

## MONITORING AVALANCHES ON CA 120 IN YOSEMITE NATIONAL PARK

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**ABSTRACT:** Avalanches are a serious hazard to Yosemite National Park personnel during spring snow removal operations along California Highway 120, the Tioga Pass Road. The Road is the link to surrounding communities in California's Central Valley, the Eastern Sierra, and the urban centers on the West Coast. The Tioga Pass Road is closed during the winter months; snow removal operations begin on April 15. Road clearing operations often coincide with wet snow and glide avalanche activity especially along the granite dome dominated landscape in the Tuolumne Meadows area. Several glide and wet snow avalanche zones have been identified on north, northwest, west, and southerly aspects where glide cracks and glide avalanches occur annually. Glide occurs when the entire snowpack slowly slides downhill; glide cracks can form on slopes where glide rates vary. Glide avalanches are difficult to forecast and explosive mitigation techniques are mostly ineffective. While glide cracks may culminate in glide avalanches, they often widen and calve into blocks or melt out. During the 2016 winter season, Yosemite National Park authorized implementation of an avalanche monitoring program including installation of a weather station and a time-lapse camera to monitor avalanche and glide activity. Installations occurred after the peak of glide avalanche activity, but valuable information was obtained from satellite images and in situ snowpack and avalanche observations. Continued monitoring will create a more complete record for this remote area of glide and other types of avalanche activity. This monitoring program will greatly augment existing knowledge about the location, timing, frequency and magnitude of avalanches along the Highway 120 corridor.

**KEYWORDS:** avalanche, glide, Yosemite National Park, wet snow

### 1 INTRODUCTION

Highway 120 going through Yosemite National Park, known as the Tioga Pass Road, was completed in 1915 and paved in 1937. The Tioga Pass Road is the link between the tourism based economies in the sparsely populated Eastern Sierra, California's Central Valley, and the urban centers on the West Coast. Forty-eight miles of the Tioga Pass Road are closed to motorized traffic from mid-October to April 15, when snow removal operations begin. Glide avalanches and movement of snow initiated by cornice drops can impact these operations in locations where the road passes through runout zones on several granite domes. Glide avalanches are difficult to forecast and explosive mitigation techniques are mostly ineffective (Simenhois and Birkeland, 2010; Peitzsch et al., 2015). Glide occurs when the entire snowpack slowly slides downhill; glide cracks can form on slopes where glide rates vary. While glide cracks may fail as a glide avalanche, they may also calve into large blocks pieces or melt in place (Höller, 2014).

During the 2016 winter season, Yosemite National Park authorized implementation of an avalanche monitoring plan including installation of a weather station and a time-lapse camera to monitor

avalanche activity and glide crack opening. Guidelines were developed that integrate avalanche forecasting and daily weather observations. An updated avalanche path inventory is being compiled. Installations occurred after the peak of glide avalanche activity, but valuable information was obtained from satellite images and from in situ snowpack and glide avalanche observations. Continued observations of gliding and other signs of avalanche activity will greatly augment existing knowledge about the location, timing, frequency and magnitude of avalanches along the Tioga Pass Road.

In April of 2016, a weather station was installed and avalanche occurrences were documented using standard guidelines (Greene et al., 2010). The time-lapse camera failed to capture avalanche images due to a late purchase of the equipment. Time-lapse imaging has been used to monitor glide crack opening based on dark pixel counts that proxy glide rates by showing temporal and spatial crack expansion (van Herwijnen et al., 2013). The glide process can be relatively quick, taking place over a few hours, or slow, taking several months. Previous research (e.g. Höller, 2014; Pietzsch et al., 2015) has shown that glide rates increase exponentially before a glide avalanche releases; thus monitoring changes in glide rates is essential for glide avalanche forecasting. Time-lapse imaging will also

identify buckling and bulging that is known to occur prior to glide avalanche release.

## 2 STUDY AREA

Yosemite National Park (Figure 1) is located on the western slopes of the Sierra Nevada. The region has a maritime climate with occasional intrusions of cold air from the Great Basin in Nevada. Prevailing storm winds are from the south southwest and west. Long periods of fair weather occur each spring, but winter storms can occur in April, May and June. Average long term (1995-2016) snow water equivalent on April 1 is 57.4 cm at the Tuolumne Meadows site (TUM, California Department of Water Resources, 2015). Elevations range from 1890 m at the point of winter closure to 3048 m at Tioga Pass.



