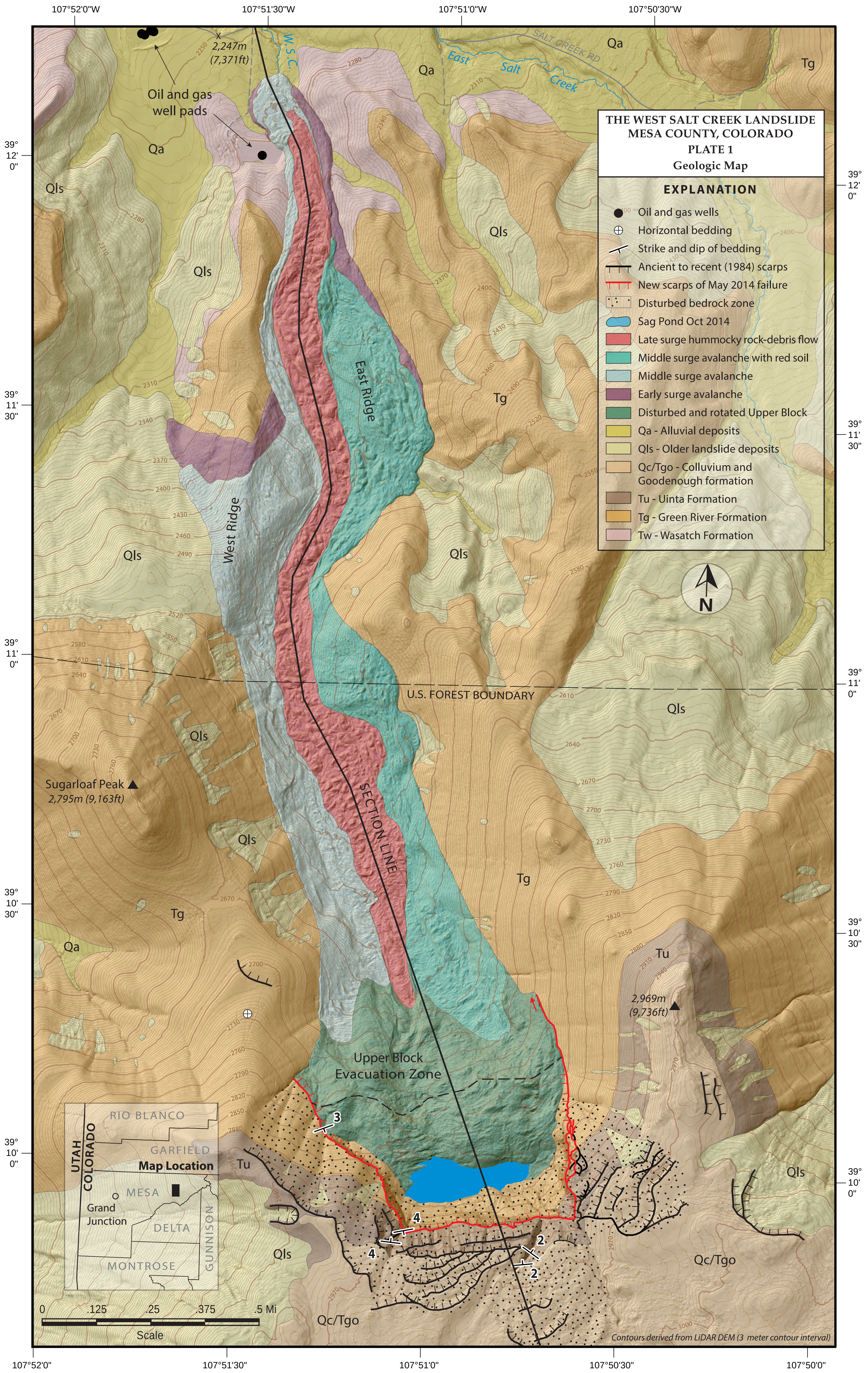
TB/tb

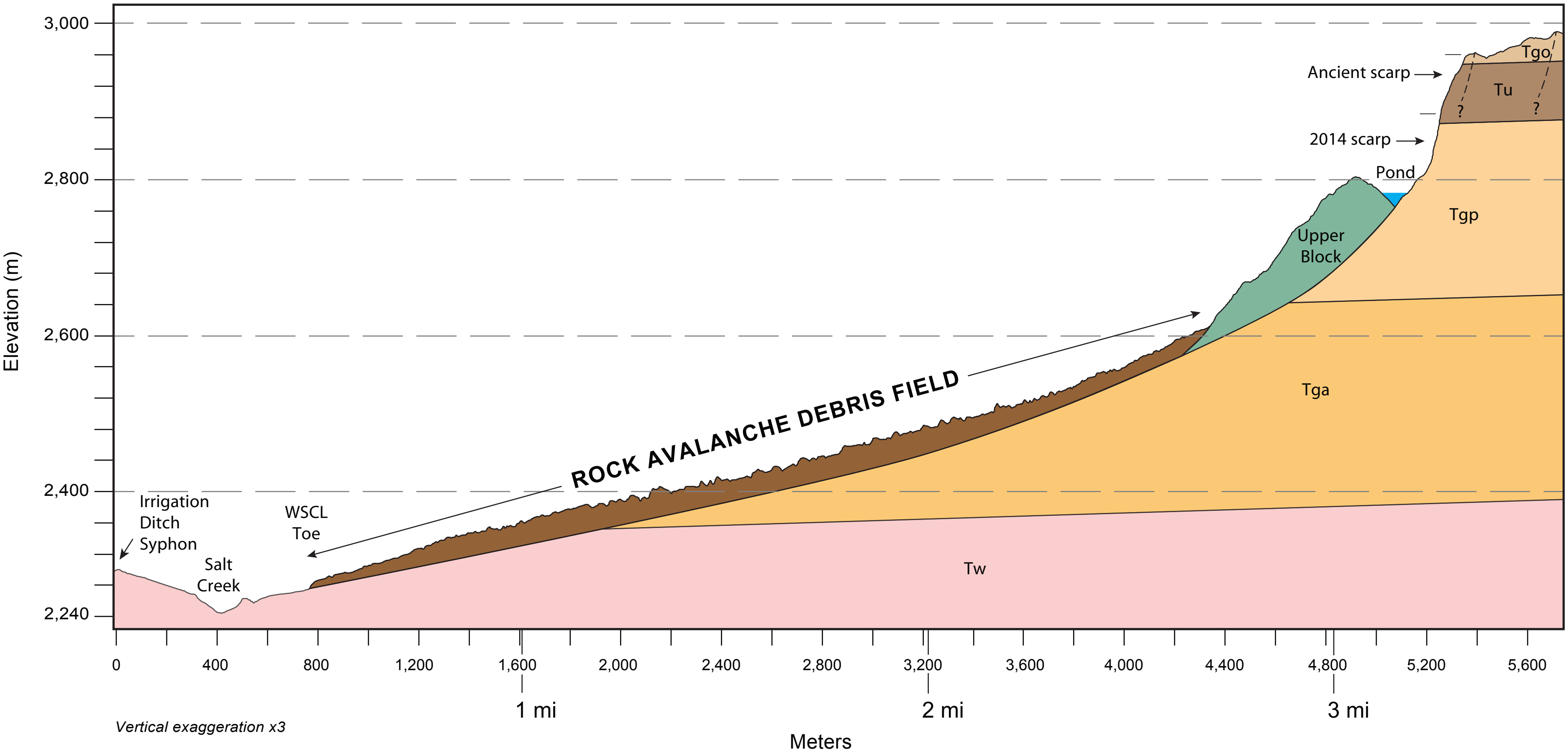
Appendix B - Eyewitness Interviews

Eyewitness Account - Melvin "Slug" Hawkins

Recorded from an interview with Mr. Hawkins on June 24, 2014

At approximately 7:15 AM on May 25th, 2014 "Slug" Hawkins was attending to his cattle in the southern part of the West Salt Creek valley when he heard trees snapping, the "earth moving at a slow pace" and the "sound of a gas well blowing off" on the east side of the valley near the area that is locally called the "old shale slide." The "old shale slide" is a pre-historic landslide, a portion of which of which was previously mapped by Colton (1975) and Soule (1988). Early that morning he noticed the valley was clouded in and light mist filled the air, which followed two days of light rain. He returned home at approximately 9 AM and noticed a scar on the east side of valley wall near the location he had been earlier that morning. At 11 AM he returned to the same area and noticed an additional landslide scar on the west side of the valley at roughly the same level as the earlier landslide. At this point, the large event had yet to occur. In the afternoon, his son and two men from the Mesa County Road and Bridge crew were investigating possible disruptions to local irrigation