May 29, 2014

Geologic Report on the Slide near Budge Drive, Jackson, Wyoming to the Jackson Town Council by the Geologists of Jackson Hole

Contents

Abstract

The Budge Drive landslide nucleated behind a steep rock face created by extensive quarrying from the late 1950s through the 1970s. This rock face has slopes up to 55 degrees, more than three times the 15-degree slopes typical in the region that had become stable over thousands of years. The presence of highly flow-foliated and fractured andesite resting on clays at the site means that water flowed readily downward through the andesite where it could then flow towards the valley floor on the underlying clay, providing a natural surface of potential slip. A high rate of precipitation

and snow melt appears to have triggered rapid motion of this slide in 2014. But the fractures surrounding the slide mass began to form, nucleate, by the fall to winter of 2011. Nucleation could have been caused by a plumbing water leak in April, 2011, removal of additional quarry material during the summer of 2011, spontaneous failure resulting from the much earlier quarrying, or some combination of all of the above. The Town of Jackson and Teton County may wish to consider all of these factors while working towards a solution of the present landslide and while considering regulations and practices designed to minimize future instances of slope failure.

Introduction

Beginning in the fall to winter of 2011, deformation of the home at 1045 Budge Drive was observed, suggesting the possibility of earth movements. By June 5, 2013, the floor on the south wing of the residence had sunk 6.1 inches. The house was then ripped in two, primarily between April 16 and 20, 2014, with the southern part of the house having sunk close to 20 feet by late May along a scarp at the head of a landslide. At the same time, the toe of the landslide, including a pump house belonging to the Town of Jackson, moved nearly 11 feet to the south towards West Broadway. This report describes the geologic setting of the Budge landslide, geologic knowledge about slope stability in Jackson Hole, and many geologic observations and interpretations related specifically to this landslide. Our goal is to provide information that may prove useful to the Jackson Town Council for dealing with this crisis by adding context to the geotechnical reports and recommendations being submitted by consulting company Landslide Technology.

Slope Stability in the Vicinity of Jackson

Jackson Hole is surrounded by tall mountains with bedrock exposed at the higher elevations, smaller mountains typically with rock cliffs exposed, and hills that may have some rock exposed. All of these features have bedrock cores or rocky caps that helped them survive millennia of erosion and numerous glaciations over the past 2.6 million years. During this time ice not only filled high mountain cirques and mountain canyons but sometimes filled all of Jackson Hole with thousands of feet of ice (Pierce and Good, 1992). Above the floor of Jackson Hole, on the flanks of surrounding mountains and along elevated features contained within the valley, are found steep slopes of debris derived from these rock-cored elevations that are, geologically speaking, continuously creeping, sliding, flowing, toppling, and falling down slope primarily under the influence of gravity.

This movement of rock and soil debris down slope, known as mass wasting, occurs as long as the gravitational forces acting on material on the slope exceed forces resisting downslope movement. Over time, slopes reach an angle of repose, the steepest angle that the slope can maintain for long periods of time without spontaneously losing its stability. All of the natural slopes that we see surrounding Jackson Hole are at or very near their own angle of repose based on their soil/rock/debris type, covering vegetation, typical water content, and their response to the most severe local weather including rainfall, snowfall, and temperature extremes primarily over the 14,000 years since the last major glaciation. It does not take much to upset this balance. The basic rule of thumb is that gravity always wins ultimately.

Boulders and occasionally large rock masses dislodged by erosion, freezing/thawing, rain, or earthquakes sometimes move down these slopes. On May 10, 2008, a boulder (4 by 4 by 3 feet) rolled down East Gros Ventre Butte crashing through the living room wall and floor of County Commissioner Andy Schwartz's home with other pieces damaging a truck parked by Flat Creek Inn below. There are numerous boulders high on the butte that are available to roll but luckily these events have not been common and to date have not injured people. Within the short documented

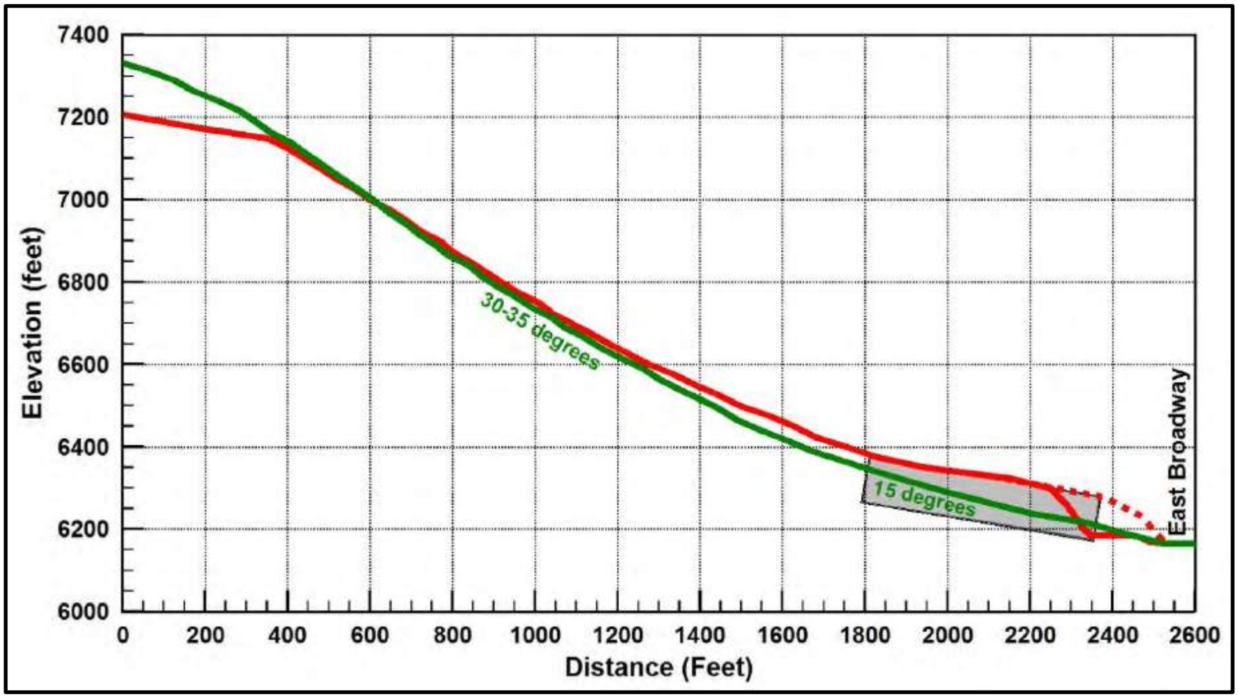

Figure1: Topographic profiles of the south slope of East Gros Ventre Butte north of West Broadway at Virginian Lane (green line) and at Scott Lane (red line). The dashed red line shows the slope north of Scott Lane before extensive quarrying based on the 1963 USGS topographic map. The gray-shaded rectangle shows schematically how a 140-foot thick slab of andesite might underlie the current slope. The locations of the profiles are shown on a map in Figure 2.

human history of Jackson Hole there have been no damaging earthquakes, but the mountain building forces that release them are geologically common in Jackson Hole and when the next large earthquake occurs, it will cause some currently stable materials to be dislodged and move catastrophically towards the valley floor. People who build on and live at the base of steep slopes need to recognize the potential hazards and consider possible ways to mitigate their particular risk.

Torrential rains may form flash floods, another natural process in Jackson Hole that can move large amounts of debris suddenly down slope. On July 26, 2007, a localized storm dropped 2 to 3 inches of rain in 2 hours in the upper reaches of Jensen Canyon, triggering a debris flow that roared down the canyon. This event, 2.5 miles southwest of Teton Village, carried boulders and mud across Fish Creek Road.

The green line in Figure 1 shows a topographic profile of the south slope of East Gros Ventre Butte north of West Broadway at Virginian Lane (green line CD in Figure 2). This profile is typical of the slopes surrounding and within Jackson Hole. The angle of repose is 30 to 35 degrees on the upper slope at distances plotted between 800 and 1200 feet (along the horizontal axis) and decreases to 15 degrees between 1800 and 2200 feet (along the horizontal axis). Near the top of the slope, the angle of repose is determined primarily by the coherency of the soil/rock formation – how well it holds together – how slowly it is eroded. Further down slope, debris accumulates that is less coherent, less consolidated, and the angle of repose is determined more by the support of

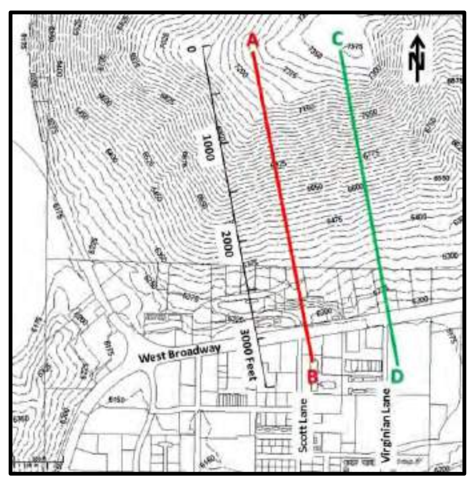

Figure 2: Map of the south end of East Gros Ventre Butte showing the location of the two topographic profiles plotted in Figure 1. Up is to the north.

Figure 3: East slope of East Gros Ventre Butte just north of the Jackson town line along Highway 89 showing a typical slope and removal of buttress material to build the highway.

material downslope, the buttressing effect of debris piled up downslope, holding the upper slope of debris in place. Debris that accumulates along the base of steep slopes from a point source is called an colluvial-alluvial fan; these fans coalesce to form colluvial-alluvial aprons. The result is that nearly every slope within Jackson Hole has a colluvial-alluvial apron along its base. Colluvium is loose bodies of unconsolidated soil, sediments, or rocks deposited near the bottom of a slope that were transported primarily by gravity. Alluvium is loose, unconsolidated soil, sediments, or rocks that have been eroded, reshaped by water in some form, and redeposited in a non-marine setting.

The buildup of these colluvial-alluvial aprons is clearly observed, for example, along Highway 89 just north of the town boundary (Figure 3) where the road cuts through several colluvial-alluvial debris fans. Figure 3 shows that part of the rocks and debris holding up the original slope has been removed in the process of building Highway 89, decreasing the stability of the whole slope, making it more at risk for land slumping or sliding. The angle of repose of the cut face is now dependent on the internal coherency of the poorly consolidated debris. Any removal of rock and soil debris (colluvium) from the lower slope of colluvial-alluvial aprons to grade a highway or create a building pad compromises the stability of the whole slope. The result is that over time an altered slope such as that seen in Figure 3 is much more likely to settle or slide in order to re-establish a more stable configuration with respect to gravity.

Naturally occurring landslides typically form where the toe of a steep slope has been removed by erosion, such as undercutting by a river. This process erodes the naturally formed buttress holding up the slope, creating a potential hazard. Slope failure does not occur until the forces holding the slope together change beyond some critical point. Typically increases in ground water pressure reduce the friction across the incipient slip surface. Water might also decrease the shear strength of the incipient slip surface. An earthquake might shake the mass of the slide enough to initiate slip.

The Gros Ventre River east of Kelly eroded the north slope of Sheep Mountain (Sleeping Indian) over millennia. Five inches of rain fell between mid-May and mid-June, 1925. Daily temperatures rose to 77°F causing rapid melting of winter snows. Swampy pools of water with no outlet high up on the mountain had been observed suggesting and probably intensifying water-saturation of the soil (Woodmencey, 2014). There were also reports of felt earthquakes in the Gros Ventre River valley at about this time, an area that has had felt earthquakes within the past decade. On June 23, 1925, an estimated 50 million cubic yards (450 million cubic feet) of sedimentary rock and other debris released from the mountainside and slid into and across the Gros Ventre River valley, forming Lower Slide Lake. On May 18th, 1927, part of this dam failed, causing a flash flood that destroyed the town of Kelly six miles downstream.

Steep slopes lying at or near their angle of repose must often be cut to build highways through mountain passes and canyons. Highway engineers take special precautions in regions deemed most likely to slide including building retaining walls, using various methods to stabilize the slope, or by reducing mass uphill of the cut. It simply is not possible to build highways through steep terrain without accepting some landslide risk. Highway engineers try to determine the most effective ways to reduce risk and generally are successful. But in 2011, for example, after 5 inches of rain had fallen in 45 days and when high temperatures in the mid-60s caused rapid melting of a record winter snowfall, a landslide flowed across Highway 89 in Snake River Canyon near milepost 127 on May 15, closing the highway for two weeks (Woodmencey, 2014).

