Rockfall instability on high granitic domes: Stawamus Chief, B.C., Canada

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ABSTRACT: The rock slope stability of high granitic-granodiorite domes has become of increasing concern over recent decades. As tourism increases in popularity the risk posed by rockfall from these domes has also increased. Using the 417 m high Stawamus Chief, in Squamish, BC, Canada as a case study, we describe the use of multi-sensor remote sensing in understanding the failure mechanisms and the factors controlling instability. The Grand Wall and the North Wall of Stawamus Chief experienced significant rockfalls in 2021. Remote sensing using LiDAR and thermal imaging has added to our understanding of rockfall at Stawamus Chief. The application of these methods is discussed through detailed characterization of the rock slopes. Evidence shows that potential causal failure processes include root jacking, freeze-thaw effects, heavy precipitation, and expansion of joints due to extreme heat.

Keywords: Geohazards, Remote Sensing, Slope Stability, Rock Mechanics, Rockfall.

1 INTRODUCTION

Rockfalls are well documented in high granitic-granodiorite domes worldwide (e.g., Stock et al. 2013). Despite this hazard, these terrains form some of the most popular recreation areas in the world, Yosemite National Park, U.S.A, being the most famous example. Increased participation in outdoor recreational activities such as hiking, and rock climbing has heightened the risk posed to the public by these rockfalls. Stawamus Chief Provincial Park in Squamish, British Columbia, is no exception with BC Parks noting a province-wide increase in visitors of 26.5% between 2019 and 2022 (BC Gov. News, 2022). The 417m high granodiorite cliffs of Stawamus Chief dominate the landscape of the park and have produced numerous rockfall events in the past decade.

Stawamus Chief Provincial Park is located 60 km north of Vancouver, BC (Fig. 1). The Chief, as it is known locally, is a granodiorite pluton thought to have crystallized roughly 100 million years ago (Mathews and Monger 2005) and exhumed by tectonic processes involved in the formation of the Coast Mountain Range. During the last glaciation, ice was up to 2 km thick in the area, covering the Chief in ~1300 m of ice (Turner et al. 2010). Tectonic and glacial unloading are thought to have led to the distinctive exfoliation joints observed at the Chief and other granitic domes (Hencher et al. 2011). The cliff faces consist predominantly of massive, unaltered rock with fresh to slightly weathered discontinuities. A rock mass assessment carried out on the Chief determined the rock mass quality as excellent, with GSI values between 80 and 90 (Tuckey 2012). A distinctive feature on the Grand Wall is the "Black Dyke", an intrusive mafic body steeply dipping at 80° and which has an estimated GSI value between 70 and 80 (Tuckey 2012).

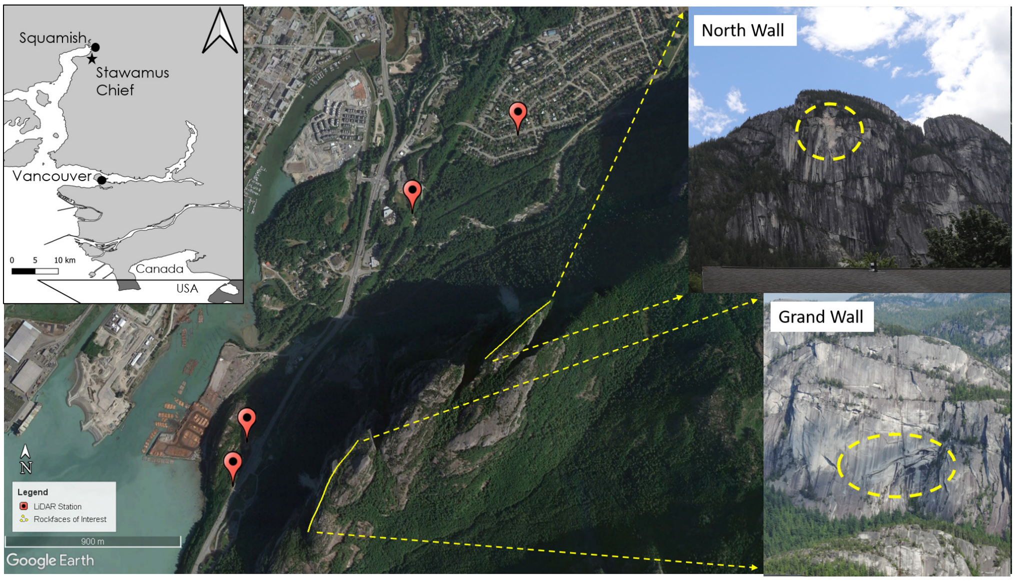

Figure 1. Map of Stawamus Chief indicating the location of LiDAR stations. Upper left inset shows the location of the Chief in the context of British Columbia. Right insets show photographs of the slopes with 2021 rockfall source zones highlighted in yellow.