Figure 1. Yosemite National Park and Olmsted Point

The Tioga Pass corridor in the Tuolumne Meadows area provides a unique setting to study glide snow avalanches. The granite dome features are a Class 4 (extreme gliding intensity, Margreth, 2007) ground type, with smooth outcropping plates and stratification planes parallel to the slope. Glide avalanches can occur on all aspects on the granite domes along the Tioga Pass Road.

Olmsted Point (Figure 2a,b) is smoother at the km scale than other granite domes the pose avalanche hazards to the roadway. Cornice drops from the ridge above the smooth steep slopes of Olmsted Point are another unique feature. Photographs of glide cracks in February 2010 and glide avalanches

in February 2016 suggest glide avalanches occur during the winter and spring.

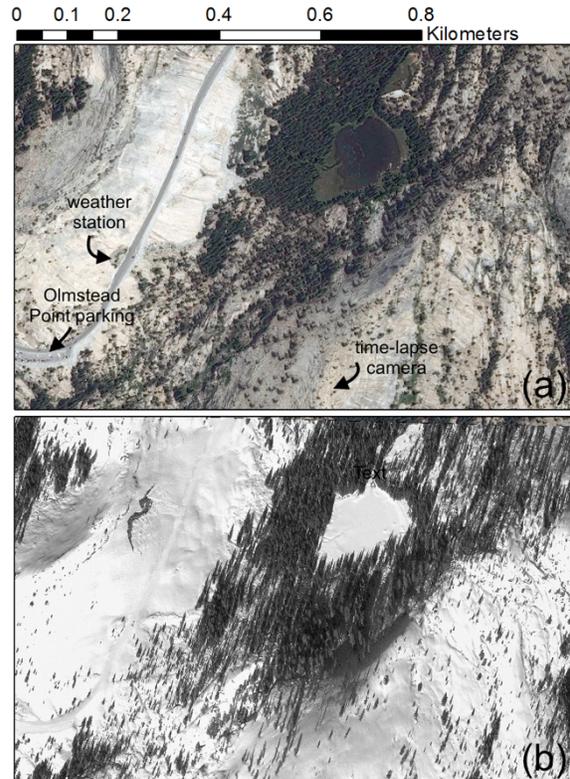


Figure 2 Summer (a) and winter (b) Worldview-3 satellite images of Olmsted Point from 2015-08-06 and 2016-01-12, respectively. Glide cracks and debris from what we hypothesize is a dry glide avalanche is clearly visible crossing the road in (b).

## 3 OLMSTED POINT AVALANCHE HISTORY

Numerous avalanches have occurred at Olmsted Point over the years, both wet and dry, with glide avalanches and cornice falls comprising the majority. A number of near-misses have occurred, notably in 1967, 1969, 1986, 1993 and a fatal accident in 1995. In June 1995, a Yosemite National Park employee operating a bulldozer was killed by blocks of ice and snow dislodged during snow removal operations at Olmsted Point. In response to the 1995 accident, specific recommendations regarding procedures, equipment, and training for the annual spring snow removal operations were implemented (Wilson, 1996). Wilson (1998) then recommended continuation of the practice of using explosives to spread charcoal on the snow surface to increase

melt. Twenty four potential avalanche paths along the Tioga Pass Road, grouped into six avalanche zones were identified (Wilson, 1996). The zones detailed in this report are still used operationally during road clearing operations.

Avalanche paths on the Tioga Pass Road are located on granite domes. The Road is located in the runout zone of at least three glide avalanche paths on Olmsted Point. Avalanche activity is highly variable year-to-year. In drier years, snow may be melted out on the avalanche zones by April 15. In wetter years, avalanche activity can continue into June. For example, Wilson (1999) reported 26 days of snow and/or rain from 1998 April 15 to June 12 with dry slab avalanches released by explosives on multiple days in 1998 June.

Due to a prohibition of the use of motorized equipment to access Tuolumne Meadows during the winter, few avalanche observations are made. Observations of avalanche activity are generally limited to those that deposit debris on the road after April 15. Natural avalanche activity was documented prior to the April 15 road opening in 1998 and 1999, but from 2000 to 2015, observations of avalanche activity prior to April 15 were not documented.