Humans in Jackson Have Increased the Local Risk of Landslides

Rocks and debris on mountain slopes throughout Jackson Hole had reached a stable equilibrium with gravitational forces during thousands of years of mass wasting typically occurring during major rain storms. Since the town of Jackson was named in 1894, humans have regularly increased the local risk from landslides by removing rocks and other debris from the base of these stable slopes in order to quarry rock, grade roads, level building pads, and make commercial buildings more accessible to highway traffic.

The greatest amount of development of these types in all of Teton County has been concentrated just north of West Broadway from the region across from Virginian Lane on the east to just west of the intersection of West Broadway with Highway 22 on the west. The base of the slopes of East Gros Ventre Butte and High School Hill have been partially removed to build West Broadway originally as two lanes, to increase the width of West Broadway to 5 lanes, and to allow commercial development at highway level. But the greatest removal of rocks and debris by far was done during extensive quarrying operations from the late 1950s through the 1970s, removing in excess of an estimated 20 million cubic feet of highly flow-foliated and fractured andesitic rock and associated debris that now forms the foundations of roads and buildings throughout the region.

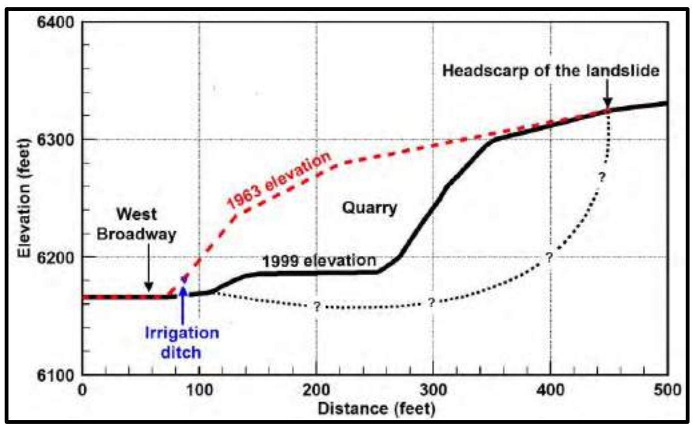

Figure 4: Topographic cross-section from south to north from West Broadway just east of Budge Drive through the house destroyed at the top of the headscarp of the landslide. The dashed red line shows elevations in 1963. The black line shows elevations in 1999 after quarrying.

The primary quarry, known as the “County Quarry” (Love and Albee, 1972) was located at the base of the current Budge Drive. Rock quarried consisted primarily of andesite, a light gray colored volcanic rock, along with some conglomerate, a light brown rock composed of rounded sedimentary debris that has been cemented together by minerals dissolved in ground water. Extensive quarrying from the late 1950s through the 1970s created a 1200-foot-long cliff more than 100 feet high. Slopes were increased to as much as 55 degrees, more than three times the angle of repose of slopes nearby. The red line in Figure 1 shows a topographic profile of East Gros Ventre Butte passing just to the east of Budge Drive near its intersection with West Broadway (red line AB in Figure 2) based on 1999 topographic data from the Teton County Map Server (2014). The dotted red line in Figure 1 shows this profile based on the 1963 U. S. Geological Survey topographic map prepared prior to significant quarrying. This quarrying removed the naturally formed toe of the slope that had supported the south end of E Gros Ventre Butte for thousands of years.

A more detailed topographic profile is shown in Figure 4 from West Broadway northward to the house at 1045 Budge Drive that was destroyed straddling the headscarp of the landslide. The black line is based on one-foot 1999 topographic data and the dashed red line on the 1963 USGS topographic map with 40-foot contours. The dotted black line with question marks in it shows a rough approximation of the slip surface along which the rocks and debris above most likely slid dramatically in April, 2014. Note that the cross-section of rock quarried is approximately equal to the cross-section of rock that has recently slid.

The cross-sectional area of material removed from the quarry near Budge Drive shown in Figure 4 is approximately 15,600 square feet. While the quarry face is 1200 feet wide, the western part includes Budge Drive. Even assuming conservatively that this cross-section applies to only a width of 900 feet along the cliff, the volume of rock and debris removed was approximately 14 million cubic feet. No effort was made after the quarry was closed to restore this hillside to a safer slope, closer to the natural angle of repose. No restoration was or is currently required by local planning and building codes or by state or federal regulations. The need for such restoration has generally not been addressed nationally. It is rare nationally to develop major building facilities at the base of a manmade cliff more than 100 feet high made up of highly flow-foliated and fractured rock severely over-steepened by quarry operations without trying to manage the hazard.

The fractures surrounding the Budge Landslide of 2014, described below, are symmetric about the cut face on the north side of this quarry, strongly suggesting that the removal of more than 14 million cubic feet of rock and related debris weakened the slope, increasing the risk of slope failure. Much smaller amounts of rock and debris were removed to build Gros Ventre Drive at the time of quarrying and to realign this road to become Budge Drive in 2002 soon after the Town of Jackson annexed the region. Small amounts below the west edge of the landslide were removed in 2003 to develop the Hillside Building. Still 8 feet more was removed in 2011 to prepare to build the Walgreens store. But more than 90% of the material removed was during quarrying from the late 1950s through the 1970s, so that it is quite reasonable to conclude that the slope failure observed in 2014 would have been highly unlikely to have occurred had this quarry not been excavated.

When record rates of rainfall and snow melt saturated the hillside in mid-February, early March, and late March, 2014, a large portion of the slope mass behind the quarry-cut face began to slide and moved nearly 11 feet south primarily between April 15 and 20. But deformation began several years earlier in 2011 and the size and shape of this slide reflects at least in part the distinctly different geology of this particular part of East Gros Ventre Butte.

Regional Surface Geology

Surface geology of East Gros Ventre Butte and more broadly the area in and surrounding the Town of Jackson was first mapped in detail by Love and Albee (1972). Their map documents that andesite (labelled QTg on the map) outcrops primarily along the top of East Gros Ventre Butte and near the top of High School Hill with a small isolated outcrop along the quarry-created cliff near the base of Budge Drive within the red ellipses shown in Figure 5. Their mapping makes it clear that this andesite and related conglomerate near Budge Drive cannot currently be in the place where they were formed but rather must have slid down slope from the prominent outcrops found above at the top of East Gros Ventre Butte. This is consistent with geomorphic evidence discussed below. Dates for the age of the andesite are on the order of 7 to 8 million years based on work by David Adams and therefore pre-date significant Basin and Range extensional faulting that formed and continues to form the valley of Jackson Hole. Regional mapping demonstrates that most extensional movement in Jackson Hole and the accompanying rise of the Teton Mountain Range occurred within the past 2 million years although it may have started 4 to 5 million years ago (Pickering-White et al., 2009).

Jackson Hole was covered with thick glaciation multiple times over the past 2.6 million years. The Pinedale glaciation (30,000 to 14,000 years ago) covered much of this region, but the Bull Lake glaciation (200,000 to 130,000 years ago) was much more extensive and was thick enough to have flowed over the top of East Gros Ventre Butte, with more than 1500 feet of ice present in what is today the Town of Jackson (Pierce and Good, 1992). This glaciation would have moved through Jackson Hole from the north flowing around and over East Gros Ventre Butte and then onward to the south-west from where the town of Jackson is located today, potentially plucking rock from the southern face of the butte. Such plucking could have undercut the andesite, allowing large blocks, hundreds of feet across, to slide downslope. The end of that glacial episode would have left bare slopes that had not yet had sufficient time to become vegetated again, and the climate would have been wetter than today's climate. It is reasonable to suspect that these conditions would have facilitated downslope block movement around 130,000 years ago, at the end of the glaciation that flowed through this area, but no evidence has been found for a specific date. Slide blocks both smaller and much larger are common in the geologic record of western Wyoming and easternmost Idaho (Moore et al., 1987).

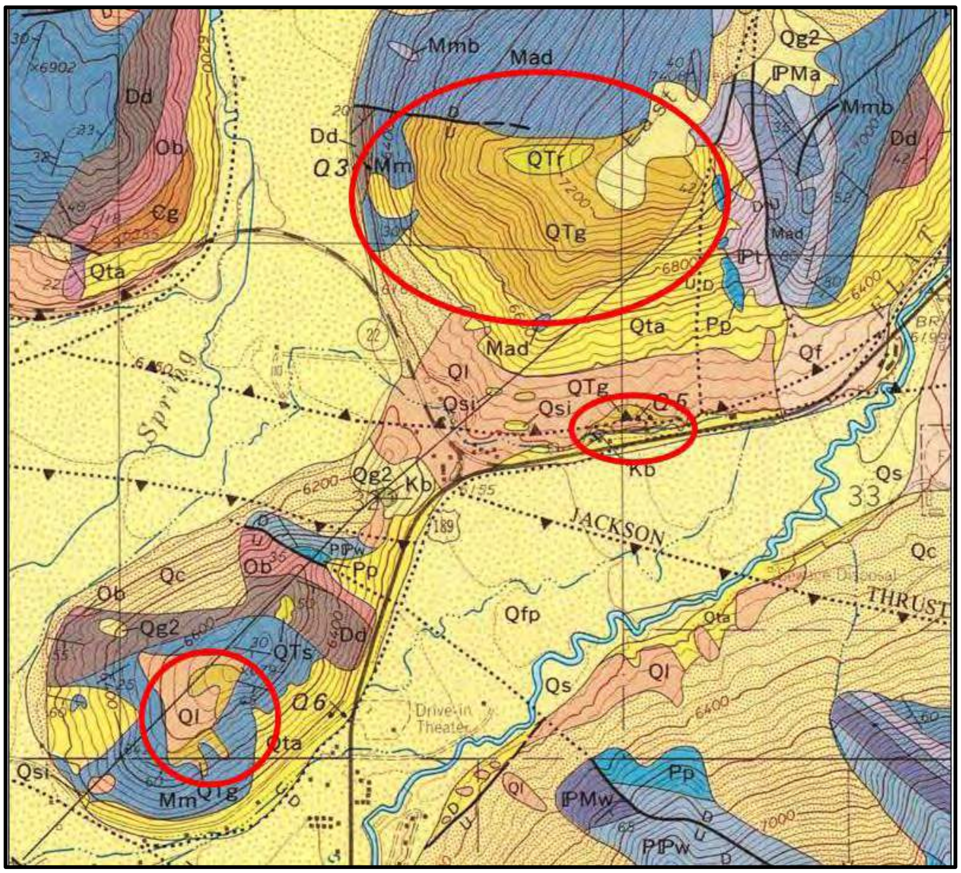

Figure 5: A portion of the Love and Albee (1972) geologic map showing High School Hill in the lower left and the southern part of East Gros Ventre Butte in the upper right. The andesites (QTg) only outcrop in the three areas outlined by the red ellipses.

Following the end of the most recent Pinedale glacial period, approximately 14,000 years ago, western North America was considerably wetter than it is today. Giant lakes filled many of the basins between the Wasatch Range and the Sierra Nevada Range of which the Great Salt Lake is but a trivial remnant. The western United States has on average become steadily drier since that time. But during the retreat of and immediately after the last Pinedale glaciers melted, there was considerable erosion occurring on all slopes within Jackson Hole. Evidence for this exists in the colluvial-alluvial fans and aprons that are seen at the base of every significant slope in the valley. These are largely all inactive today as shown by their covering of sage brush and other vegetation.

