Structural characterization of rockfall sources in Yosemite Valley from remote sensing data and field surveys

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ABSTRACT
Yosemite Valley poses significant rockfall hazard and related risk due to its glacially steepened walls and approximately 4 million visitors annually. To assess rockfall hazard, it is necessary to evaluate the geologic structure that contributes to the destabilization of rockfall sources and locate the most probable future source areas. Coupling new remote sensing techniques (Terrestrial Laser Scanning, Aerial Laser Scanning) and traditional field surveys, we investigated the regional geologic and structural setting, the orientation of the primary discontinuity sets for large areas of Yosemite Valley, and the specific discontinuity sets present at active rockfall sources. This information, combined with better understanding of the geologic processes that contribute to the progressive destabilization and triggering of granitic rock slabs, will help to assess rockfall susceptibility for Yosemite Valley and elsewhere.

RÉSUMÉ
Dans la vallée de Yosemite le risque lié aux instabilités rocheuses est très important à cause des grandes parois de granite et des environ 4 millions de visiteurs annuels. Pour évaluer l'aléa de chutes de blocs il est nécessaire d'analyser les structures géologiques et de localiser les futures zones sources les plus probables. Grâce au couplage de nouvelles techniques de télédétection (Scanner Laser Terrestre et Scanner Laser Aérien) et d'observations de terrain il a été possible d'étudier le contexte géologique et structural régional et l'orientation des familles de discontinuités pour une grande partie de la vallée et plus en détail pour des sources de chutes de blocs actives. Ces informations, combinées avec une meilleure compréhension des processus géologiques qui contribuent à la déstabilisation progressive et au déclenchement des écailles de roche, vont aider dans l'évaluation de la susceptibilité aux chutes de blocs dans la vallée de Yosemite et ailleurs.

1 INTRODUCTION

Yosemite Valley, California, poses significant rockfall hazard and risk due to the presence of steep granitic cliffs, and to the approximately 4 million visitors to Yosemite National Park each year. Between 1857 and 2010, 832 documented rockfalls and other slope movements caused 15 fatalities and at least 81 injuries.

Yosemite Valley is an E-W 11 km long, ~1 km deep valley cutting the western slope of the central Sierra Nevada mountain range, California (Fig. 1). The steep cliffs of the valley were carved into granitic rocks by Quaternary glaciers (Matthes 1930 ; Huber 1987).

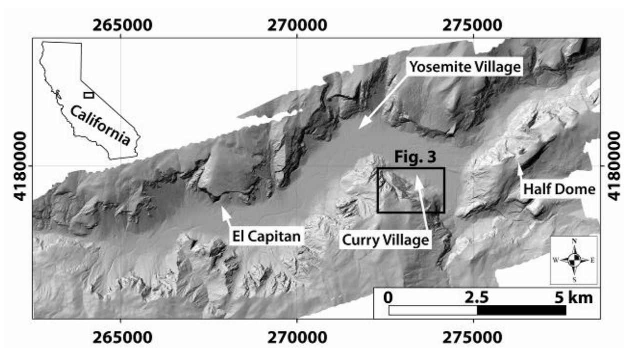

Figure 1: 1 m Digital Elevation Model (DEM) of Yosemite Valley derived from Aerial Laser Scanning (ALS) data. The black box shows the location of the cliff beneath Glacier Point shown in Figure 3.

Since the retreat of the Last Glacial Maximum glaciers in Yosemite Valley about 20,000 years ago, rockfalls have been the primary process responsible for erosion of the valley walls. An inventory of rockfall events has been regularly updated since AD 1857 (Stock et al., *in press*). Earthquakes, freeze/thaw, precipitation, snowmelt, root and soil wedging and thermal stress have been proposed as triggering mechanisms for many rockfall events in Yosemite Valley (Wieczorek and Jäger 1996; Wieczorek and Snyder 1999; Wieczorek et al. 1998, 1999, 2000; 2008; Stock and Uhrhammer 2010). To fully assess rockfall hazard, it is necessary to locate the most probable rockfall source areas, establish

