Addendum to "The Mud Creek Debris Flow of September 20, 2014, on Mount Shasta"

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Contents

BACKGROUND

Due to recent mudflow activity at Mud Creek this addendum to the report documenting the large 2014 event entitled "The Mud Creek Debris Flow of September 20, 2014, on Mount Shasta" was developed to characterize immediate and future relative risk to Pilgrim Creek Road. The addendum also explores possible mechanisms for the mudflows on Mud Creek and the estimated contribution of each mechanism to the risk profile at Pilgram Creek Road.

Periodic large debris flows and floods have occurred historically at Mud Creek. These floods often carry large volumes of soil and rock with them which are deposited on the Mud Creek alluvial fan that includes Pilgrim Creek Road. Given the primary deposition zone is an alluvial fan the pathways for water flow and deposition are relatively random shifting with each event.

Baseline and historic conditions are covered extensively in the 2014 report.

OVERVIEW OF POSSIBLE DEBRIS/MUDFLOW MECHANISMS

Over the past 100 years there have been approximately nine major debris flow events at Mud Creek. Some events included multiple debris flows over a period of several months. The 2014 report outlines possible mechanisms that could generate debris flows on Mud Creek. The most likely mechanisms are summarized as follows,

> **Summer Convective Storms (small to medium size)** – The most common. These include thunderstorms. In most instances the resulting debris flows are relatively small. The recurrence interval for this mechanism was estimated at approximately 10 to 20 years in the 2014 report.
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> **Warm Summer Frontal Storms (medium size)** - The recurrence interval was estimated at 50 years in the 2014 report.
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> **Warm Winter Storms (small to medium size)** - Winter storms can produce warm rain up to 10,000 feet in elevation which have triggered debris flows at Mount Shasta. The recurrence interval is estimated at 30 years in the 2014 report. A similar event occurred in 1997 along a tributary of Cascade Gulch.
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> **Glacial Melt/Outbursts (medium to very large size)** – 2014 was likely the last major event based on observational evidence. The recurrence interval is estimated at 50 to 100 years in the 2014 report. A hypothetical failure mechanism is described in this addendum.

Less likely mechanisms were described in the 2014 report. Those mechanisms, and several others, are summarized as follows,

> **Seismically triggered events** – Earthquakes occur regularly around Mount Shasta. In most instances accelerations resulting from earthquakes are relatively low and do no appear to have resulted in major impacts from landslides and rockfalls over the last 200 years. A complicating factor, however, is the topography of Mount Shasta which is essentially a cone. Like an ear trumpet that focuses sound waves topographic cones focus seismic energy. In general terms the effect of topology on the seismic response at any location is called 'topographic effects'. For longer earthquake recurrence intervals topographic effects could increase spectral accelerations to 1 g or more at Mount Shasta. Volcanoes are inherently unstable geologic formations. The geology includes large colluvial and erosional deposits, moraine deposits, deposits from past

lahars, deposits from pyroclastic flows, large deposits of ash and cinder, steep jointed and fractured rock and associated talus. Thus, high spectral accelerations at longer recurrence intervals coupled with relatively unstable geologic formations could trigger large landslides and rockfall.

Due to the large amount of energy imparted to seismically triggered landslides there is potential for some to transition to debris flows especially if saturation levels are high. An example of an impactful earthquake induced landslide/debris flow was the 1959 Hebgen Lake earthquake near Yellowstone National Park. The earthquake triggered a massive landslide that caused 28 fatalities and dammed the Madison River forming Quake Lake in Montana.

Volcanic triggered events – A volcanically triggered event could cause catastrophic, rapid, melting of existing glaciers on Mount Shasta. Large landslides could also occur. The resulting debris flows could be much larger than what has been observed in recent history. An extreme example of those debris flows can be found on the northern side of Mount Shasta. The debris flow there covers an area of about 260 square miles and appears to have occurred about 300,000 and 380,000 years ago. The estimated recurrence interval for volcanic triggered events is greater than 10,000 years.