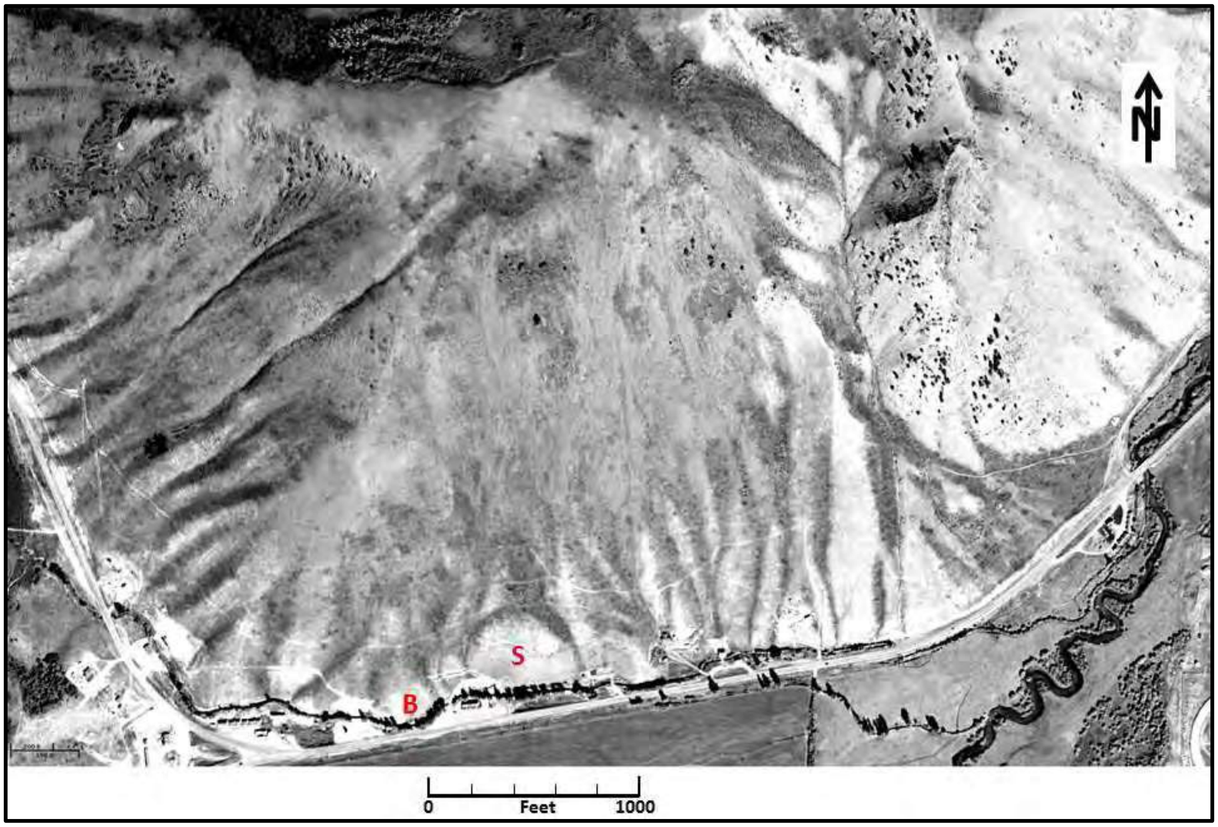

Figure 6: Aerial photograph taken in 1955 showing the south end of East Gros Ventre Butte, the region of the future Budge Slide (S) and the region of the future branch of The Bank of Jackson Hole (B).

Thus the basal slopes of East Gros Ventre Butte had thousands of years to reach stability following rapid post-glacial erosion. With limited exceptions prior to settlement of Jackson Hole in the late 19th century, slopes such as the southern end of East Gros Ventre Butte were quite stable. Excavation of these slopes to build highways, buildings, or rock quarries upset this balance in a number of places. Quarrying at the base of Budge Drive created the largest, non-highway-related, man-made cliff in the valley and the recent landslide is an active demonstration of what can result from such human modification of these slopes.

Geomorphic Evidence for Andesite Slide Blocks

Figure 6 shows a 1955 aerial photograph of the south end of East Gros Ventre Butte just west of the town of Jackson. The location where the Budge Drive Slide would later occur, marked with a red “S”, includes most of the land within the light colored circular feature in the lower central part of this image. This circular feature looks like a dish or depression to many eyes, but it is actually an area that is elevated compared to the adjacent slope. The darker areas surrounding it are vegetation showing the primary routes for drainage of water from off the higher slopes of the butte. This circular feature appears much lighter because there is less vegetation on it, and less moisture in its soil. The brightest white areas, such as just southwest of the “S” and further to the west, though which an irrigation ditch can clearly be seen to run (red line Figure 7), are lands that were graded by the summer of 1955 when this photo was taken, for construction or to extract road metal, which is broken rock and sandy soils used in the foundations of roads and buildings.

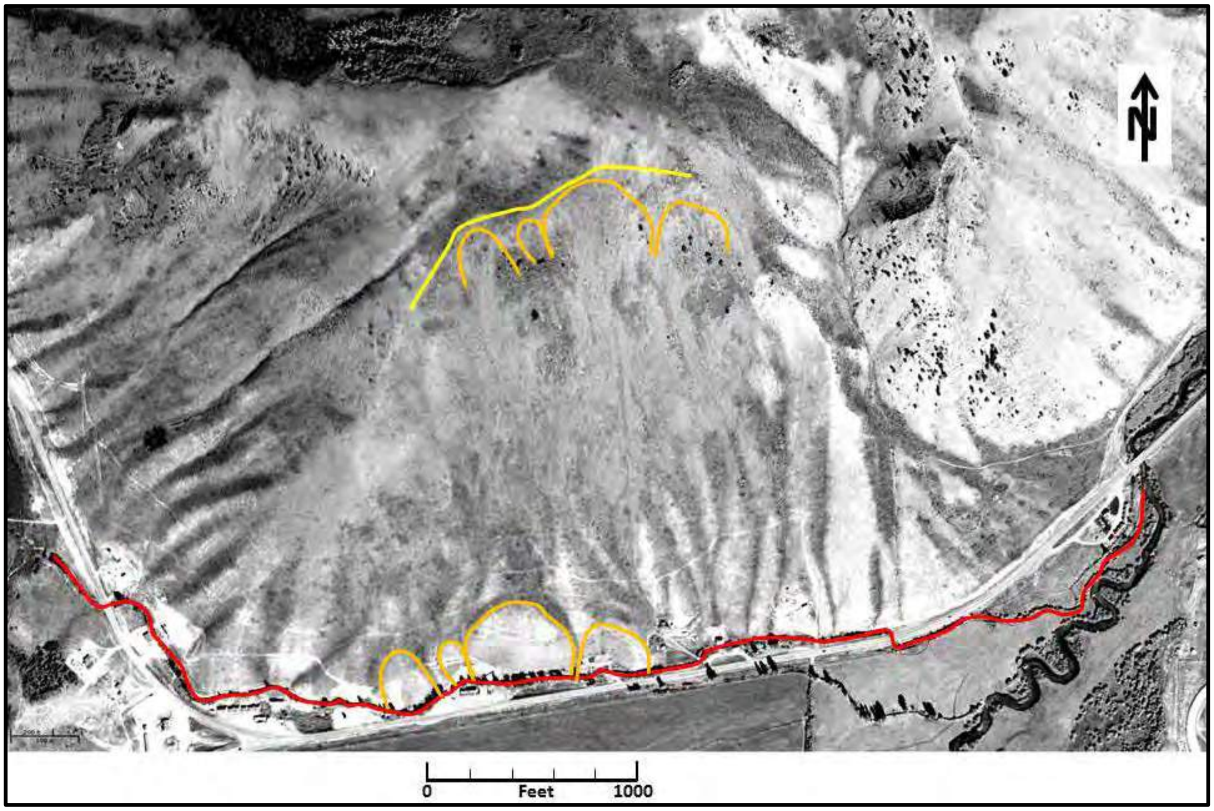

Figure 7: Aerial photograph of the southern end of East Gros Ventre Butte taken in 1955. The lower arcuate orange lines outline the geomorphic anomalies of poorly vegetated parts of the hillside. These are likely to contain the majority but not all of the blocks of andesite and conglomerate that appear to have slid down the butte from somewhere in the vicinity of the upper arcuate orange lines. The yellow line shows a cliff facing southeast. The red line traces an irrigation ditch dug before 1910.

The breadth, shape, and gray shading of the future quarry and later slide area is distinctively different from any other area shown in this photo. There is one area to the east and two to the west shown by orange lines in Figure 7 that are similar but smaller. The primary rock outcropping in these four areas is andesite, a light-gray colored extrusive volcanic rock, and conglomerate that, as described above in the section on geology of the area, is found near the top of East Gros Ventre Butte above the Budge Drive area and near the top of High School Hill to the southwest. The yellow line in the upper part of Figure 7, drawn along the rapid break in slope near the top of the south face of East Gros Ventre Butte, shows where the topographic contours smoothly running northwest-southeast to the left of the line suddenly change direction along a cliff. The lower group of orange lines has been duplicated and moved without rotation up the butte and slightly east to show where these blocks of andesite could have come from, and likely why the yellow line has the deflection in it. The blocks may have slid down the slope together or separately. The upper orange lines merely show the simplest of many possible points of origin and possible number of slide blocks. What is clear from the geology is that these andesite blocks must have slid down the butte in the past. Love and Albee (1972) described the quarry in the main block as "Q5. – County quarry … Rock quarried is highly shattered by Quaternary faulting and breaks into angular fragments commonly less than 6 inches in diameter; used in road construction."

The bench on the south end of East Gros Ventre Butte, extending from the region north of Virginian Lane to the west of Budge Drive, appears to have been formed by large blocks and related debris sliding down the butte. This bench is a partially consolidated body of landslide debris. The largest block appears to be in the region labeled "S" in Figure 6. This block is more than 400 feet in the east-west direction, 500 to 600 feet in the north-south direction, and, based on recently acquired drill cores, on the order of 140 feet thick. Drill-core data also show that the andesite block extends to the north of the geomorphic anomaly shown in Figure 7, under the vegetated area where the ground slope is closer to horizontal than areas above.

The gray-shaded rectangle in Figure 1 shows a possible extent in the north-south direction for this block relative to current topography. This block appears to have slid down the butte as a unit long before settlement of Jackson Hole, bringing economically valuable andesite road metal, which is broken rock and sandy soils used in the foundations of roads and buildings, close to the valley floor where it could be easily quarried. The present day Budge Drive landslide involves the southern part of this block but also other materials to the east and below the slide block. Thus the recent landslide does not appear to be a simple reactivation of the pre-settlement slide block, but was formed within the pre-existing slide block and surrounding material. The east-west extent of the current slide is coincident with and therefore appears to result from the east-west extent of the cliff face created by quarrying.

The air photograph taken in 1955 (Figure 6) and others taken more recently (Teton County Map Server, 2014) show that the soils on top of the old andesitic slide blocks have less vegetation and are likely drier - or at least were so before human-induced modifications of the area. As described in the following section, the andesite is highly flow-foliated (Figure 8) and likely additionally fractured by the slide movement, providing ready conduits for water flowing on the surface to then flow vertically downward into underlying strata.

Figure 8: Flow-foliated andesite in the cliff just north of the entrance to the upper parking lot for Sidewinders.

Recently Acquired Geologic Data from Drill Cores and Their Interpretation

Following the most rapid slip of the Budge Drive landslide between April 15 and 19, 2014, Landslide Technology had five core holes drilled within or adjacent to the slide block (Figure 9). These holes were continuously cored and provide an excellent record of the rock involved within the landslide as well as what underlies the slide block and the lower slopes of the southern face of East Gros Ventre Butte. Our descriptions of these five cores (LT-1, 2, 3, 4, 5) are given in the Addendum to this report. Figures 10 and 11 show two similar but slightly different interpretations of a cross-section of the slide block based

Figure 9: Location of drill holes LT-1, 2, 3, 4, 5, and the nearly north-south cross section (solid red line) on an air photo taken in 2013. Lot and parcel lines are shown in black including an outline of the Walgreens store completed in late 2013.

on these core data, data observed at the surface, and known geologic history. The cross-sections are in a location (Figure 9, red line through LT-1, LT-2, LT-4, LT-5) similar to that shown in Figure 4 extending from the intersection of the east side of Budge Drive with West Broadway, through the cliff, past the house on the hill at 1045 Budge Drive that was destroyed by the landslide.