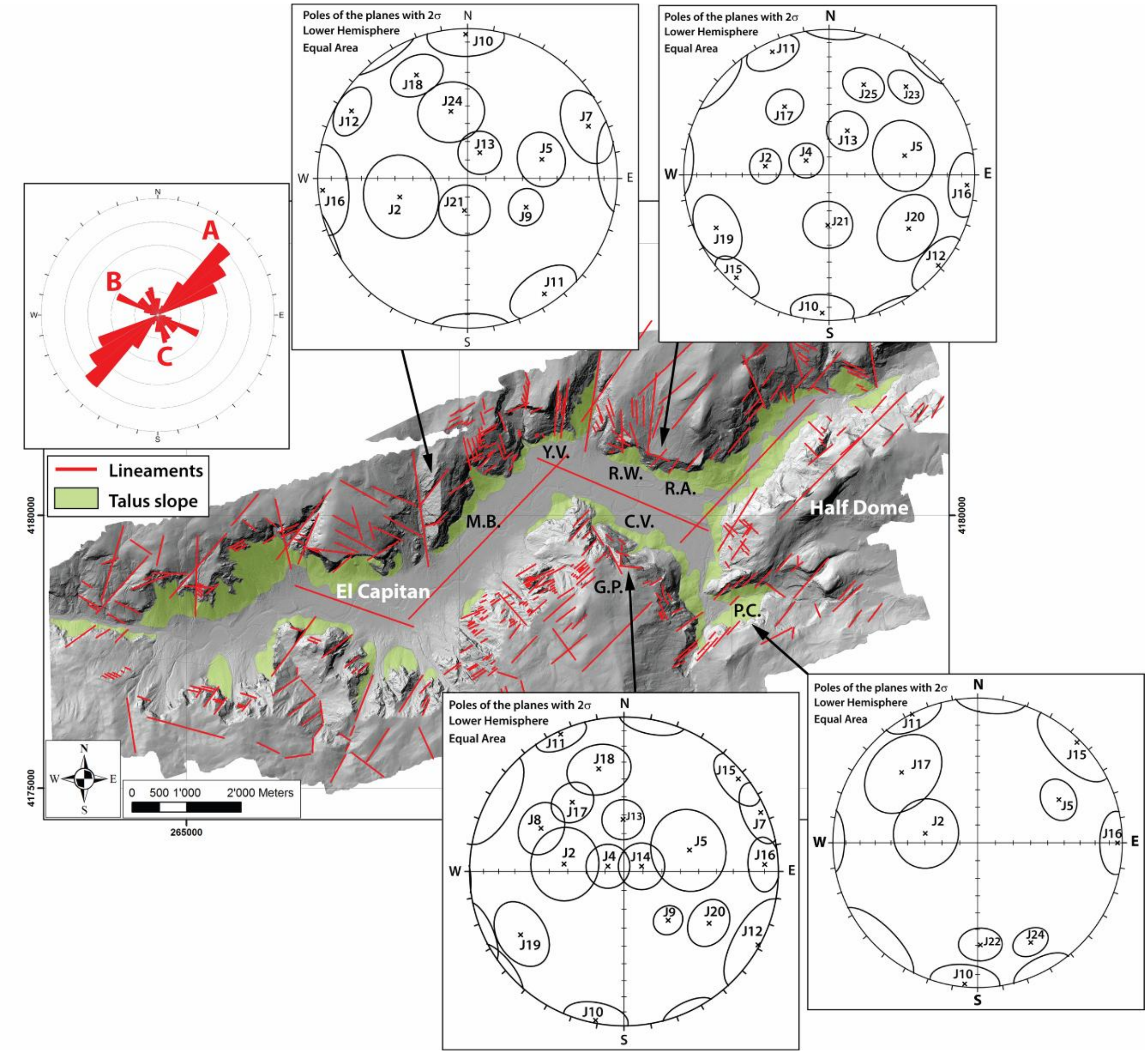

Figure 2: Map of the major lineaments in Yosemite Valley with rosette plot of their orientation (A, B and C). The four Schmidt stereoplots represent different structural domains (Middle Brother (M.B.), Rhombus Wall (R.W.)-Royal Arches (R.A.), Glacier Point (G.P.), and the Panorama Cliff (P.C.)) based on the results of the TLS, ALS and field data analysis. Abbreviations Y.V. and C.V mean respectively Yosemite Village and Curry Village.

the frequency of activity from these areas, and assess potential runout distances of rockfalls of different sizes (Dussauge-Peisser 2002; Guzzetti et al. 2003). Critical to identifying probable rockfall source areas is developing an understanding of the relation between geologic structure and processes that progressively destabilize a rock mass. New remote sensing tools such as high-resolution photography and laser scanning provide safe and effective means of quantitatively characterizing rockfall source areas (Slob and Hack, 2004; Rosser et al., 2005; Jaboyedoff et al., 2007, 2010; Oppikoffer et al., 2008, 2009; Stock et al., 2011).