2 METHODS

Remote sensing is now routinely conducted in both research and rock slope engineering practice (Stead et al. 2019). This study uses remote sensing data to characterize the block geometries and source zones of two major rockfall events that occurred at the Chief. Remote sensing campaigns were carried out in December 2021, as well as June and August 2022. Survey stations are located at the base of the Chief (Fig. 1). The measurements were combined with historical data collected in 2013 and 2015.

LiDAR data were collected from two stations for both the North Wall and Grand Wall (Fig. 1) using a long range Riegl VZ-4000 (max. range 4000 m). Station locations were chosen to maximize coverage of the rockfaces and reduce occlusion. Distances from the survey stations to the top of the slopes vary from 600 to 1100 m. Historical LiDAR data of the Grand Wall were acquired by Simon Fraser University researchers in 2010 using an Optech ILRIS-3D terrestrial laser scanner (Tuckey 2012), while data for the North Wall was acquired in 2016 using a Riegl VZ-4000 (Sampaleanu 2017). Infrared thermography data was acquired for the Grand Wall portion of the Chief in November 2013 with a handheld FLUKE TiR32 CAM thermal imager (-20°C to 600°C range, sensitivity ≤ 0.045°C); (Vivas 2014).

3 ANALYSIS OF 2021 ROCKFALLS

Historical records of rockfalls at the Chief are sparse with little information on frequency or magnitude of slope failures (Sampaleanu 2017). The District of Squamish authorized a limited study following a major rockfall from the North Wall on April 29, 2015 (GeoPacific 2015). This study focused on cliff face stability in the area of the rockfall detachment zone. The volume of the April 2015 slope failure was estimated at 1200 to 1600 m^3 and attributed to root jacking along the rear release joint. Eye-witness accounts suggest precursory activity in the form of small rockfalls occurred in the month leading up to the larger failure (GeoPacific 2015).

A large block (Fig. 2a, highlighted in yellow) detached from the North Wall on September 20, 2021. The volume of the rockfall was thought to be similar to the 2015 slope failure (Struik and Adam 2021), though a detailed analysis has not been carried out until this study. While no trigger has been directly attributed to these rockfalls, an unusually hot summer and 100 mm of rain two days prior have been proposed as contributing factors (Brend 2021). Seepage has been observed and characterized at the Chief (Vivas 2014), which acts to increase pore pressures and weather joint surfaces. Another possible contributor to instability is damage caused by the 2015 rockfall, with GeoPacific (2015) noting evidence of an impact in the form of intact rock fractures that are open and persistent. A closer view (Fig. 2c) shows the damage more clearly and may suggest that a previous rockfall impact destabilized the block that subsequently failed in 2021.

Significant rockfall events also occurred on the Grand Wall section of the Chief in the summer of 2021. At least four slope failures have occurred ranging in size from 4 m^3 to ~ 2500 m^3. The first two rockfalls occurred on June 27 and July 3 but went largely unnoticed due to their small size. The largest rockfall (hereafter referred to as the 2021 Grand Wall rockfall) took place on July 27 when an overhang detached from the cliff face (Fig. 2d) and unlike the previous two events, attracted significant media attention. Struik and Adam (2021) speculated that these rockfalls were associated with the extreme heat experienced in the summer of 2021, though no detailed study has yet been undertaken. Finally, a ~ 10 m x 10 m portion of the Black Dyke fell on September 10, 2021. No records exist of higher frequency of rockfall in any given year than in 2021. Our study aims to examine these rockfalls to understand their kinematics, failure mechanisms and possible triggers.

Previously acquired remote sensing data enabled a volumetric analysis of the 2021 rockfalls through comparison of pre- and post-failure point clouds. The historical data sets were compared with our post-failure data sets acquired in 2021 and 2022. Analysis was carried out using CloudCompare, an open-source 3D point cloud processing software (CloudCompare 2021).