Regionally, all of East Gros Ventre Butte is interpreted by geologists to be a fault block tilted (rotated) to the west in a process that began 2 to 4 million years ago as a result of the ongoing Basin and Range extensional faulting that continues to form Jackson Hole. There is a deep and fairly narrow valley between East Gros Ventre Butte and Snow King Mountain that has been filled at different times with lakes and rivers. Outcrops of andesite and conglomerate found along Budge Drive have clearly slid down East Gros Ventre Butte from the cliffs above. Both cross sections show that the andesite and conglomerate sit directly on top of fluvial (river) and lacustrine (lake) sediments documented by the five core holes. These sediments were deposited in a geomorphic setting very similar to that which we see today, suggesting that the fluvial and lacustrine sediments shown in the cross sections are in-place, have not significantly moved since being deposited. These sediments incorporate significant amounts of the 7 to 8 million year old andesite and thus clearly post-date its formation. We have no age dates for the sediments encountered beneath the andesite, conglomerate, and other slide debris, but given the compelling argument that the topography was not dramatically different than that seen today, it is likely that these strata are no more than a few hundred thousand years old. Without dates for the sediments, our constraints on timing are circumstantial. But the relationships seen suggest that the slide block (or blocks) were deposited directly into or on top of the lacustrine and fluvial sediments seen most prominently in cores LT-4 and LT-5. The environment when these sediments were deposited appears to have been much wetter than today and the geomorphology suggests this may have been at the end of the Bull Lake glacial episode (which ended ~130,000 years ago), or possibly in the prior interglacial between

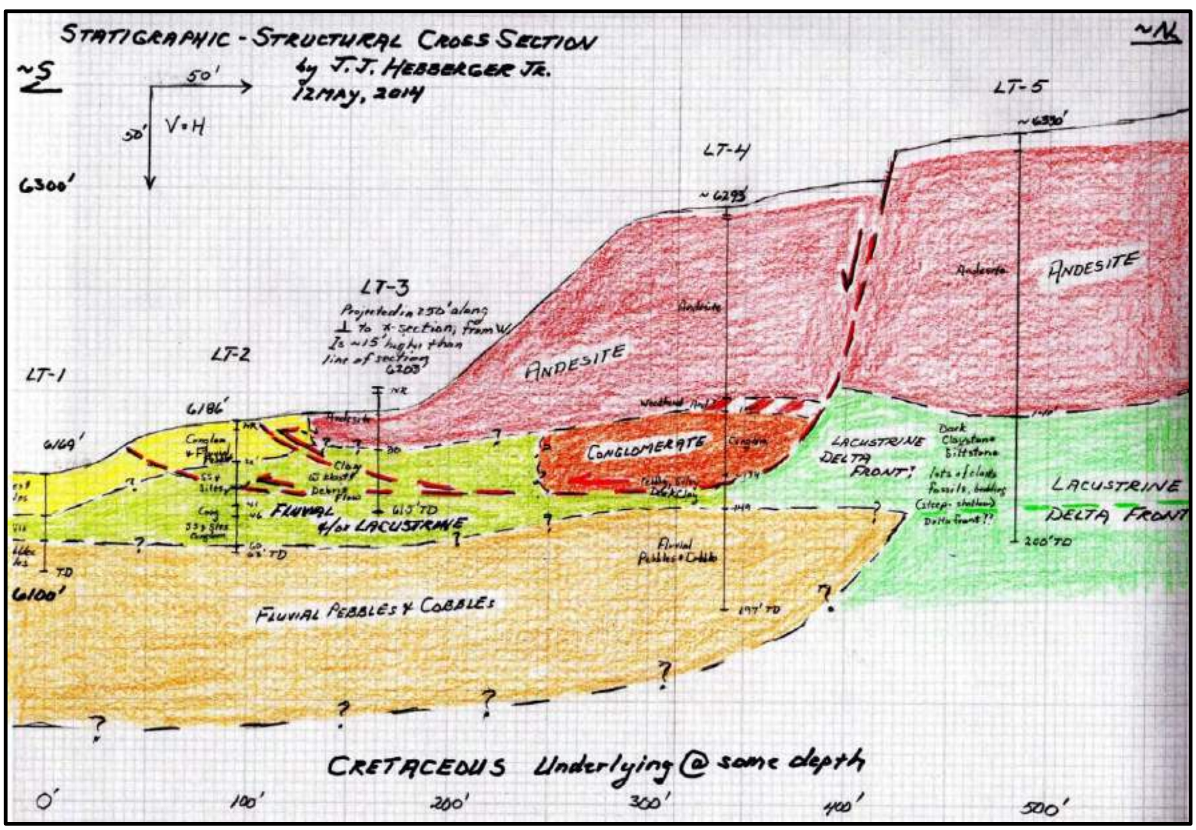

Figure 10: Initial interpretation of the core and surface data from LT-1, 2, 3, 4, & 5 core holes.

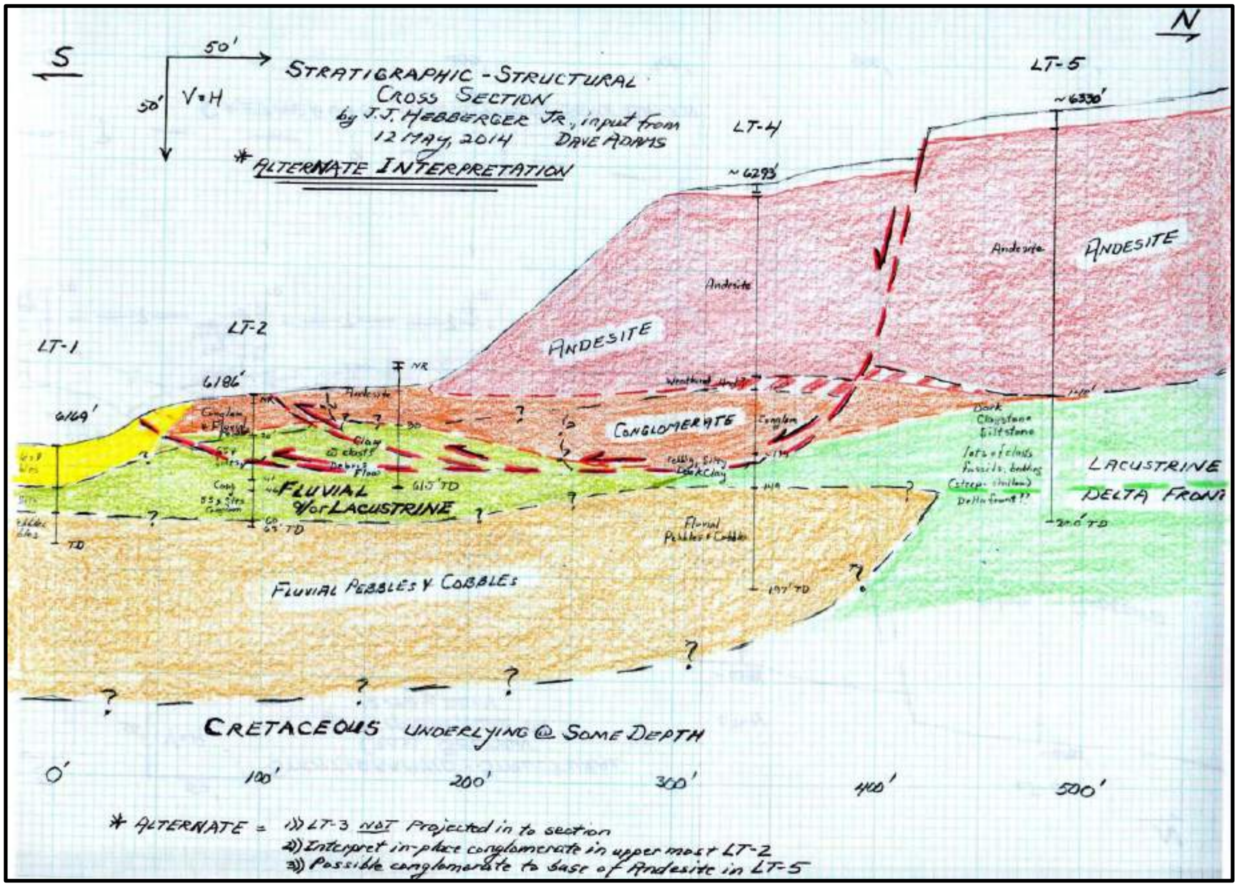

Figure 11: Alternate interpretation of the core and surface data from LT-1, 2, 3, 4, 5 core holes.

300,000 and 200,000 years ago.

The interpreted setting, which is similar to the geomorphology seen today, and the type of sediments encountered in the "Lacustrine Delta Front" and "Fluvial &/or Lacustrine" strata indicate that it can be expected that these sediments extend east and west along the lower flank of East Gros Ventre Butte. Even where there is no older slide block on top of them, the colluvium forming the lower flank of the colluvial-alluvial apron along the south flank of East Gros Ventre Butte is likely also to rest directly on top of these older sediments. So while there is no incentive to drill expensive core holes east or west of the current slide block it should be expected that if they were drilled the "Lacustrine Delta Front" and the "Fluvial &/or Lacustrine" clay, silt, and sand rich facies would be encountered in those locations as they are in cores LT-5, LT-4, LT-3, LT-2, and likely LT-1.

The location of the slide (fault) surface for the present day slide block may reactivate a portion of the slide surface of the ancient slide block, but this appears largely because the ancient slide block came to rest on relatively impermeable and clay rich sediments (of the "Lacustrine Delta Front" facies). It is clear that the slide surface encountered in LT-4 and as depicted in Figures 10 and 11 is located at the base of the conglomerate that forms part of the old slide block, and therefore on top of the more clay-rich sedimentary layer below. But this is the only part of the ancient slide surface that could have been reactivated. The headscarp of the current slide block is in the middle of the ancient slide block that is largely andesite, is located approximately half way between core holes LT-4 and LT-5 (see Figures 10 and 11), so only the lower part of this old slide block is involved in the present day slide. The current slide has not caused ground movement at the LT-5 location and so the old slide surface, which is at approximately 140 foot depth in LT-5 at the contact between the andesite and the Lacustrine Delta Front, has not been reactivated.

Important conclusions that can be drawn from the core descriptions, cross sections, and outcrop data are:

- The old slide blocks, whatever their age, sit on top of poorly lithified and clay rich strata that provide surfaces on which the current Budge Drive slide block can readily move; these clay rich strata will readily deform beneath present-day movement of the more competent largely andesite old slide block, of which the toe was removed during decades of quarrying operations.
- The data and interpretation also demonstrate that there is no well-lithified, in-place, and competent rock unit into which engineering solutions for slide block stabilization might be anchored. (But geotechnical engineers do have a variety of methods to deal with this problem.)
- The pre-existing slide block consists of highly flow-foliated andesite and massive conglomerate that is approximately 140 feet thick.
- The present-day slide block is not a simple reactivation of the original slide block. The current slide surface initially cuts steeply through the predominantly andesitic block and at least in the toe area (Walgreens parking lot area) and along its eastern extent incorporates weakly lithified older fluvial and/or lacustrine sediments.
- The andesite is highly flow-foliated (layered and folded), as is well seen in the outcrop above Budge Drive in the cliff face (Figure 8) and as shown by the less than 50% average recovery of andesite in the LT-4 and LT-5 cores. These flow-foliation surfaces are open conduits that allow water to readily move downward through the andesite to reach the underlying clay-rich layers. Once water reaches to a clay-rich layer, it would tend to then flow on top of the clay rich strata, providing the natural slip surface that the present day slide is utilizing.
- The predominance of steeply dipping conglomerate in outcrop above lower Budge Drive, to the west of the current slide block, strongly supports the suggestion in Figure 7 that multiple slide blocks underlie the relatively flat area above Budge Drive developed with housing over the past 45 years.
- Cores from LT-5 show that the andesite block continues north of the headscarp of the landslide and suggests that it continues for at least for a short distance north of the geomorphic anomaly shown in Figures 6 and 7 where a bench formed on the hillside. This bench, most likely, is debris piled up against the top end of the andesite block where the decrease in slope encourages more vegetation.

Detailed LT-1, LT-2, LT-3, LT-4, and LT-5 core descriptions with photos of the core material may be found as Addendum to this report. In brief what the core data and above cross sections document is that alternating intervals of low and very high energy deposition occurred in this area. These quite different depositional environments are indicated in Figures 10 and 11 as the "Lacustrine Delta Front" (low to moderate energy), "Fluvial Pebbles & Cobbles" (very high energy), and "Fluvial &/or Lacustrine" (low to moderate energy) environments. Stratigraphic relationships in the cross sections show that:

1. The oldest unit cored was the "Lacustrine Delta Front" environment, primarily in LT-5. This interval consists of fossil rich, very dark, silty clay that has an admixture of sand to occasional pebble sized rock fragments typically called clasts; there are also layers of light colored quartz silts and fine grained sands. Dips in all of these units range from nearly horizontal to dips in excess of 30 degrees. There is a zone below 168 feet of intermixed fine

sand and clay that appears to be a slump deposit. The combination of these features suggests entry of a moderate energy fluvial system (river delta) into a low energy and relatively deep water lacustrine (lake) environment.