water on a canal that ran through the West Salt Creek valley. Late in the afternoon, Mr., Hawkins was watching television intermittently while looking up the valley. Within a 15 minute time span, he noticed the valley was filled with rock debris. Immediately following the catastrophic landslide at 5:45 PM (time taken from a seismic record of the main event), Mr. Hawkins went looking for his son and the two other men; however, after seeing the devastation in the valley he knew the chances of finding any survivors were slim. Search and recovery efforts by local law enforcement and Mesa County emergency officials began in the morning of May 26th but were halted late that afternoon due to potential instability of the upper parts of the landslide. The effort failed to locate the three men and their vehicle. Mr. Hawkins believes the men were on the west side of the valley when the slide occurred and the small landslide on the eastern section of the "old shale slide" blocked the irrigation ditch. After noticing the catastrophic event that filled the valley, Mr. Hawkins noticed additional small sloughs occurring on the slide but the overall appearance of it remained unchanged.


THE WEST SALT CREEK LANDSLIDE
MESA COUNTY, COLORADO
PLATE 1
Geologic Map
EXPLANATION
Oil and gas wells
Horizontal bedding
Strike and dip of bedding
Ancient to recent (1984) scarps
New scarps of May 2014 failure
Disturbed bedrock zone
Sag Pond Oct 2014
Late surge hummocky rock-debris flow
Middle surge avalanche with red soil
Middle surge avalanche
Early surge avalanche
Disturbed and rotated Upper Block
Qa - Alluvial deposits
Qls - Older landslide deposits
Qc/Tgo - Colluvium and Goodenough formation
Tu - Uinta Formation
Tg - Green River Formation
Tw - Wasatch Formation
107°52'0"W
107°51'30"W
107°51'0"W
107°50'30"W
107°52'0"
107°51'30"
107°51'0"
107°50'30"
107°50'0"
39° 12' 0"
39° 11' 30"
39° 11' 0"
39° 10' 30"
39° 10' 0"
Oil and gas well pads
2,247m (7,371ft)
W. S. C.
East Salt Creek
SALT CREEK RD
East Ridge
West Ridge
SECTION LINE
U.S. FOREST BOUNDARY
Sugarloaf Peak
2,795m (9,163ft)
2,969m (9,736ft)
Upper Block Evacuation Zone
Qa
Qls
Tg
Tu
Qc/Tgo
N
UTAH
COLORADO
RIO BLANCO
GARFIELD
Map Location
MESA
Grand Junction
DELTA
MONTROSE
GUNNISON
0
.125
.25
.375
.5 Mi
Scale
Contours derived from LiDAR DEM (3 meter contour interval)


3,000
2,800
2,600
2,400
2,240
Elevation (m)
Tgo
Ancient scarp
Tu
?
?
2014 scarp
Pond
Tgp
Upper
Block
ROCK AVALANCHE DEBRIS FIELD
Tga
Irrigation
Ditch
Syphon
WSCL
Toe
Salt
Creek
Tw
0
400
800
1,200
1,600
2,000
2,400
2,800
3,200
3,600
4,000
4,400
4,800
5,200
5,600
1 mi
2 mi
3 mi
Vertical exaggeration x3
Meters