Initial estimates of the 2021 rockfall volumes were performed by visual inspection of photographs. Estimates for the North Wall failure were stated as roughly the size of the 2015 failure (1200 - 1600 m^3; GeoPacific 2015) while the Grand Wall failure was estimated at 2500 m^3 (Struik and Adam 2021). The "2.5D Volume" tool in CloudCompare was used to compute the volume difference between the pre- and post-failure LiDAR point clouds for each wall. The 2.5D Volume tool projects the point clouds onto a grid of user-defined size, computes the height difference between the two clouds in each cell, and then sums the contribution of each cell to obtain the volume. By summing the minimum, maximum and average height of each cell, a range of possible volumes can be determined. The volume of the North Wall and Grand Wall failures were calculated at 3594 – 3692 m^3 (avg. 3624 m^3) and 2580 – 2645 m^3 (avg. 2607 m^3), respectively. Compared to initial estimates, the Grand Wall volumes are similar whereas the North Wall volumes were significantly under-estimated.

Automated discontinuity mapping using the software "Discontinuity Set Extractor" (Riquelme et al. 2014) identified three joint sets bounding the North Wall block and four bounding the Grand Wall block. Orientations (dip direction/dip) for these joint sets in the North Wall are 304°/87°, 343°/85°, 055°/83° and in the Grand Wall are 292°/69°, 091°/82°, 078°/40°, 059°/69°. The pre and post-failure source zone geometries were analyzed in CloudCompare by creating profiles along the pre- and post-failure point clouds. Horizontal and vertical profiles were created for both, although only the vertical profiles are shown for the Grand Wall (Fig. 3b) and horizontal profiles for the North Wall (Fig. 3d) as these are the most informative given the block geometry. The pre- and post-failure geometry of the Grand Wall are similar and the same overhanging block geometry is present, albeit to a lesser extent (Fig. 3b). By contrast, the pre-failure geometry of the North Wall changes to a more stable geometry that lacks the protrusions present prior to failure (Fig. 3d) and is also confirmed in high-resolution photographs (Figure 2a, b, c).

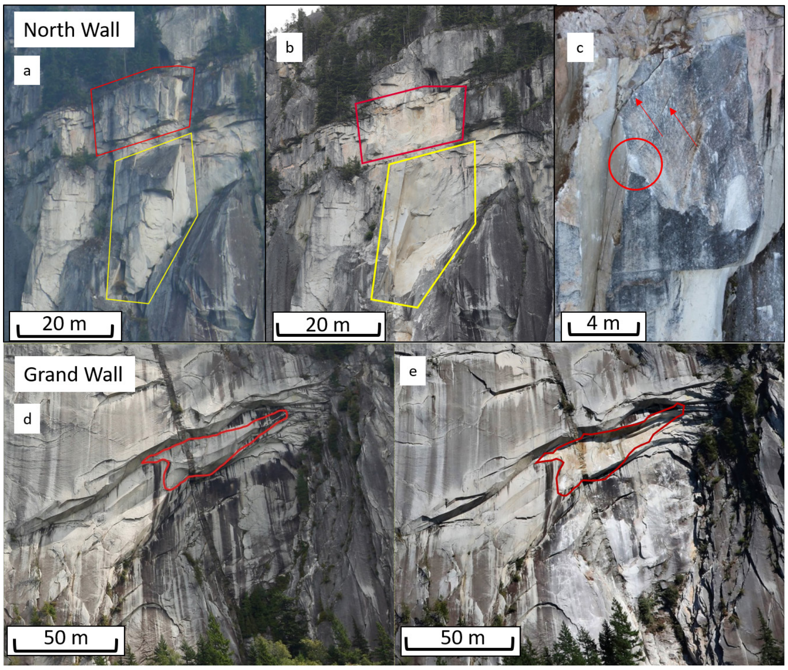

Figure 2. a, pre-2015 photograph of the North Wall (2015 block in yellow, 2021 block in red). b, post-2021 photograph of the North Wall. c, close up view of the slope damage caused by the 2015 rockfall. d, pre-2021 photograph of Grand Wall (block in red). e, post-2021 photograph of the Grand Wall. Photos by Jim Hegan.