2. A younger unit is the "Fluvial Pebbles & Cobbles" environment encountered in LT-4, LT-2, and LT-1. This is a very high energy environment with recovered clasts ranging in size from pebble to at least large cobble in size. These clasts are highly rounded and highly varied in rock type. They clearly represent an environment not unlike the Snake River of today. Rare zones of pebbles in a silty clay matrix (167 to 169.5 feet in core LT-4) indicate changes in the channel system and occasional lower energy environments. This unit is the most laterally extensive unit and represents a significant channel deposit cut into the older "Lacustrine Delta Front" environment, as drawn in the cross sections above.
3. Younger than the "Fluvial Pebbles & Cobbles" unit is an upward continuation of the "Lacustrine Delta Front" sediments that is required by the stratigraphically higher position of the LT-5 sediments above a depth of approximately 180 feet. Lateral continuation of this unit is likely represented by the LT-4 interval of clay, silt, and sand encountered between depths of 134 and 149 feet.
4. Possibly younger yet, or alternatively representing a lateral slightly higher energy facies change, are the silty clays and silts to fine sands encountered below about 30 feet in LT-3 and below about 18 feet in LT-2. The strata of this interval in LT-3 contains generally sub-angular to sub-rounded clasts from coarse sand to small cobble size that are predominantly andesite, and that are matrix supported. This appears to document one or more debris flows with predominantly andesite clasts introduced from colluvium on the slopes above into what is likely to have been a lacustrine environment.

The alternating low-to-high energy environment suggest that a "proto-Flat Creek" flowed through the valley in which Jackson is today located during the wetter inter-glacial period(s) of the past several hundred thousand years. Periodically the natural outlets for this area, between East Gros Ventre Butte and High School Hill, and between High School Hill and Snow King Mountain, were dammed and allowed lakes tens of feet in depth to form and trap very fine-grained sediments. These periodic dams would have been a result of either or both landslide debris or fault block rotation resulting from the on-going Basin and Range extension that was and still is forming Jackson Hole.

Removal of Rock and Debris from the Southern Lower Slopes of East Gros Ventre Butte

The long red line in Figure 12 traces The Little Gros Ventre Irrigation Ditch dug by the original homesteaders of this region before 1910. The ditch runs from where Flat Creek flows under West Broadway at an altitude of 6195 feet to fields west of Highway 22 just north of the intersection with West Broadway at an altitude of 6180 feet. This ditch is shown most clearly by the row of mature trees seen in the 1955 aerial photo (Figures 6 and 7). Parts of the ditch were piped underground as development increased north of West Broadway. The system was last used in 1987 and large parts were removed in 2003 with the development of the Hillside Building at 945 West Broadway. The depth of the ditch is unknown but was most likely shallow since it must have been dug by hand or by horse-drawn implement. This creates an excellent reference for ground level elevation prior to development. Water in the ditch formerly flowed in the vicinity of Budge Drive at an elevation of approximately 6187 feet (average of the elevations at both ends). This is 10 feet above the southern edge of the Walgreen building currently at an elevation of 6177 feet, which is ten feet

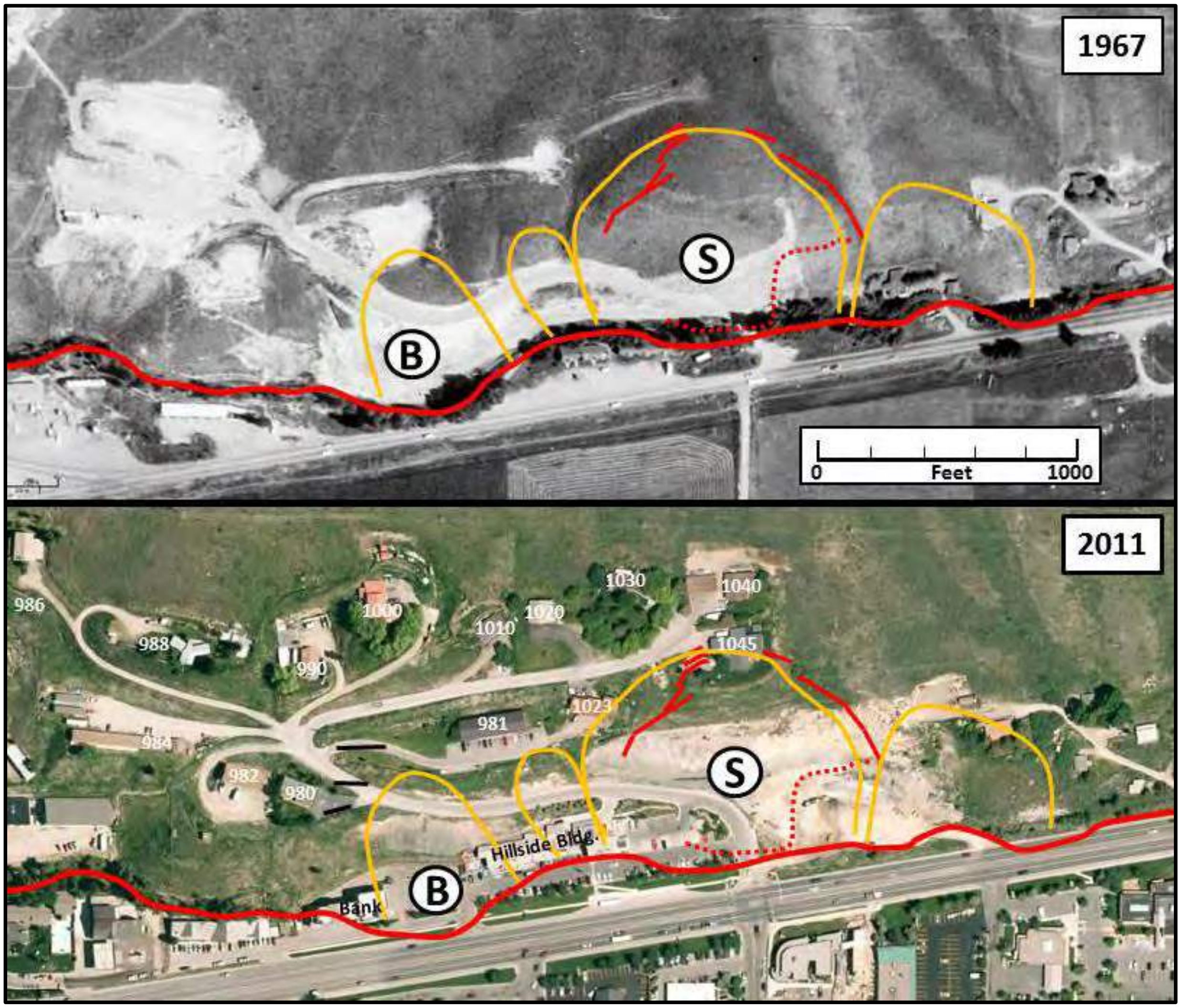

Figure 12: Air photographs of the Budge Drive region taken in 1967 and 2011. The long red line marks the position of the irrigation ditch as shown in Figure 7. The orange arcs show the location of the geomorphic anomalies shown in Figure 7. The dashed red line shows the southern limit of deformation observed in April, 2014. The short red lines show ground fracturing observed in April, 2014.

above West Broadway. Thus we can assume that this irrigation ditch in 1955, in the vicinity of the future Budge Drive, was at an elevation approximately 20 feet above the West Broadway of today and that natural slopes to the north of the ditch were all uphill as shown by the 1963 U. S. Geological Survey topographic map (dashed red line in Figure 4). South of the irrigation ditch, a wedge of soil and rock up to 20 feet thick was removed during the initial construction of West Broadway as a two-lane road, the widening to a 5-lane road between 1967 and 1977, and the development of street-level businesses west of Budge Drive. Assuming this wedge extended 50 feet to the south, then 2.3 million cubic feet must have been removed along the 4500-foot east-west extent of this aerial photograph (Figure 12).

The cross-section of material removed from the quarry near Budge Drive in the vicinity of the 2014 landslide (S) shown in Figures 4 and 12 is approximately 15,600 square feet. While the quarry face is 1200 feet wide, the western half includes Budge Drive. Assuming a width of at least 900 feet, the volume of rock and debris removed is conservatively estimated as being approximately 14

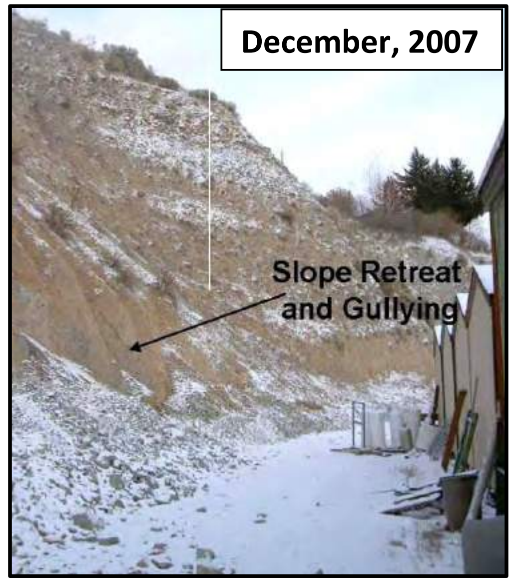

Figure 13: Photos of the northeast corner of the property developed for Walgreens. Note the trees in the upper right corner of each photo for comparison of views. Upper two pictures from the Geotechnical Report by Womack and Associates December 20, 2007. Photo to left by Ulrich. Lower photo from the website of the Town of Jackson.

million cubic feet. This includes material removed in 2003 to create a parking area and access east of the Jackson Hole Athletic Club building formerly located east of Budge Drive. Reconstruction of Budge Drive in 2003, removed an additional approximate 0.3 million cubic feet. Removing 8 feet of material in 2011 in preparation for the construction of Walgreens totaled another approximately 0.6 million cubic feet of material, approximately 4% of the total material removed from the quarry area. Photographs in Figure 13, all looking east-northeast towards the same trees on the horizon, show that considerable slope debris falling from the quarry cliff was removed since 2001.

South of the irrigation ditch, a wedge of soil and rock up to 20 feet thick was removed during the initial construction of West Broadway as a two-lane road, the widening to a 5-lane road between 1967 and 1977, and the development of street-level businesses west of Budge Drive. Assuming this wedge extended 50 feet to the south, then 2.3 million cubic feet must have been removed along the 4500-foot east-west extent of this aerial photograph in Figure 12.

The cross-section of material removed from the quarry near Budge Drive in the vicinity of the 2014 landslide (S) shown in Figures 4 and 12 is approximately 15,600 square feet. While the quarry face is 1200 feet wide, the western half includes Budge Drive. Assuming a width of at least 900 feet, the volume of rock and debris removed is conservatively estimated as being approximately 14 million cubic feet. This includes material removed in 2003 to create a parking area and access east of the Jackson Hole Athletic Club building formerly located east of Budge Drive. Reconstruction of Budge Drive in 2003, removed an additional approximate 0.3 million cubic feet. Removing 8 feet of material in 2011 in preparation for the construction of Walgreens totaled another approximately 0.6 million cubic feet of material, about 4% of the total material removed from the quarry area.

Photographs in Figure 13, all looking east-northeast towards the same trees on the horizon, show that considerable slope debris falling from the quarry cliff was removed since 2001.

In the vicinity of the Hillside Building, a wedge estimated to be 50 feet high, 200 feet north-south, and 500 feet east-west was removed between 1960 and 2003 for a total of 2.5 million cubic feet. The Hillside Building was designed, in part, to be a buttress for the preexisting slope to the north created by quarrying in the late 1950s and throughout the 1960s. The owners, based on recommendations by their geotechnical consultant, also decided to have 188 soil nails, 35 to 45 feet long, installed on 6-foot centers in the quarried cliff, primarily for the safety of workers constructing the building but also to provide more slope stability. This decision was not required by the Town of Jackson but was made by the owners even though it increased the projected cost of the building considerably.