In this study we focused (1) on improving knowledge of rock discontinuity characteristics in relation to topography, orientation and rock type; and (2) on the processes that lead to progressive destabilization and triggering of rockfalls. Rockfall source locations are strongly linked to discontinuities and, especially in Yosemite Valley, to the widespread occurrence of surface parallel sheeting or exfoliation joints (Matthes, 1930; Bahat et al. 1999; Martel 2006). Therefore, the dominant joint sets must be correctly characterized from a geometrical and mechanical point of view, which means that their orientation, persistence, spacing, roughness and opening must be determined. Detailed inspection of rockfall-prone cliffs provides valuable information about these features (Fig. 2; Table 1). This was achieved using the 1m cellsize Digital Elevation Model (DEM) of the valley derived from Aerial Laser Scanning (ALS) data, new Terrestrial Laser Scanning (TLS) data, and field surveys of specific rockfall sites.

The wall beneath Glacier Point was investigated in detail from a structural point of view, with a focus on the 1998-1999 and the 2008 rockfall source areas (Wieczorek and Snyder, 1999; Stock et al. 2011). The structures cutting the southeast face of Middle Brother, the south face of Yosemite Falls, the Castle Cliffs, the Rhombus Wall-Royal Arches cliffs, the east facing cliff below Glacier Point, and the Panorama Cliff were also examined by TLS and detailed structural analyses.

This study illustrates the application of new remote sensing techniques and field measurements in order to improve the understanding of the structural conditions existing at rockfall source areas and to approach a rockfall susceptibility estimation for the cliffs of Yosemite Valley.

2 REGIONAL TO LOCAL STRUCTURAL STUDY

2.1 Geologic setting

Yosemite Valley was carved into the Cretaceous plutons of the Yosemite Valley suite, which is part of the Sierra Nevada batholith (Bateman, 1992). These plutons are mainly composed of granites and granodiorites, with lesser amounts of tonalites, diorites, and aplites (Huber 1987; Bateman 1992; Calkins et al. 1985; Peck 2002).

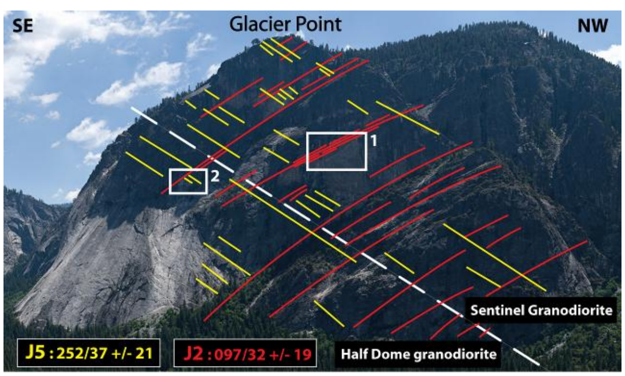

Figure 3: View looking south of the cliff beneath Glacier Point, with traces of the prominent joint sets J2 (red) and J5 (yellow) shown. The white dashed line represents the approximate contact between the Half Dome granodiorite (SE) and the Sentinel granodiorite (NW) (Calkins et al., 1985; Peck, 2002). The white boxes numbered 1 and 2 represent respectively the source areas of the 7-8 October 2008 rockfalls and of the 1998-1999 rockfalls.

The most widely represented units in the valley are the El Capitan granite, Sentinel granodiorite, and the Half Dome granodiorite. Near El Capitan, there are significant exposures of diorite intrusions (visible in the North American wall) and of the Taft granite (Calkins et al. 1985, Peck, 2002). The southeast face of Middle Brother displays very complex interactions between the El Capitan granite, Sentinel granodiorite, dioritic intrusions, and aplite dikes; the density of geologic contacts here likely played a role in destabilizing the 600,000 m^3 rock mass that failed on 10 March 1987 (Wieczorek, 2002). In the cliffs of Yosemite Falls, the Castle Cliffs, and on the northwest face of Sentinel Rock, the El Capitan granite is intruded by the Sentinel granodiorite. The contact between the Sentinel granodiorite and the Half Dome granodiorite is exposed in the wall beneath Glacier Point (Fig. 3) and in the Rhombus Wall-Royal Arches area north of the Ahwahnee Hotel. Farther east the Half Dome granodiorite alone constitutes the valley bedrock (Calkins et al. 1985; Peck, 2002).