Landslides along stream alignment – Due to unstable, over-steepened slopes, landslides occur frequently along the entire Mud Creek alignment. When they occur most pinch the stream temporarily impeding flow with no significant water storage upstream of the slide. The stream erodes the landslide debris until natural armoring stabilizes the stream channel. During large floods increased flow velocity and flow density (which is increased by suspended sediment and rock) can entrain large boulders transporting them downstream. As indicated in the 2014 report scour occurs along the entire Mud Creek alignment to varying degrees during large floods. Scour can trigger additional slides/debris flows on the channel slopes that may temporarily dam the creek. This is especially true during large storm events which can increase soil saturation levels. When these natural dams fail, they cause a surge in flow and debris downstream. Thus, landslides are probable contributors to debris and mud flow impacts downstream.

Landslides from retreating glaciers – As glaciers grow and move downslope they scour the bounding bedrock and soil. The scoured soil and rock are supplanted by glacial ice maintaining the force balance (buttressing) and stability in the slope. If the glacier retreats boundary forces provided by the ice in the glacier are removed causing a force imbalance and increased risk of slope failure. Historically this mechanism could be at play at Mud Creek but does not appear to be a substantial factor in the 2014, 2021, and 2022 events based on photographic evidence.

Thawing Soil Glacier/Permafrost– Volcanic, erosional, and colluvial deposits on the flanks of Mount Shasta are generally loose and unconsolidated. At higher elevations these deposits are often frozen or permafrost with high water content. Thus, thawing may also cause slope instability. High water content coupled with steep slopes increases the probability that landslides would transition to mud or debris flows.

CLIMATE CHANGE IMPACTS ON DEBRIS FLOW MECHANISMS

A warmer atmosphere holds more water vapor. Increased atmospheric water vapor content enhances moisture convergence and rainfall intensity in storm systems. Additionally, as the atmosphere warms there is increasing evidence that average wind speeds are slowing globally leading to longer duration storms. This trend points to the potential for larger storm-driven debris flows in the future around Mount Shasta.

2014 OBSERVATIONS AND ESTIMATES

The sheer volume of the debris and/or mudflows on Mud Creek require a tremendous amount of liquid water to transport. Critical observations were made in the 2014 report. Blocks of ice measuring 100 feet wide, 200 feet long, and 20 feet deep had dislodged from the toe of Konwakiton Glacier. Two narrow outflow tracks were also observed leading from the toe of the glacier – 20 feet and 40 feet wide approximately. Slopes where the outflow tracks occurred were estimated at 55%. With that information peak outflows from the glaciers could have been in excess of 15,000 cubic feet per second using open channel flow assumptions and an average channel depth of at least 3 feet. Total sediment deposition on the alluvial fan at Pilgram Creek Road was estimated at 800,000 cubic yards. Assuming most of the sediment was transported as debris flows and a sediment-rock concentration by volume of approximately 50% at least 800,000 cubic yards of water would have been required to transport the deposited soil and rock. It is doubtful that this amount of water could be stored by Kowakiton Glacier. Water contributions from antecedent soil moisture, scoured frozen soil along the stream alignment, entrained ice from the glacier, and entrained/melting ice/snow along the channel were likely contributors to the total water volume in the debris flows. Possible evidence for several of these additional water sources was provided by observations made in 2014. As seen in Figure 1 scoured frozen soil embankments were observed along the debris flow path. Additionally, the Forest Service team that surveyed the debris flow reported chunks of ice entrained in the flow. As seen in Figure 2, contributions from the Red Banks above Kowakiton Glacier could have also contributed water since flow and erosion tracks are visible and appear to discharge into the Kowakiton Glacier below.

HYPOTHETICAL GLACIAL MELT/OUTBURST MECHANISM

Forces driving movement in the glacier are induced by gravity acting on the ice it contains. Forces resisting movement are the shear stresses induced at the glacial slide plane between the ice and bedrock. The balance between the driving and resisting forces changes as a function of bedrock slope and depth of the ice above a particular point. If ice moving along the slide plane encounters steeper bedrock driving forces promoting movement would increase while shear forces resisting movement would decrease. Thus, steeper bedrock could result in more rapid movement in the glacier. Extensional zones are likely locations of steeper bedrock.

Mechanics leading to glacier destabilization.