The second largest amount of rock and debris removed from the hillside north of West Broadway in the late 1950s through the 1970s was in the vicinity today of the Bank of Jackson Hole

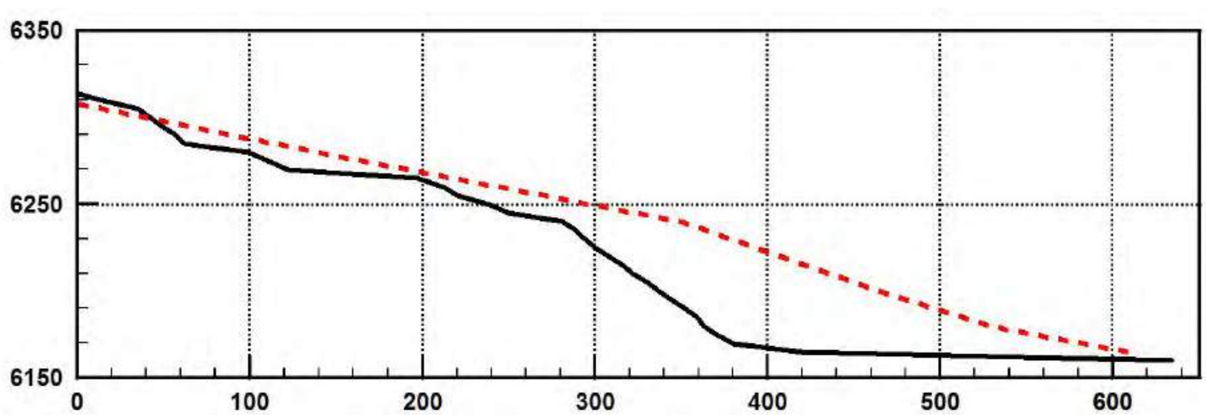

Figure 14: Topographic profile north-northwest to south-southeast through the circled B in Figure 12. The black line shows 1999 topographic data. The dashed red line shows topographic data from the 1963 USGS Jackson Quadrangle map.

Figure 15: Crack in the driveway at 980 Budge Drive (left) and just to the north along Budge Drive (right) that were first observed in 2009 shortly after a malfunction of the sprinkler system for the condominiums at 981 Budge Drive caused considerable water to flow down the hill. Views looking west.

and its parking area to the East shown by the circled B in Figure 12. Figure 14 shows a profile through the circled B in Figure 12. The area of the cross-section removed is approximately 10,000 square feet. Assuming a width of 500 feet, the volume removed approaches 5 million cubic feet. The remaining slope is unsupported except for a 7-foot high retaining wall at its base.

Small cracks in the pavement (Figure 15 and 16, black lines in Figure 12) were first observed by the residents at 980 Budge Drive near the south edge of their driveway, in Budge Drive itself just to the north, and in the driveway to 981 Budge Drive during 2009, shortly after some malfunction with the sprinkler system at the condominiums at 981 Budge Drive caused considerable water to flow down the hill. These cracks have not been observed to grow since 2009 but should be monitored, at least by carefully sealing them to prevent inflow of water and then keeping a watch out for new or renewed cracking. Budge Drive just north of the circled B and nearby homes appear to have a higher risk of slope failure than anywhere else on the hill after the Budge Slide is stabilized. Increased stabilization of this area together with developing systems to divert and control runoff should be considered as part of efforts to stabilize the Budge Slide.

Figure 16: Cracks in the driveway to the condominiums at 981 Budge Drive, looking west.

Rainfall Thresholds

Landslides worldwide are typically associated with a rapid increase in rainfall that results in saturated soils and slopes, and increased hydraulic pressure at depth. These are all factors that are highly likely to have contributed to landslide initiation. Figure 17 shows the intensity of rainfall plotted as a function of the duration of the rainfall for 124 regions around the world (Guzzetti et al., 2007). The details of line thickness and the numbers are described in that paper. What is important for this report is that very high intensity rainfall for a short duration or more moderate intensity rainfall for a longer duration than normal often triggers landslides typically by increasing the fluid pressure in incipient slip zones and thus decreasing the friction. Rainfall that runs off a slope without penetrating the surface has little effect. But rainfall penetrating the surface by flowing down cracks or ponding in low, poorly drained regions can have major effects in changing the balance of forces of an incipient landslide.

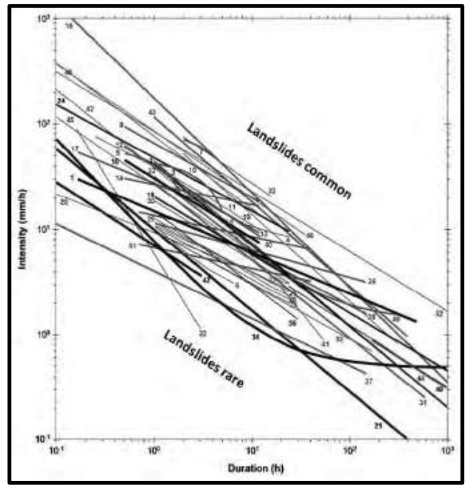

Figure 17: Landslides are more common when the intensity of rainfall is very high for a short duration or more moderate for a longer duration. A logarithmic plot of intensity in millimeters per hour as a function of duration is in hours.

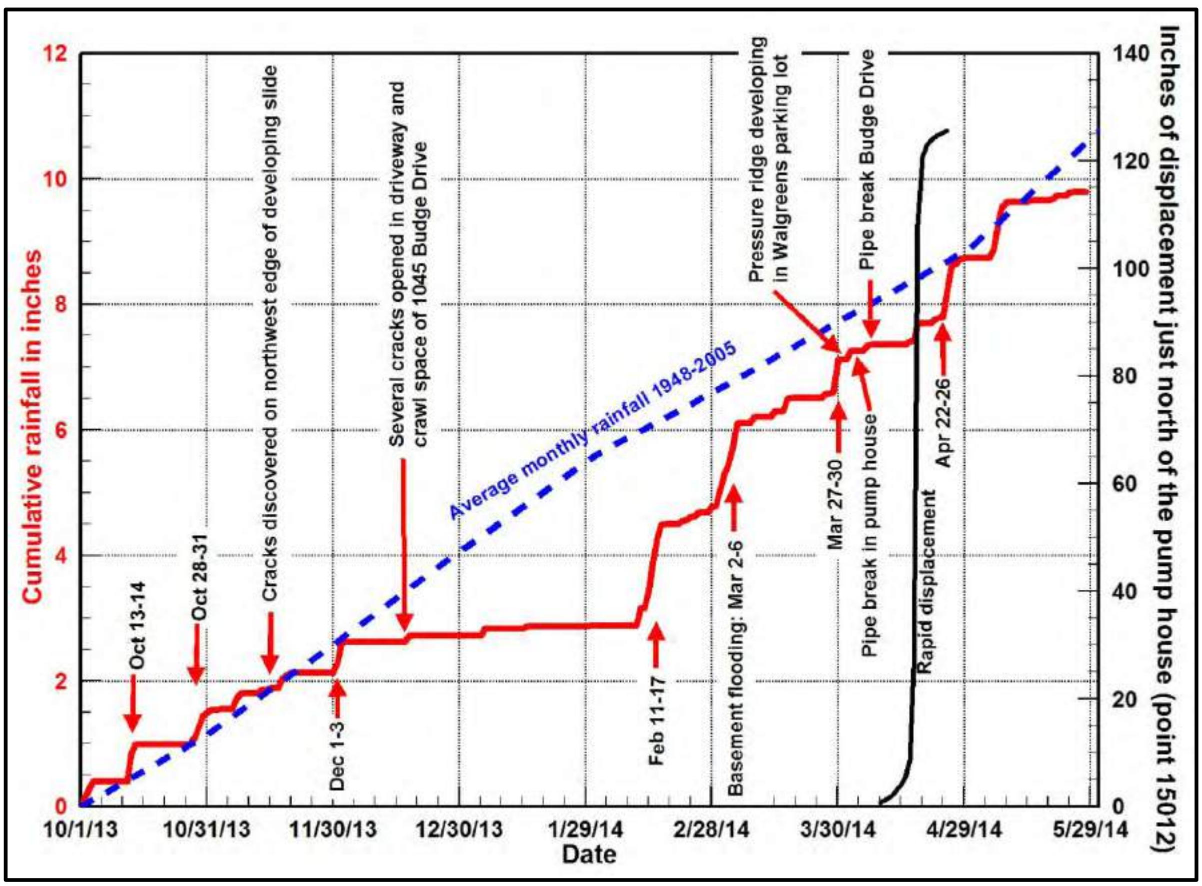

Figure 18: Rapid displacement of the town pump house southward toward West Broadway occurred after a much more rapid increase in spring rainfall than normal compounded by rapid melting of record snow cover over frozen ground causing the worst flooding of basements along Budge Drive remembered by residents who had lived there for many decades.

The red line in Figure 18 shows the cumulative rainfall measured on the north end of East Gros Ventre Butte from October 1, 2013 through May 30, 2014. The dashed blue line shows the cumulative average rainfall per month for this period. These data cover the period from August, 1948, through 2005 for the Town of Jackson (Western Regional Climate Center, 2014). Rainfall at a rate more than twice average began on February 11, 2014. From March 2 to 6, a particularly warm rain fell, melting snow still covering the hillside above Budge Drive. Residents say the ground was still frozen so that there were “sheets” of water from both rainfall and rapid snow melt flowing down the hill. At 7:30 am on March 6, residents at 1030 Budge Drive, just above and slightly west of the slide, put laundry in their washing machine in a dry basement. When they returned at 11 am to fetch the laundry there was two inches of water in the basement. Such flooding was reported from homes east of the slide to homes west of Budge Drive. Residents of the hillside for more than four decades could not remember similar flooding.

The black line shows the cumulative displacement to the south towards East Broadway of survey point 15012, located just north of the Town of Jackson pump house. While displacement had been increasing slowly since 2011, the toe of the landslide suddenly moved 112 inches between April 16 and 19. This movement then slowed rapidly and has been slowing ever since.

Movement of the residence at 1045 Budge Drive, which ultimately was split in two by this landslide, was reported by fall to winter of 2011 with a $1/16^{th}$ inch crack reported in the floor above the developing headscarp by Christmas, 2011. By February 11, 2014, when precipitation began to increase rapidly, the headscarp would have been large enough to divert water running down East Gros Ventre Butte down the crack and through the highly flow-foliated (porous) andesite to the layers of clay cored at a depth of 137 feet in drill hole LT-4, 70 feet south of the headscarp. Here the water would flow along the less-permeable clay layers, increasing fluid pressure and decreasing the friction, creating an effective slip surface.

Note in Figure 18 that the amount of rainfall (red line) from October 1, 2013, to May 28, 2014, is very close to the long-term average (dashed blue line). What was different was the lack of rainfall, which includes snowfall, in December and January, and the very high rate of rainfall in February, March, and April.

A Water Leak and Down Cutting of the Walgreens Site in 2011

From April 13 to April 17, 2011, water leaked at 1045 Budge Drive while the owners were out of town on vacation. They returned to find a very wet crawl space and no clear evidence of this water flowing down the hill. The leak occurred before the water reached the water meter, but Bob Norton at Nelson Engineering calculated, based on records at the Town of Jackson pump house at the base of Budge Drive, that 200,890 gallons of water was leaked. This is a considerable amount of water that would cover a football field (300 feet by 160 feet) to a depth of 6.7 inches.

The north-sloping part of the roof at 1045 Budge Drive drains to the north of the house where there is no gutter, French drain, or any other type of drain to move the water away from the house. As a result, water tends to pond north of the house and especially north of the northeast part of the house. Here it permeates or flows under the foundation causing dampness observed in April, 2014 (Figure 19, lower left photograph). Then the water flows east and south past the east end of a pony wall, ponding just inside the southeast foundation of the home (Figure 19). At this point, there is only one way for the water to exit and that is downwards. Just north of the southeast foundation is precisely the headscarp of the Budge landslide (Figure 20), suggesting the possibility that this major leak could have been one of the factors causing the nucleation of the slide in 2011, the formation of the initials cracks that ultimately defined the northern physical extent of the slide.