Yosemite Valley was initially carved by the ancestral Merced River, and was subsequently occupied by several Quaternary glaciers that deepened the valley and steepened the walls. Sheeting (exfoliation) joints formed in response to stress changes associated with changes in the topography, and are ubiquitous throughout the valley (Matthes 1930; Huber 1987).

2.2 Methods

We performed regional and site-specific structural studies of Yosemite Valley using the software Coltop 3D (Jaboyedoff et al. 2007) on a base of existing Aerial Laser Scanning (ALS) and of new local Terrestrial Laser Scanning (TLS) data. Terrestrial Laser Scanning technology is based on the time-of-flight of a laser beam (Slob and Hack 2004; Rosser et al. 2005; Oppikofer et al. 2008, 2009). The laser pulse is back-scattered by the terrain depending on the reflectivity and on the distance of the target. The time-of-flight of each laser pulse is automatically converted by the device into the distance between the laser scanner and the target. The 3D coordinates of each point of the cliff are automatically calculated as a function of the distance and direction to the scanner. Using an Optech ILRIS-3D extended range laser scanner, we collected detailed (15x15cm) point clouds of the cliffs in the ~1.2 km maximum range of the scanner. In particular we collected detailed point clouds of the wall beneath Glacier Point, the southeast face of Middle Brother, the south face of Yosemite Falls, the Castle Cliffs, the Forbidden Wall, the Rhombus Wall-Royal Arches area, and the Panorama Cliff. The 3D point clouds were georeferenced using the 1m DEM (ALS) of the valley.

The regional structures that control the preferential erosion by rivers and glaciers were mapped by analyzing the 1m cellsize DEM (Ericson et al. 2005; Wieczorek et al. 2008) (Fig. 2). The detailed structural analyses were performed on both the ALS and TLS data sets using Coltop3D software. Coltop3D computes the spatial orientation (dip direction and dip) of each point within a point cloud with respect to its neighboring points. Coltop3D attributes a unique RGB color to each spatial orientation, allowing accurate identification of the major discontinuity sets. Thus, it is possible to quickly obtain a great number of measurements of the orientation of joint planes responsible for shaping a rock cliff (Fig. 4 and 8). The amount of dip direction/dip data collected by TLS is huge with respect to traditional compass measurements. Thus all the joint sets are recognizable and the mean value of each set can be determined with high accuracy. We used field observations and examination of high-resolution photographs to ensure that our structural measurements were made on joint-controlled bedrock

surfaces, as opposed to soil or talus covered slopes or erosion surfaces with little or no structural relevance. The Coltop3D measurements can be exported to other softwares to identify and display the discontinuity sets on stereoplots and calculate their mean orientations and variability (Oppikofer et al. 2009) (Table 1).
Classical field surveys of joint set orientation measurements and joint characterization (e.g., undulation, persistence, spacing, opening, roughness, infilling, water presence) were essential for validating the ALS and TLS data, for observing joint conditions, and to improve understanding of the geological processes leading to failure.

2.3 Structural domains

Analysis of the 1m ALS DEM allowed us to identify three main regional lineations in Yosemite Valley (Fig. 2). These lineations are likely responsible for the overall orientation of the Valley (Matthes, 1930; Huber, 1987, Ericson et al. 2005).

A) The most well represented and persistent lineation structure is oriented SW-NE, and affects the orientation of prominent cliff faces such as the northwest face of Half Dome (Fig. 2).

B) A second structure oriented WNW-ESE is persistent, but less represented than the first one. This structure affects the orientation of cliff faces such as the Rhombus Wall. Yosemite Valley appears to have been carved following these two lineation sets (A and B) (Fig. 2).

C) The third structure is oriented NNW-SSE and is more closely linked to the formation of numerous lateral tributary streams and gullies, such as LeConte Gully at Glacier Point (Fig. 2; Wieczorek et al. 2008).

Coltop3D analysis of the ALS and TLS data allows precise determination of the orientation of the predominant joint sets visible in a cliff and thus different structural domains throughout the valley (Fig. 2). Eighteen joint sets were mapped in the Glacier Point area and are listed in Table 1 following the naming convention of Wieczorek et al. (2008). Comparing our joint orientation data with those reported in Wieczorek et al. (2008) highlight the following items: 1) joint sets J3 and J7 of Wieczorek et al. (2008) are here considered to be a single set named J7; 2) the difference between J5 and J6 was not clear in the TLS data so only one joint set named J5 is retained; 3) the mean value for J2 reported here is slightly different compared to that of Wieczorek et al. (2008) (a more easterly dip direction), mainly because of detailed analysis of the ALS data, which display well the prominent bedrock ledges formed by the regional J2 planes.