Wilson (1998) reported winter avalanche conditions during 1998 May and June, and several small slab avalanches were released with Pentolite and ammonium nitrate and fuel oil (ANFO) explosive charges. Wilson documented a glide avalanche on 1998 May 18, five days after 10 cm of rain was measured at the nearby Tuolumne Ranger station study plot. On June 24, 1998, a glide avalanche deposited large blocks of snow and ice onto the road with individual blocks estimated to weigh 2 tons (Wilson 1998). A Yosemite National Park employee photographed a glide avalanche on Olmsted Point in May 2003. There is one report of blocks reaching the Tioga Pass Road after a cornice drop in May 2010 and a report of a natural avalanche that occurred between 2011 June 6-12 that left 1.5 m of debris on the inside lane. In 2016, glide avalanche activity on Olmsted Point was reported to Tuolumne winter rangers, who photographed a moderate size (D2) glide avalanche that released in an area of Olmsted Point where glide avalanches have occurred in the past. There are a few references from 2010 and 2011 of blocks falling off the ridge, and breaking up the slab below the ridge or falling to the road.

ANFO is used by Yosemite to spread charcoal on snow, promoting increased snow melt from slopes that threaten crews plowing the Tioga Road.

Explosives are ineffective at triggering glide avalanches (Simenhois and Birkeland, 2010), though after cold storms in 1998, explosives were effective in releasing small avalanches in the upper layers of the snowpack after a cold winter like storm. Wilson also documented one post control release 48 hours after 64 lbs. of Pentolite was detonated on Olmsted Point. Despite the considerable cost and effort of explosives work and ensuing delays in opening the road, little is known about the avalanche problem in this location, including occurrence data and factors that contribute to glide avalanche activity. The current plan to eliminate wet snow hazards to the road involves waiting for snow to melt off the dome at Olmsted Point and can be a lengthy and expensive process.

#### 4 METHODS

The primary objectives of this project include installation of a portable weather station on or near Olmsted Point and installation of a time-lapse camera with a cellular modem. Hourly measurements of air temperature, relative humidity, incoming solar radiation and wind speed/direction were collected hourly from a DataGarrison Satellite portable weather station on Olmsted Point starting on 2016-04-15. A Judd snow depth sensor will record snow depths for the 2017 season. Real time measurements are transmitted via the General Electric Iridium satellite network. Photographs of February and March 2016 glide avalanche activity were obtained from the Tuolumne winter rangers. LIDAR images of Olmsted Point (Figure 3) were obtained from the National Center for Airborne Laser Mapping and analyzed in Spatial Analyst (ArcGIS 10.4).

To better understand the snowpack in the Olmsted area, the SNOBAL (Marks et al., 1998) snow mass and energy balance model was run for Olmsted Point from 2016 January 1 - April 16 since in situ observations (e.g. snow pit data) were not available prior to April 15. SNOBAL requires the following inputs: net shortwave, incoming longwave, vapor pressure, air temperature, wind speed, precipitation (amount and phase), and ground temperature. Incoming shortwave and longwave radiation were taken from radiometer measurements at a nearby energy balance site on Mammoth Mountain (CUES, Bair et al., 2015). The direct solar radiation was adjusted (Dozier and Frew, 1990) to a 30° slope

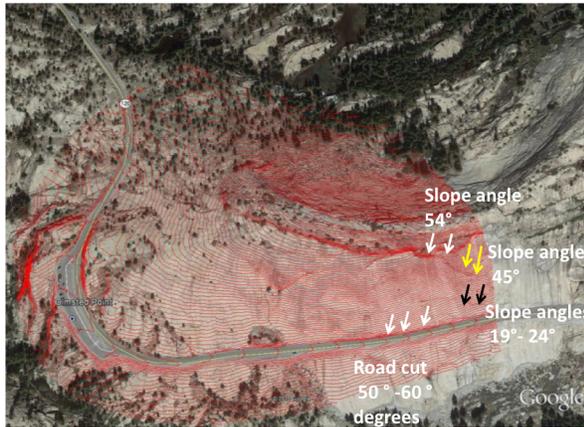


Figure 3 Topographic contours at 1 m intervals from a LIDAR scan of Olmsted Point.

with a  $106^\circ$  aspect, representative of the starting zones at Olmsted Point. Incoming longwave radiation was lapsed using a verified rate (Hinkelman et al., 2015) based on the difference in elevation between CUES (2940 m) and the starting zones at Olmsted Point (2597 m).

Snow albedo was computed from terrain-adjusted incoming and outgoing shortwave radiation at CUES (for details see Bair et al., 2015). Air temperature and precipitation were taken from the nearby TUM station. A rain snow discrimination based on dew point temperature was used (Sims and Liu, 2015). We suspect that the precipitation gauge at TUM suffers from substantial undercatch bias and that it is not representative of accumulated precipitation at Olmsted, especially when considering wind redistribution of the snowpack. Nonetheless, TUM is the closest precipitation gauge to CUES. Vapor pressure was computed using relative humidity and air temperature measurements from TUM. Wind speed was taken from sonic anemometer measurements at CUES. Last, soil temperature was taken from measurements at CUES. The soil at CUES is not representative of the smooth granite at Olmsted, but conduction between the ground and the bottom of the snowpack is a tiny part of the energy balance (e.g. a few  $W\ m^{-2}$ , Marks and Dozier, 1992), so this misrepresentation probably does not matter.