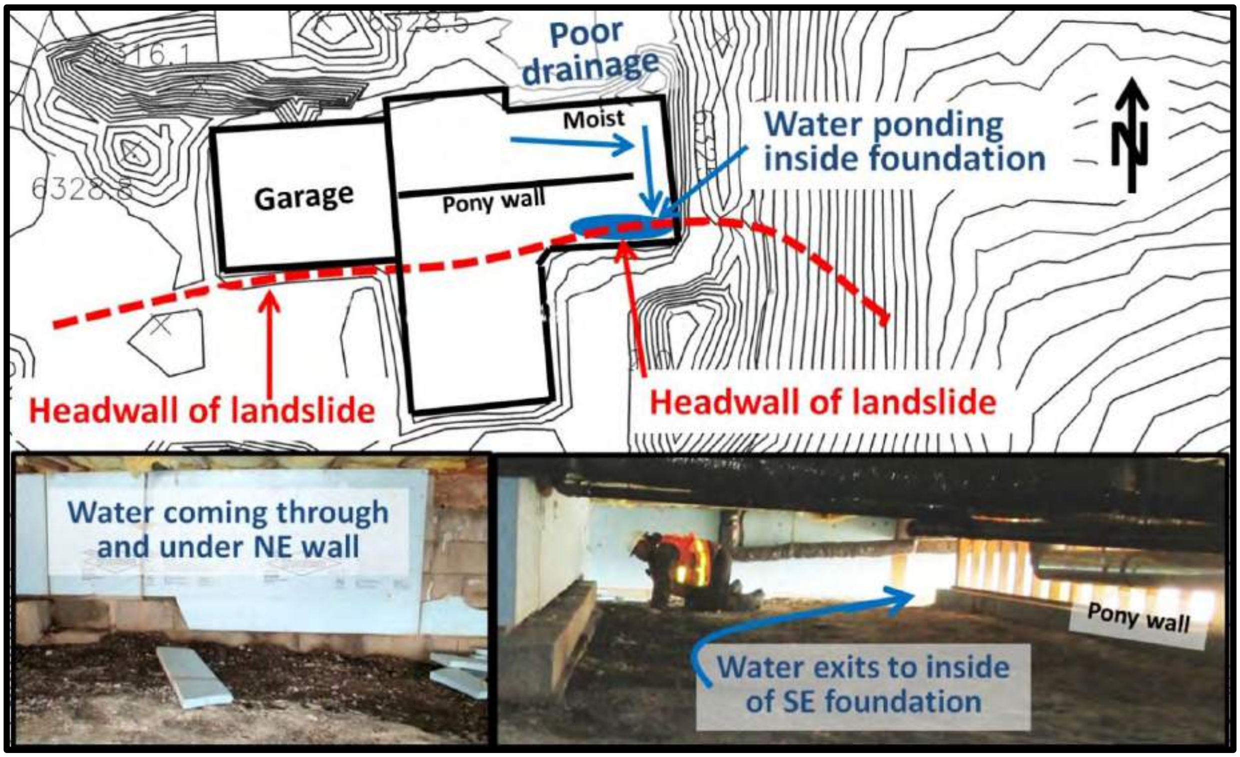

Figure 19: Foundation of the home at 1045 Budge Drive plotted on a one-foot contour map showing where water flows around the pony wall to pond behind the southeast foundation. Picture lower left is looking north where moisture regularly comes through or under the concrete block foundation. Picture lower right is looking east.

The other event in 2011 that could have helped nucleate the slide was the removal of 8 feet of rocks and dirt from the future site of Walgreens at the base of cliff face excavated by quarrying during the summer. The volume removed is only about 4% of the total volume removed since 1960, but one can always argue that it was "the straw that broke the camel's back." In this case, one would argue that the spatial extent of the south-facing cliff created by removal of rock and debris created a stress field through which the fracture surfaces of the slide nucleated and the home at 1045 Budge Drive was in an unfortunate location.

Figure 20: Headscarp of the landslide directly under the inside edge of the southeastern foundation of the house at 1045 Budge Drive

We see no way to prove whether either or both the leak or the removal of 8 feet of rock and debris at the Walgreens' site caused the slide to nucleate in 2011, but both are plausible explanations. The overall hazard was clearly created by the cumulative removal of rock and debris since 1960, but especially during the active quarrying from the late 1950s through the 1970s. The rapid motion in March and April, 2014, appears to have been triggered by greater than normal rainfall and rapid melt of snowfall. What initially nucleated the slide, what initiated deformation observed by late 2011 is, as discussed above, more debatable.

Extent and History of the Deformation

Surveys commissioned by the Town of Jackson since April 1, 2014, at more than 190 points around and in the region of the former quarry showed no detectable deformation outside of the immediate area of the landslide as defined primarily by the red fracture zones mapped in Figure 12 on the north and the southern extent of deformation shown by the dashed red line in Figure 12. There was a report of new cracks in the ground seen on the hillside just east of the Walgreens residences, but flooding of water in March and April was also observed in this area and we are not aware of any evidence that ground fractures here were related to the landslide. Surveys show that no deformation was detected at the Walgreens store, the Walgreens residences, or the hill to the east.

Residents at 1045 Budge Drive report they first noticed movements in their residence in the fall to winter 2011. The following details are from the Jackson Hole News and Guide April 16 and 23, 2014. By December 25, 2011, a crack 1/16th inch wide opened between the kitchen and dining room, the location of the future headscarp. By April 1, 2013, a crack had developed in their driveway and some deformation of the house was observed. By May 12, 2013, the southern part of the house had dropped a few inches, doors fit worse, cracks were becoming larger.

Western Engineering and Research determined that during June, 2013, the floor of the southern part of the house had sunk 6.1 inches and the two-car garage was up to 2 inches out of level. CTL Thompson installed an inclinometer in the driveway near the southeast corner of the garage on September 17, 2013, that had moved ¼ inch down slope by September 23, 2013.

During 2013, 3 to 5 feet of rock and debris was removed from where the Walgreens foundation would be and replaced with engineered fill. Compactors used to consolidate this fill set up vibrations reported by people both south of Broadway and at the top of Budge Drive. Similarly when the H-beams holding the retaining walls between West Broadway and Walgreens were being driven by a pile driver. While these vibrations are felt well by people in the vicinity, they are generally not strong enough to cause damage under normal circumstances (Brown, 1971).

By October, 2013, increased rock fall was observed above the Walgreens parking lot. Local residents report a large number of truckloads of fallen rock from behind the H-beam and wood retaining walls north of the Walgreens parking lot being hauled away during late fall, 2013, through March, 2014. This rock fall would probably have been the first indication observed of a developing slide, had there not been a home existing at 1045 Budge Drive that was demonstrating deformation as early as 2011.

On November 15, 2013, an opening crack was discovered along the upper west part of the developing slide (Figure 12) and reported to the town. Residents of 1045 Budge Drive moved out soon thereafter. In early December, 2013, local residents reported a 2 to 3 inch crack in the concrete retaining wall just north of lower Budge Drive according to the Jackson Hole News and Guide. Workers installed a steel net over the cliff in December in order to make it more difficult for rocks to fall out into the parking lot. By December 16, 2013, several cracks had opened up in the driveway and crawl space at 1045 Budge Drive.

By March 31, 2014, a pressure ridge began developing in the parking lot of Walgreens outlining the southern edge of the toe of the landslide. By April 19, the ridge was more than 8 feet high and at least 10 feet north to south, north of the Walgreens building. On April 4, 2014, the pipe supplying the town pump house just east of lower Budge Drive broke in the evening. On April 8, the water pipe under Budge Drive near the cracked retaining wall broke. According to surveys by Jorgensen Associates, a survey point just north of the pump house was moving (black line, Figure 18) 0.5 inches per day as measured on April 10 and 11, 0.7 inches per day on April 12, increasing to 1.7 inches per day on April 15, 2.8 inches per day on April 16, 17.1 inches per day on April 17, and 82.5 inches per day measured on April 18. Then motion slowed to 12.5 inches per day on April 19, 2.1 inches per day on April 20, 0.4 inches per day on April 23, and has been slowing consistently since.

Continuing Deformation

Roger Bilham, Professor of Geological Sciences at the University of Colorado and world-class leader for many decades in measurement of ground strain, offered, through a close friend living in Jackson, to loan to the Town of Jackson four extensometers slated for installation in California and to install them in the vicinity of the headscarp of the Budge Slide. These unique instruments, designed and built by Roger, not only measure movement of the slide, but provide instant notification if the rate of motion of the slide starts to increase. Sudden collapse of landslides is typically preceded by an exponential increase in rate of motion so that detecting this increase can provide important warning for workers and observers in the immediate vicinity of the slide. Installation was delayed by several issues, but the instruments were finally installed between April 23 and 26, 2014, less than a week after the most rapid motion of the slide (black line, Figure 18).

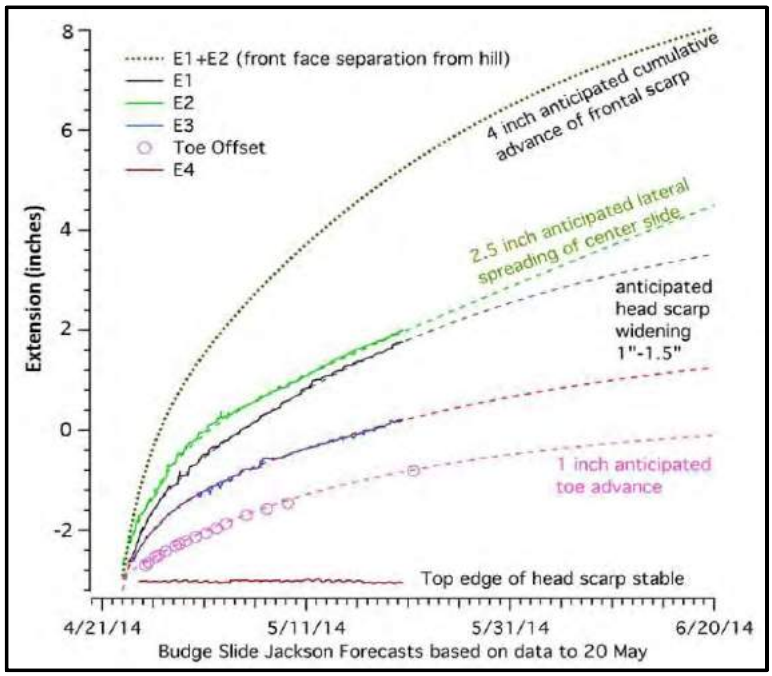

Figure 21: Extension measured by four instruments spanning the headscarp of the Budge Slide and modelled advance of the frontal scarp. Observations shown were from April 23 through May 20, 2014.

Figure 21, provided by Roger to the Town of Jackson, shows extension measured since installation through May 20, 2014, and the anticipated future extension based on similar observations elsewhere. The rate of motion of the slide has decreased steadily and Roger predicts up to 4 more inches of motion over the next month. We have been very fortunate to have access to such state-of-the-art instruments.

Recent Earthquakes as a Factor

Might an earthquake have caused the Budge Drive landslide? There are certainly numerous examples of earthquakes having caused landslides, such as was seen with the Magnitude 7.1 to 7.3 1959 Hebgen Lake earthquake and resultant landslide in Madison Canyon, just west of Yellowstone National Park. Closer to home there were reports of earthquakes being felt about the time of the 1925 Gros Ventre slide. But an examination of the magnitude of earthquakes experienced near the Town of Jackson from 2011 to the present and the likely effect of these earthquakes suggest that there is no reasonable relationship.

Figure 22, provided by the University of Utah Seismology and Active Tectonics Research Group, shows that during the past 3 years there have been no earthquakes larger than magnitude 1 (M1) within at least 15 miles of the Town of Jackson. The approximate site of the Budge Drive landslide is indicated by the yellow star, and there have been nine M1 earthquakes within 5 to 10 kilometers of the site, though none closer than approximately 1 to 2 miles distance.