Table 1: Joint sets for Glacier Point based on field, TLS and ALS data. J1 are the sheeting joints, parallel to the cliff face.

GLACIER POINT : Field data and Coltop TLS – ALS data			
ID	dip direction (°)	dip (°)	Variability 2σ
J1	Sheeting joints	-	-
J2	097	32	19
J3	-	-	-
J4	109	09	12
J5	252	37	21
J6	-	-	-
J7	247	86	12
J8	118	51	13
J9	318	35	8
J10	011	88	12
J11	155	87	10
J12	299	90	19
J13	179	27	11
J14	253	10	12
J15	231	85	12
J16	267	80	11
J17	143	46	11
J18	166	58	15
J19	058	67	15
J20	301	54	12

In addition to those at Glacier Point, we identified 13 primary joint sets in the southeast face of Middle Brother, 16 joint sets in the Rhombus Wall-Royal Arches area, 10 in the Panorama cliff area, 11 in the Forbidden Wall area, and 16 in the Yosemite Falls-Castle Cliff area.

The joint sets J2, J5, J10, J11, J16 are very persistent and visible throughout the valley (Fig. 2). Subhorizontal planes due to the joint sets J4, J13, J14 or J21 are also very common and are often responsible for forming roofs. J7 is another principal set present throughout the valley, except in the Rhombus Wall - Royal Arches cliff and in the Panorama Cliff, where it is substituted by J15. J12 has an orientation similar to J11 and is present in all the cliffs we examined, except in the Panorama Cliff. The couple J17-J18 forms SE-dipping planes existing in all the valley walls.

The lineation set A) of Fig. 2 is mainly linked to the vertical sets J12, J11 and partially to the less steep sets J8, J9, J17, J18 and J20. The lineation set B) of Fig. 2 is linked to the ubiquitous J10 set and partially to J15. In the Panorama Cliff area, J22 contributes to this fracturing direction, as well as J23 and J25 in the Rhombus Wall-Royal Arches area. The lineation set C) is mainly linked to J7 and partially to the other similar vertical sets J15 and J16. The less steep sets J2, J5 and J19 likely contribute to this fracturing direction.

3 GLACIER POINT ROCKFALL SOURCE AREAS

3.1 The 7 and 8 October 2008 rockfalls

On 7 and 8 October 2008 two large rockfalls occurred from an area of previous instability located in the middle of the cliff beneath Glacier Point (Fig. 3) (Stock et al.

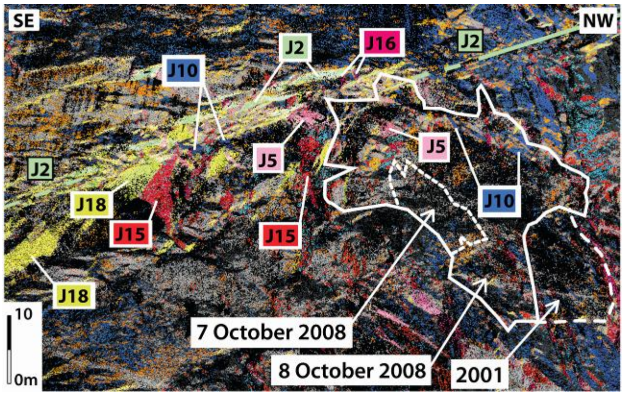

Figure 4: Visualization of the TLS point cloud with Coltop3D for the 7-8 October 2008 rockfall source area. The area is represented on Fig. 3 by the white box numbered 1. Coltop3D assigns a color to every point according to the orientation of the point with respect to its neighbourhood. The white line shows the detachment area of the 8 October 2008 rockfall. The white dashed lines show detachment areas for the 7 October 2008 and 2001 rockfalls.