Due to their location the glaciers at the south-facing headwaters of Mud Creek receive significant solar radiation. Over the summer months the increased solar radiation and rising mean air temperatures cause glaciers to gradually lose mass as first seasonal snow, then underlying glacier ice melts. With the loss of snow and increased melt the albedo of the glaciers can decrease (melt causes retained soil to concentrate darkening the glacier) which leads to increased absorption of light energy warming the glacier and increasing the rate of melt. Crevasses penetrate the existing glaciers from the surface to the underlying bedrock/soil. Ice along the alignment of the glaciers is in different states of lateral compression and extension. In zones of extension the crevasses are open allowing meltwater to flow from the surface of the glacier to the base causing advective heat transfer to the base. In crevasses where water is backing up and stored heat transfer would occur in the intervening fractures in the ice increasing the rate of melt. As water flows along the base the flow regimen would likely be a mix of open channel flow at atmospheric pressure and flow through a closed conduit (with pressure head) as water backs up (into crevasse's) in the glacier at locations where flow capacity is reduced. The flow condition at a specific location would vary with time as a function of the incoming flow and changing flow capacity of the pathway caused by heat transfer from the flowing water.

A portion of the subglacial flow likely seeps into the underlying bedrock and/or soil. Thus, advective heat transfer would likely enhance the melt rate at the glacier bed.

As the rate of melt increases large blocks of the glacier can shift or slide over the bed. This could be due to several mechanisms which include structural collapse, decreased ice shear strength, increased hydrostatic pressure, pressure transients, and buoyancy. Each mechanism is summarized as follows,

Structural collapse: Structural collapse is caused by a decrease in the contact area between the glacier and underlying bedrock as the ice melts from flowing water along the glacial slide plane. The decreased contact area increases stress in the remaining ice leading to an eventual collapse.

Loss of ice shear strength: As ice warms research suggests its shear strength decreases. As the shear strength decreases the ability of the ice to resist shear induced by gravitational forces acting on the ice decreases. If the induced sheer exceed the shear capacity of the ice the glacier may move locally or globally (due stress redistribution) especially if the ice shear strength is reduced over large areas.

Increased hydrostatic pressure: Increased hydrostatic pressure would occur in areas where flow is constrained backing water up in the glacier causing uplift. If the ice decouples from the bounding bedrock buoyant forces would also act on the ice to decrease normal forces (and resisting shear force between the ice and bedrock) induced by the weight of the ice along the bedrock contact.

Pressure transients/perturbations: Rapid changes in water flow velocity through and under the glacier could lead to pressure transients. A rapid reduction in flow velocity transforms kinetic energy contained in flowing water, described as velocity head, into pressure head. Rapid decreases in velocity head (which is squared) cause large spikes in pressure head. Water hammer is an example of this phenomenon.

Buoyancy: Ice is less dense than liquid water and will float.

Another complicating issue is varying confining stress in the glacier especially near the toe. As glacial blocks move downslope their movement is also resisted by longitudinal compressional stresses from ice downslope of the block. At the glacier toe longitudinal extensional stresses dominate. There are no longitudinal compressional stresses where crevasses are open to resist movement. This makes blocks of ice near the toe much more susceptible to displacement from all mechanisms described.

Thus, localized shifting and sliding could be due to several factors in isolation or combination – increased slope in the bounding bedrock surface along the base of the glacier (increased gravitational forces driving movement coupled with lower resisting shear stress), lower ice shear strength along glacial slide plane to develop resisting shear stress, lower confining and compressional stresses especially at the downslope edge of the glacier, structural collapse where the contact area between the glacier and bedrock has been significantly reduced, increased hydrostatic pressure and buoyancy as water backs up at constrictions in the flow path, and possible pressure transients/perturbations generated from rapidly moving ice.

Generally, global movement in the glacier is the result of a force imbalance between gravitational forces acting on the glacier and averaged resistive shear stresses developed along the glacial slide plane.

Possible mechanisms leading to 2014 event

Sliding, shifting, and collapses can constrict or cutoff the natural drainage pathways in the glacier. If drainage is significantly restricted liquid water storage in the glacier could increase dramatically increasing hydrostatic pressure in and under the glacier upstream of the constriction magnifying shifting and sliding. This is especially true along the downstream toe of the glacier where compressional and lateral confining stresses are lower. Increased hydrostatic pressure and buoyant forces could dislodge blocks of ice unplugging the drainage pathway leading to a sudden release of water from the glacier. The dislodged blocks of ice observed in 2014 could have been such an event.