What is the effect of magnitude one (M1) earthquakes? A table on the Michigan Tech "UPSeis" website shows the following:

Magnitude	Earthquake Effects	Estimated Number Each Year
2.5 or less	Usually not felt, but can be recorded by seismograph.	900,000
2.5 to 5.4	Often felt, but only causes minor damage.	30,000
5.5 to 6.0	Slight damage to buildings and other structures.	500
6.1 to 6.9	May cause a lot of damage in very populated areas.	100
7.0 to 7.9	Major earthquake. Serious damage.	20
8.0 or greater	Great earthquake. Can totally destroy communities near the epicenter.	One every 5 to 10 years

http://www.geo.mtu.edu/UPSeis/magnitude.htm

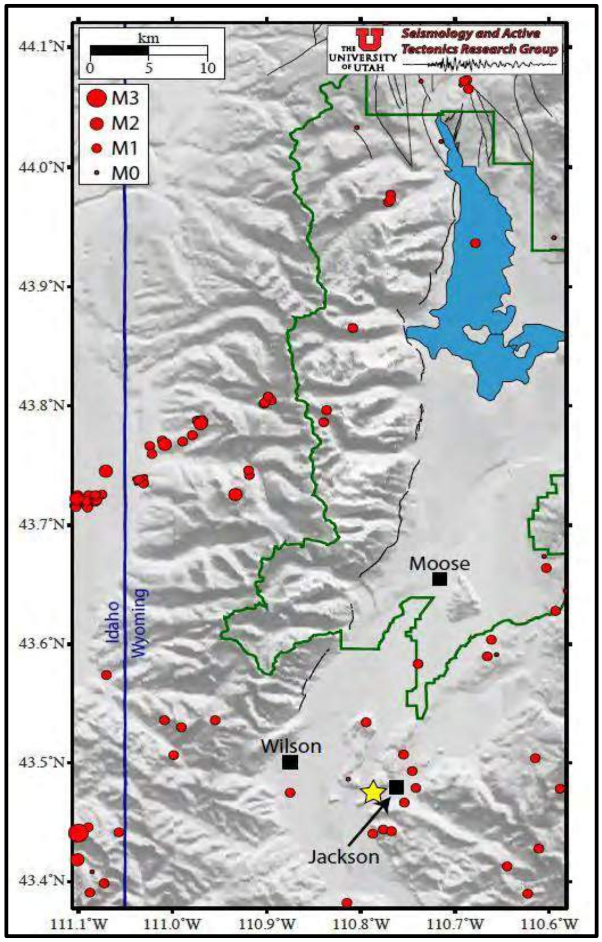

Figure 21: Local Earthquakes, 2011 to present.

None of the seismic events within miles of the Budge Drive landslide are larger than magnitude one (M1), and the Michigan Tech table demonstrates that even a magnitude 2.5 earthquake (M2.5) is commonly not felt. Note that a magnitude 2 (M2) earthquake would release approximately 32 times as much energy as a magnitude 1 (M1) earthquake. Therefore the M1 earthquakes near Jackson between 2011 and the present would have released approximately 1/32 of the energy of a quake that is "Usually not felt".

The data available suggest that we can confidently rule out an earthquake as a factor in the Budge Drive landslide.

Summary

1. The slopes of mountains and hills in the vicinity of Jackson Hole reached their natural angle of repose over thousands of years so that landslides and other slope failure are relatively rare until parts of slope are undercut by rivers, removed by humans, or shaken severely by major earthquakes.
2. When the lower parts of these slopes are removed for any reason, such as to quarry rock, to build highways, to level building pads, or to make businesses more highway accessible, the stability of the slope is decreased and the risk of landslides and other slope failure is increased.
3. This risk can generally be kept within reasonable limits by appropriate land development regulations, prudent development, and appropriate geotechnical engineering.
4. The greatest amount of lower-slope material removed in Teton County for all of these purposes during the past 50 years is along and north of West Broadway, from the vicinity north of Virginian Lane to just west of Highway 22.
5. The greatest man-made risk of slope failure in Teton County was created by removal of highly flow-foliated and fractured andesite, conglomerate, and related debris from the "County Quarry" located in the vicinity of Budge Drive. This occurred primarily from the late 1950s through the 1970s and left a cliff face 1000 feet long, more than 100 feet high, with man-made slopes of up to 55 degrees, more than three times the natural slope of 15 degrees in the lower part of East Gros Ventre Butte (Figure 1). This quarry cliff was highly likely to fail at some time in the future.
6. Deformation of the residence at 1045 Budge Drive was first detected in the fall to winter of 2011. This deformation increased very slowly during 2012 and 2013 but in April 2014, after higher than usual rates of rainfall and snow melt, the ground slid primarily within a few days, dropping the south wing of the home as much as 20 feet along the headscarp of a landslide.
7. The landslide was symmetric about the quarried cliff face and involved a volume of material roughly equivalent to the volume of material removed primarily during the quarry operations plus the much smaller amounts removed during the realignment of Budge Drive in 2002, development of the Hillside Building in 2003, and the removal of 8 feet of rock and debris in 2011 done in preparation for construction of the Walgreens store.
8. Through continuous core drilling, the slip surface of the slide was identified at a depth of 137 feet in drill hole LT-4, approximately 50 feet south of the severed residence. This slip surface involved a clay-rich layer of sediments most likely formed during deposition in a lake that once existed where the Town of Jackson is today. Such lakes have covered most of Jackson Hole during many different interglacial times, so these clay-rich layers may underlie many of the lower slopes in Jackson Hole.
9. Rainfall and melt water on the ground surface was able to reach this layer along the developing headscarp fracture and by sinking down through the highly flow-foliated, fractured, and therefore porous andesite between the ground surface and the clay-rich layer.
10. The headscarp fracture appears likely to have nucleated in 2011, with movement increasing very slowly throughout 2012 and 2013, reaching a total of approximately 6 inches of

movement by late 2013 and ultimately 82.5 inches of movement in one day measured on April 18, 2014.

11. While the increased risk of this landslide appears to have been caused primarily by quarry operations from the late 1950s through the 1970s, and the trigger for rapid movement in April, 2014, appears caused by unusually high rates of rainfall and snow melt, the reason this slide nucleated in 2011 is less clear. Options include:
    a. Leakage of 200,890 gallons of water between April 13 and 17, 2011, under the residence straddling the headscarp of the slide
    b. Removal of 8 feet of rock and soil from the region of the future Walgreens store during the summer of 2011
    c. Spontaneous failure due to the overall removal of rock and debris over many decades
    d. A combination of all of the above
12. The cliff face and steep slope north of West Broadway from Virginian Lane to Highway 22 is not bedrock. It is, in large part, landslide debris from ancient landslides that likely occurred tens of thousands of years ago. This landslide debris sits on top of poorly lithified clays and silts. Large amounts of the base of this slope were removed by development, increasing the risk of slope failure. Most of this debris is highly porous andesite and porous conglomerate that can allow unusually high rates of rainfall and snow melt, or water leaked by the actions of humans, to reach the underlying clay-rich layers at depths of 100 to 150 feet that can become slip surfaces for slope failure – for landslides.
13. Restoration of the present day landslide and future development of this area needs to consider these geologic conditions and to seek appropriate engineering solutions to keep risk of future slope instability to an acceptable level.

Considerations for the Future

It is not possible to develop many parts of Jackson Hole without increasing the risk of slope failure. There are engineering solutions that have greatly reduced risk along major highways in the river canyons and over mountain passes as well as in hillside developments. The problem is determining how much risk is acceptable, given the costs of mitigating risk, given the intended use of the facilities being developed, and given how many people will be exposed to that risk. There are technical and geotechnical specialists who regularly address these issues. Their expertise is typically required by building ordinance to address issues regarding foundations and retaining walls, but not to address issues regarding the overall safety of a specific site. It is not clear, in the case of development of the Walgreens site, that any technical expert was asked by the developer or by the town to determine how safe it would be to build a major retail store next to the base of a more than 100-foot high, manmade cliff, with slopes up to 55 degrees, more than three times the natural slope before quarrying, that was prone to slope failure.

Section 49160 (A10) of the Town of Jackson Land Development Regulations states that "No development shall be permitted on **natural** slopes in excess of twenty-five (25) percent, except to provide essential access for vehicles and/or utilities when no other alternative access exists." This regulation was applied to the Walgreens site but it was superseded through the Conditional Use Permit process. We suggest consideration be given to amending this regulation to apply equally to natural and manmade slopes and to allow exceptions only when geotechnical studies of slope stability certify appropriate engineering solutions are planned to reduce risk of slope failure to an acceptable level.

Landslide risk on the south slope of East Gros Ventre Butte and most other slopes around Jackson Hole is greatly increased during times of higher than average rates of rainfall and snowmelt primarily when the excess water can reach clay-rich layers at depths, in this case, 137 feet below the surface. Systems to manage collection and safe disposal of excessive rates of rainfall and snow melt should be considered urgently for the current safety of homes and businesses north of West Broadway in the Budge Drive area west to Highway 22.

Section 4.2 of the Teton County Comprehensive plan concerning the *"Northern Hillside" says "a variety of residential types, including live/work, multifamily, and duplexes, may be appropriate in this area."* A primary lesson from the Budge Slide should be that increased development in this Northern Hillside region needs to specifically address issues of slope stability and water drainage.

The second greatest amount of rock and debris removed since 1960 from north of West Broadway, after the County Quarry, was in the region today of the Bank of Jackson Hole branch and the parking lot between the bank and the Hillside Building. Cracks have already been observed to form above these steep slopes in Budge Drive and nearby driveways following malfunction of a major sprinkler system. Ways to improve the stability of these steep slopes and to divert and control runoff should be considered carefully.

The steep east-facing scarp of the Teton Range was formed by as much as 30,000 feet of vertical motion occurring 3 feet to rarely as much as 15 feet at a time during earthquakes with magnitudes estimated to be in the 6.0 to 7.5 range. While no significant earthquakes have occurred since Jackson Hole was settled, and geologic data suggest that none have occurred for perhaps at least hundreds of years, they will occur in the future – be it tomorrow or one hundred years from now. Engineered solutions that increase slope stability, allowing large numbers of people to live in and access areas at high risk to slope failure could increase long-term risk if they are not designed to account for the large ground shaking expected during a local magnitude 6 to 7.5 earthquake.

The Geologists of Jackson Hole

The Geologists of Jackson Hole is a non-profit organization whose mission is to promote learning and sharing of knowledge about the Earth around us and the field of Earth Science with its members and the public. The organization currently has more than 330 members and an additional 260 "friends" who receive our regular newsletter. We sponsor public lectures at the Teton County Library on the 1st and 3rd Tuesdays of each month except December and have monthly members meetings as well as multiple members' field trips each year. More information about the organization can be found at our website: www.geologistsofjacksonhole.org

This report is a volunteer effort prepared primarily by local residents Peter Ward, 27 years with the U. S. Geological Survey, John Hebberger, Jr., 30 years with Chevron Corporation, David Adams, PhD Oregon State with extensive geologic research in Jackson Hole, and local part-time resident Bob Smith, Professor, University of Utah and Director of the Utah Seismology and Active Tectonics Research Group. This report and has been reviewed by the Board of Directors and many other members of the Geologists of Jackson Hole.

The Geologists of Jackson Hole seek to provide information and education to our community and the public at large concerning earth science issues. This report represents our effort to provide an earth science perspective on the Budge Drive landslide. We have attempted to summarize and integrate pertinent geologic literature, the authors' observations about general Jackson Hole geology and specifically the southern flank of East Gros Ventre Butte, while incorporating recently acquired data specific to the area of the landslide. It is our hope that this effort will assist the Town of Jackson and our Jackson Community to better understand the situation, to respond appropriately to the recommendations provided by consulting company Landslide Technology, and to work together to find the best solutions for our community.

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This report would not have been possible without access provided by the Town of Jackson to the slide site and especially to the cores recovered from the five-hole drilling program carried out to evaluate the Budge Drive slide site. Town Manager Bob McLaurin and Director of Public Works Larry Pardee were especially helpful. Staff of Landslide Technology, in particular George Machan and Adam Koslofsky, were most generous with their time and help in accessing data, and in developing our understanding of their efforts to evaluate the slide. Others who contributed to our understanding of the situation through valuable discussion, provision of copies of materials, recollection of pre-slide events in the Budge Drive area, or review of drafts of this report, though who are in no way responsible for the discussion or conclusions herein include: Reed Armijo, Terry Goss, Phil Gyr, Dennis Jones, Elizabeth Kingwill, Bob Norton, Aaron Pruzan, Jason Rolfe, Tim Sandlin, Wally Ulrich, and Ray Womack.

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Addendum: Core Descriptions

Description and pictures of cores from drill holes LT-1, LT-2, LT-3, LT-4, and LT-5.