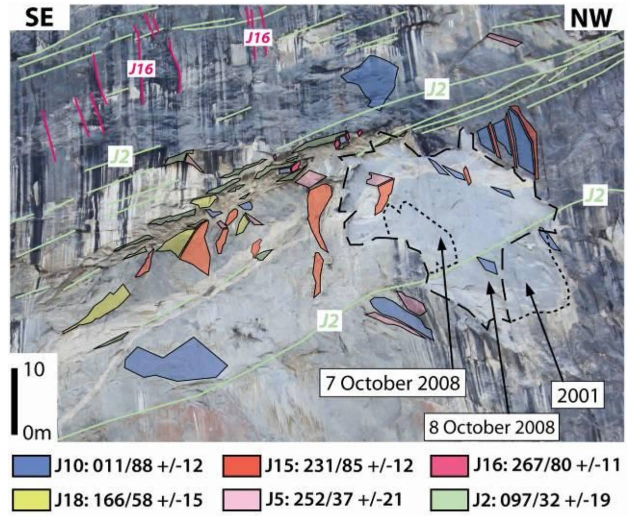

Figure 6: Photograph of the area displayed on Fig. 4 with colored polygons delineating the most important joint planes. The colored lines show traces of J2 and J16 joints.

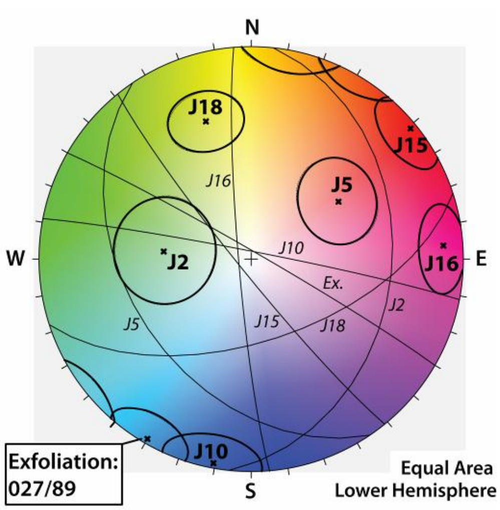

Figure 5: Stereoplot of the joint sets at the 2008 rockfall source area displayed in Fig. 4, with 2σ variability. The local topographic orientation is very similar to the local exfoliation orientation.

2011). These rockfalls caused minor injuries and damaged 25 buildings in Curry Village, which is located very close to the base of the talus slope. On the basis of repeated TLS data, Stock et al. (2011) calculated the volume of the failed slab of rock to be 5663 +/- 36 m^3.

Figures 4, 5 and 6 show the results of our structural analysis of the rockfall source area. They are based on high resolution photographs and detailed TLS data (15x15 cm) that we analyzed with Coltop3D to obtain the orientations of the major joint planes.

The 2008 rockfall source area is located just below a very persistent J2 structure and at the western limit of an area with a remarkable concave morphology and with large roofs at the top. This local lack of material must be associated with a high rockfall susceptibility. As highlighted by Stock et al. (2011), the 2008 failures occurred along a sheeting (exfoliation) joint oriented 027/89, parallel to the local topographic surface.

In addition to the sheeting joint (027/89) and overlying J2, we show on Figs. 4, 5 and 6 the significance of five other joint sets that likely contributed to the fracturing of this part of the cliff (J5, J10, J15, J16, J18). Joints J2, J18, and in part J5 form the large roofs at the top of the rockfall source area. The orientation of J10 is very similar to the local topography, perhaps accentuating the exfoliation process.

The intersections J18/J15 and J10/J16 form two wedge type structures that are highly unfavorable from a stability point of view.

Stock et al. (2011) observed that the rockfall detachment surface was dry at the time of failure, suggesting that elevated water pressure did not specifically trigger the two rockfalls of October 2008; however, they noted staining on the detachment surface and did not rule out the presence of water behind the slab prior to failure. Determining the exact role of water infiltration in rockfall triggering is challenging, but water can play an important role in the progressive destabilization of a rock mass prior to failure. The details of our concept of a possible progressive rockfall triggering mechanism are outlined in the chapter 3.3.

3.2 The 1998-1999 rockfalls

Between 16 November 1998 and 15 June 1999 four rockfalls occurred from beneath Glacier Point above Curry Village, with a cumulative volume of approximately 840 m^3 (Wieczorek and Snyder 1999). These rockfalls damaged cabins in Curry Village, caused minor injuries