In some instances, movement in the glacier may be sudden. Sudden movement might cause pressure perturbations/transients in the glacier exasperating uplift and inducing hydrofracturing and pressurized water discharges from the glacier. Such pressure transients and hydrofracturing could cause ice to detach from glacial bed and bounding bedrock leading to accelerated movement or general collapse across large portions of the glacier. The dislodged blocks of ice observed in 2014 could have been such an event.

Alternative possible mechanisms leading to the 2014 event

As previously mentioned, some of the flowing water below the glacier likely seeps into the underlying bedrock/soil. Water in the bedrock/soil is probably frozen forming a bedrock/soil glacier. Advective heat transfer into the bedrock/soil would cause zones of liquid water to exist in the soil and rock. If the geologic formation under the glacier is open with high permeability large amounts of liquid water could be stored and released suddenly once the frozen colluvial soil on the slope face thaws. There is no evidence this has previously occurred, but the mechanism is possible.

The hypothetical glacial mechanisms are portrayed in Figure 3.

GENERALIZED PROPERTIES OF MUD AND DEBRIS FLOWS

For reference Table 1 includes the generalized properties of sediment laden, mud, and debris flows. Estimated hazard levels have been included.

RECENT ACTIVITY AND POSSIBLE PREDICTIVE RELATIONSHIPS

Debris flow activity from all sources has increased in recent years at Mud Creek. Mud Creek experienced debris flows in 2002, 2014, 2015, 2021, and 2022 – a much greater rate than the historical record.

Convective storms were responsible for debris flows in 2002 and 2015. Glacial outbursts appear to be the primary mechanism for debris flows in 2014, 2021, and 2022. In addition, multiple glacial outbursts appear to have occurred in both 2021 and 2022. Since debris flow activity over the past two years coincided with periods of extreme to exceptional drought the drought record was investigated for similar trends.

A review of the historical drought record over the short and long term appears to show a strong correlation between drought severity and debris flows at Mud Creek. Figure 5 is the drought severity over the past 20 years in the McCloud watershed which Mud Creek is a part of (Figure 4). Figure 6 shows the drought severity since 1895 in the Upper Sacramento watershed. Vertical lines on both figures are occurrences of debris flow events. The primary metric both plots use is the Palmer Drought Severity Index (PDSI). There are several forms of the metric (and related factors) which are used to estimate long term drought severity. The PDSI was originally intended for agricultural use but has been extended to estimate long term drought conditions in most watersheds by the U.S. Drought Monitor and West Wide Drought Tracker. The PDSI is calculated using precipitation, temperature, and local available soil water content (computed using runoff and water flux in and out of the soil). The U.S. Drought Monitor is produced through a partnership between the National Drought Mitigation Center at the University of Nebraska-Lincoln, the United States Department of Agriculture and the National Oceanic and Atmospheric Administration. The West Wide Drought Tracker is produced by a partnership between the University of Idaho, Western Regional Climate Center, and the Desert Research Institute.

There appears to be a good correlation between drought severity and conditions in the McCloud watershed that lead to debris flows. As can be seen in Figure 5 over the past 20 years debris flows have occurred during periods of extreme or exceptional drought conditions in the McCloud watershed. An interesting aspect of the observation is that extreme drought conditions over 100% of the watershed seem to be required for debris flow risk to be elevated. Also, extreme drought conditions may need to persist at least a few months to increase debris flow risk. Assuming the observed debris flows were primarily triggered from outburst floods from the glaciers at the headwaters of Mud Creek an attempt was made to estimate glacial stability and debris erosion/deposition processes in Figure 5 based on field observations and available data.

A similar correlation is seen for the longer record in Figure 6 for the Upper Sacramento watershed which the McCloud watershed is part of. Over the past 128 years when severe/extreme drought occurs in the Upper Sacramento watershed (PDSI < -3) there was a high probability that debris flows on Mud Creek would occur. In some instances, there appears to be a delay between when extreme drought conditions are met and the eventual observed debris flow. This could be due to several factors which might include,

- A lesser correlation of the larger watershed to local conditions in the McCloud watershed.
- Convective storms.
- Structural instabilities in the watershed (glacier, slopes..) that developed during extreme drought conditions and eventually failed during the next warming cycle.

As was seen in 2021, 2022, and (possibly) the 1920's when a debris flow occurs the risk of additional debris flows is significantly elevated. In many instances it is likely that multiple debris flows occurred but were never recorded.