## 5 RESULTS

Based on 2016 observations and review of a limited number of field books, the most frequent avalanche types are cornice drops and glide avalanches. Cornices form along the eastern portion of the oblate west to east trending ridge of Olmsted Point. While cornices are small, dense snow often breaks

off in blocks onto the steep slopes below. Cornice drops can break up the slabs into large blocks on the steep  $38\text{-}45^\circ$  stauchwall areas downslope from the ridge. Cornice drops may also trigger glide avalanches. Buckling and rippling of the slab below glide cracks has been observed in photographs (Wilson, 1999) and in April 2016. Possibly due to anomalously warm temperatures in February 2016, a widespread glide avalanche cycle occurred in the Tuolumne Meadows and Olmsted Point areas and the avalanche cycle was photographed by the Tuolumne winter rangers. During April 2016, widespread glide cracks and glide avalanche activity was observed on granite domes along the Tioga Road and on Clouds Rest (Figure 4), a prominent north facing formation above the Tenaya Creek Canyon.



Figure 4. Glide cracking opening, 2016 May 2 16:31. Photo credit Steve Lynds.

Based on photographs taken in January 2010 and Worldview imagery from 2016, glide cracks and buckling were observed during early winter. The snowpack modeling suggests melt water reached the bottom of the snowpack in the starting zones at Olmsted Point in February 2016 (Figure 5a-d).

## 6 FUTURE WORK

- Time-lapse imaging  
Time-lapse imaging will improve understanding of glide avalanche release by monitoring changes in snow movement, deformation and glide crack expansion. Time-lapse imaging correlated with weather station data will help understand processes associated with wet-snow and cornice drop releases.
- Terrain factors from LIDAR

Similar to Pietzsch et al. (2015), we hope to develop a data set of glide avalanche occurrences from the avalanche paths on Highway 120 and evaluate key

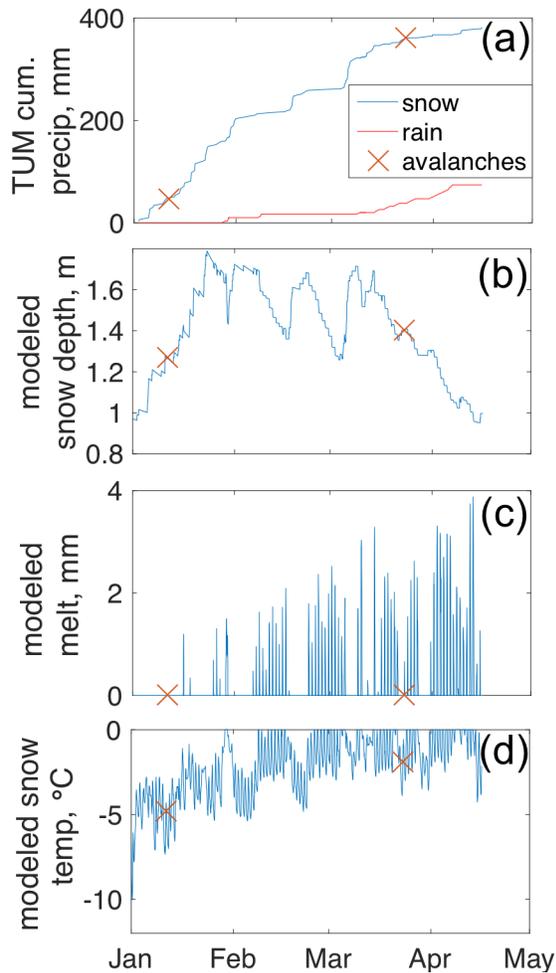


Figure 5 SNOBAL input and outputs for 2016-1-1 to 2016-4-16; cumulative precipitation at TUM (a); snow depth (b); snowmelt (c); and bulk snowpack temperature (d).

terrain characteristics associated with glide avalanche occurrence.

- Explosive mitigation techniques-Cornice removal

A combination of explosive placement and manual removal of wind deposits along the Olmsted Point ridgeline will mitigate the frequency and size of cornice drops. This technique can be applied to other avalanche prone areas along Highway 120.

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