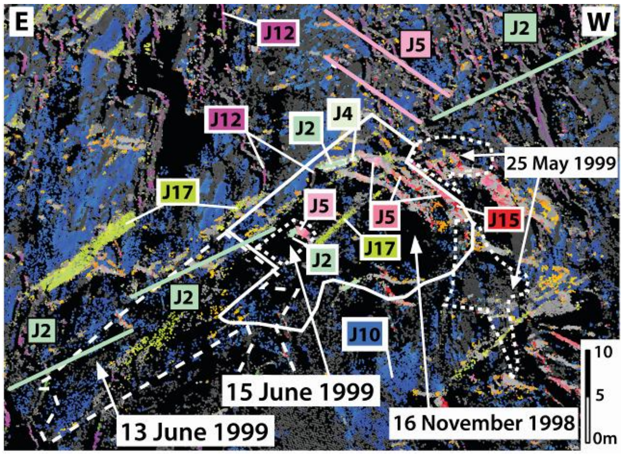

Figure 7: Visualization of the TLS point cloud with Coltop3D for the 1998-1999 rockfall source area. The area is represented on Fig. 3 by the white box number 2. The white line shows the detachment area of the 16 November 1998 rockfall. The white dashed lines show the three detachment areas of subsequent rockfalls that occurred in May and June 1999.

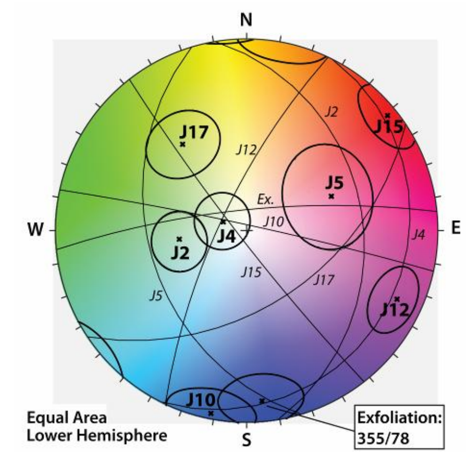

Figure 8: Stereoplot of the joint sets at the 1998-1999 rockfall source area displayed in Fig. 7, with 2σ variability. The local topographic orientation is very similar to the exfoliation.

and resulted in the death of a rock climber beneath Glacier Point (Wieczorek and Snyder 1999). Wieczorek and Snyder (1999) studied the rockfall source area in detail and mapped four distinct scars corresponding to the 16 March 1998, 25 May 1999, 13 June 1999 and 15 June 1999 events (Fig. 7). However, they lacked quantitative topographic data for the source area.

Our recent investigations of TLS data identify seven joint sets affecting this part of the cliff (Fig. 7, 8 and 9). As with the 2008 release area, the 1998-1999 rockfall occurred along a sheeting (exfoliation) joint. Also similarly, the 1998-1999 source area is located beneath a persistent J2 discontinuity. J2, J4 and J17 form ENE-SE dipping roofs within and adjacent to the source area. J5 is a prominent discontinuity that is very persistent (and well visible on Fig. 3) that forms W-SW dipping roofs. The source area is located within a convergence of J2 and J5. J15 and J12 are vertical discontinuities cutting the cliff respectively NW-SE and NE-SW. J10 is a joint set subparallel to the topography and to the local exfoliation surface, which here is oriented 355/78.

Wieczorek and Snyder (1999) proposed a freeze/thaw cycle as a trigger for the initial November 1998 rockfall, but could not recognize specific triggers for the subsequent events, which occurred over a wide range of meteorological conditions. Water seepage along J10 and the sheeting joint surfaces was observed by Wieczorek and Snyder (1999) at the time the 13 June 1999 rockfall occurred. However, the preceding 25 May 1999 rockfall and the subsequent 15 June 1999 rockfall were both dry failures. This highlights the difficulty in assigning specific triggers to specific events without detailed monitoring of the source area at the time of failure (Wieczorek et al., 2008). It also highlights the possibility of stress redistribution and rock fatigue along joints to act as a kind of progressive rockfall trigger, a concept explored in the next section.

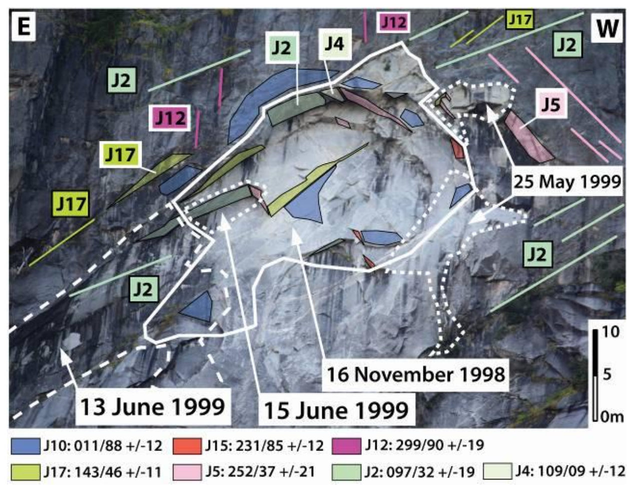

Figure 9: Photograph of the area displayed on Fig. 7 with colored polygons delineating the most important joint planes. The colored lines show traces of J2, J5, J12 and J17 joints.