In both the long and short records extreme drought conditions appear to significantly increase the likelihood of debris flows in Mud Creek.

CONCLUSION

Short term risk and recommendations

Over the past 100 years there have been about 9 significant debris flow events/periods at Mud Creek from all mechanisms. Periods include multiple debris flow events over the same season. Analysis using a binomial distribution based on available data suggests that the likelihood of a significant debris flow event occurring at Mud Creek over the next two years is about 16%. If a debris flow event occurs there is a 44% chance at least one more event will occur during the same year. The likelihood of a significant debris flow event occurring in the next 5 years is about 31%. However, an important caveat on these likelihood statistics is that future warming may cause a departure from past debris flow trends, making prediction of debris flow probability uncertain using available data.

Debris flows appear to be strongly correlated to drought severity with the occurrence of debris flow events increasing when drought conditions in the McCloud watershed are extreme or exceptional.

The available data suggest Pilgram Creek Road should be closed when drought conditions in the McCloud watershed are extreme or exceptional or when significant storm events are forecast. If the road is reopened signage indicating the potential risk is a critical component of risk management. Similar signage exists for areas where there is significant natural hazard risk along transportation corridors including, but not limited to, rockfall, landslide, debris flows (in general), avalanche, flooding, tsunami...etc...

Long term risk

Rising global air temperatures will likely exacerbate debris flow activity on Mount Shasta.

If the described hypothetical debris flow triggering mechanisms are reasonably accurate it could indicate increased downstream risk in the future from debris flows in the Mud Creek watershed.

Increasing global temperatures increase the capacity of the atmosphere to hold water. Increasing temperatures may be slowing winds globally. Thus, precipitation events in the future will have the potential to be more intense and of longer duration leading to larger storm generated debris flows on Mount Shasta. A changing hydrologic landscape from increased wildfire activity will compound the situation by increasing the risk of amplified post fire runoff and debris flows during the recovery period after fires. Post fire recovery of the landscape could extend far longer than predicted during periods of persistent drought. Thus, the risk of larger storm generated debris flows will increase in the future resulting in increased impacts downstream.

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FIGURES AND TABLES

TABLE 1: Characteristics of Sediment Laden, Mud, and Debris Flows (Modified and adapted from Bradley, 1986)

Flow Bulking Factor							
0	1.11	1.25	1.43	1.67	2.00	2.50	>3.33
Sediment Concentration by Weight (100% by weight = $1x10^6$ ppm)							
0	23	40	52	63	72	80	87 to 100
Sediment Concentration by Volume (specific gravity of suspended material = 2.65)							
0	10	20	30	40	50	60	70 to 100
Normal Stream Flow			Hyperconcentrated flow		Debris/Mud Flow		Landslide
Newtonian			Non-Newtonian		Non-Newtonian		Non-Newtonian
Utilize depth x velocity curves to determine hazard			High Hazard at any depth		High Hazard at any depth		High Hazard at any depth

FIGURE 1: Scour of frozen soil embankment by glacier outburst flood in 2014

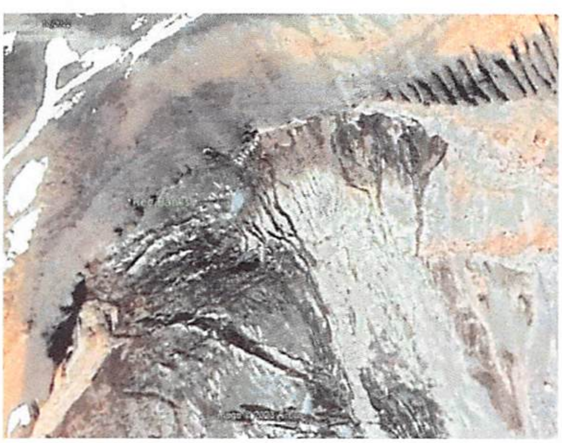

FIGURE 2: Water erosion and tracks from Red Banks into Konwakiton Glacier

FIGURE 3: Hypothetical Glacier Outburst Mechanism (see attachment)

FIGURE 4: McCloud Watershed

FIGURE 5: U.S. Drought Monitor vs Mud Creek Debris Flows Since 2000 (see attachment)

FIGURE 6: Western Wide Drought Monitor vs Mud Creek Debris Flows Since 1895 (see attachment)