3.3 Progressive rockfall triggering mechanism

Many rockfalls in Yosemite Valley cannot be directly related to a unique and specific triggering mechanism, even when those events were closely observed (Wieczorek and Jäger 1996; Wieczorek and Snyder 1999; Wieczorek et al. 2008; Stock et al. 2011). Numerous rockfalls occur during the summer when no earthquake, freeze/thaw period, exceptional rainfall or snowmelt (water pressure) or other mechanism can be identified as a final trigger. In these cases fatigue of the rock along joints should be taken into account as a kind of trigger that we consider to be progressive in time. Furthermore, even when a final trigger can be recognized, we consider that the progressive process existed and prepared the rock mass for subsequent failure.

We consider the main factors of destabilization that can occur during the progressive process to include:

1. Water circulation along sheeting joints and persistent discontinuities (sometimes associated with a very fractured layer).
2. Water infiltration and weathering of the rock along a preferential exfoliation joint.
3. Expansion and widening of the joint by freeze/thaw cycles and/or seasonal and daily thermal variations, and associated fracture propagation. At the same time there can be weathering, expansion and widening along other joint sets (significance of the overhangs).
4. Stress-induced propagation of exfoliation joints.
5. Progressive weakening of rock bridges and reduction of their areal extent (stress concentration and resulting fracture propagation).
6. Eventually the weight of the instable block leads to final fracture propagation that causes breaking of the last rock bridges. This last action can occur in the absence of recognized triggering mechanisms.

4 TOWARD ACCURATE SUSCEPTIBILITY ASSESSMENT

Given the significant rockfall hazard and risk present in Yosemite Valley, accurate susceptibility assessment of the valley walls is needed. Preliminary efforts (Pannatier et al. 2009, Jaboyedoff et al. 2010) were based on ALS DEMs that allowed obtaining some structural data and a regional susceptibility map using the software Matterocking (Jaboyedoff 2002). This software utilizes cliff and discontinuity orientations to evaluate potential planar and wedge failures (Jaboyedoff et al., 2010). Our field surveys and ALS and TLS analyses of different rockfall source areas throughout Yosemite Valley suggest some preliminary criteria to establish a more complete rockfall susceptibility rating at the local and regional scale. These criteria include:

- The slope of the topography.
- The local convexity of the cliff face.
- The proximity to a very fractured layer (close spacing between the joints).
- The proximity to a very persistent discontinuity.
- The rock type and proximity to geologic contacts.
- The proximity to Last Glacial Maximum trimlines (degree of weathering greater in rocks not subjected to recent glaciation).
- The degree of water infiltration and seepage visible along the joints.
- The proximity to overhanging roof surfaces.
- The presence of joint sets forming wedge or planar structures.
- The development of exfoliation slabs (isolation of a rock flake).
- The proximity to a previously active area (stress redistribution and fracture propagation associated with earlier rockfalls).

Remote sensing data have the potential to provide information regarding many of these criteria; for example, our results from Yosemite Valley suggest that our TLS data can be used to map both geologic units and discontinuities, integrating these two important variables in one data set. The differences between granitic plutons are related to the mineral composition and to the texture of the rock. These aspects are probably somehow linked to the stability of the rock faces in the vicinity of geologic contacts. The effects of thermal expansion and contraction and freeze/thaw cycles on rock slabs are likely to be different depending on the rock type, and are a target for future research.

5 CONCLUSIONS AND PERSPECTIVES

The coupling of new remote sensing techniques (ALS, TLS, high-resolution photography) and traditional field surveys greatly improves quantitative characterization of rockfall source areas and increases our understanding of the structural settings and destabilizing processes leading to rockfalls.

The occurrence of many rockfalls in the absence of recognized triggering mechanisms suggests that a progressive rockfall triggering mechanism may explain the fracture propagation and the destabilization of rock flakes in Yosemite Valley. A complete structural analysis, performed at both regional (valley-wide) and local (rockfall source area) scales, results in a better understanding of rockfall failure mechanisms. It can also provide important details about the most probable future rockfall sources such as location and volume, which are key to evaluating the potential run-out distance of blocks. Further studies focusing on improved remote detection of sheeting (exfoliation) joints and detailed documentation of progressive destabilization processes are needed to improve rockfall susceptibility assessment in Yosemite Valley.

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