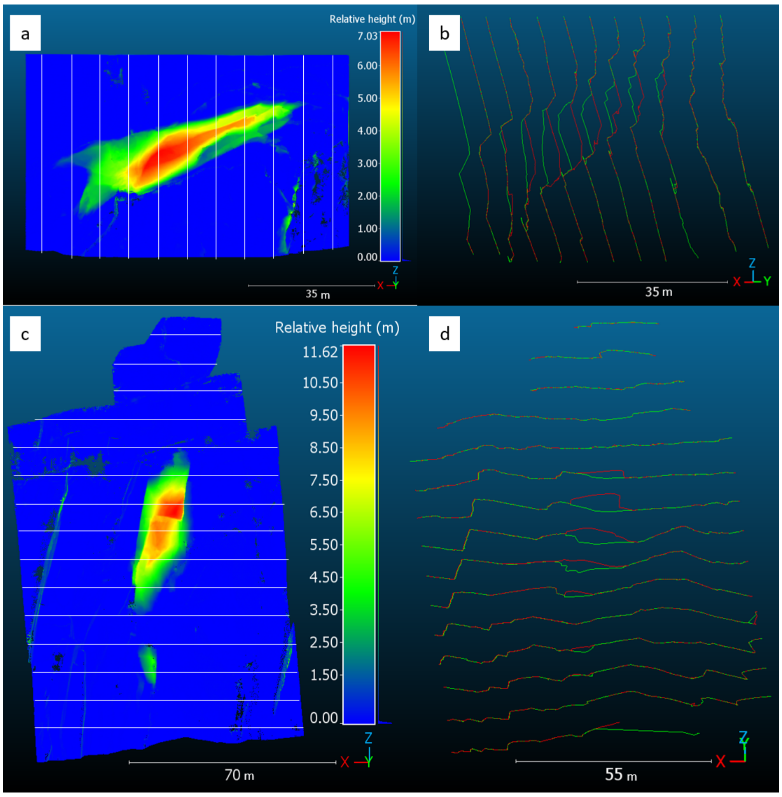

Figure 3. a, relative height calculation used to determine the volume of the Grand Wall rockfall. b, vertical profiles along the Grand Wall rockfall source zone. c, relative height calculation used to determine the volume of the North Wall rockfall. d, horizontal profiles along the North Wall rockfall source zone. White lines in a and b show location of profiles in b and d.

4 DISCUSSION

With three large rockfalls in less than a decade, the frequency of slope failures at Stawamus Chief appears to be increasing. However, whether this is a real or perceived increase is uncertain. As noted, the rockfall record for the Chief is sparse and does not allow for an accurate determination of event frequency. Common triggering mechanisms for rockfalls in general include precipitation, freeze-thaw cycles, and seismic shaking. However, it is typically the accumulation of multiple conditioning factors that ultimately lead to seemingly spontaneous failure (Stock et al. 2012). Nevertheless, a final triggering mechanism leading to some of the failures at the Chief can be proposed.

Analysis of the 2015 North Wall rockfall attributed the event to root jacking (GeoPacific 2015). The growth of roots in discontinuities can physically dilate them, increasing exposure to weathering, and ultimately encouraging rockfall initiation (Stock et al. 2013). Vegetation is visible along the upper boundary of the block (Fig 2a), supporting this as a viable trigger. The impact of the 2015 rockfall on the block that eventually dislodged in 2021 is evident from the damage and persistent, open fractures (Fig. 2c, red circle and arrows). This likely played a significant role in promoting the instability in the block that constituted the 2021 rockfall event. Examination of the geometry of the source zone indicates that a rockfall is unlikely to occur again in this exact area. Unlike the North Wall, the 2021 Grand Wall rockfall was not preceded by another large event in the last decade. There was, however, some precursory activity in close proximity to the source zone prior to failure. On June 27 and July 3 two small rockfalls occurred, indicating that there was some instability prior to this event. Heat waves in the Pacific North West in the summer of 2021 set record high temperatures for British Columbia, with temperatures consistently ≥ 40 C with nightly lows of ~ 20 C (Philip et al. 2021). Collins and Stock (2016) demonstrated that cyclic thermal expansion of exfoliation joints leads to fracture propagation and can promote rockfall. Thermal imaging of the Grand Wall shows that the rockfall detachment zone is susceptible to larger thermal fluctuations (Fig. 4). It is likely that the initiation of the 2021 Grand Wall rockfall was exacerbated by increased thermal stresses. Analysis of pre- and post-failure geometry suggests that this source zone may be prone to future failures.

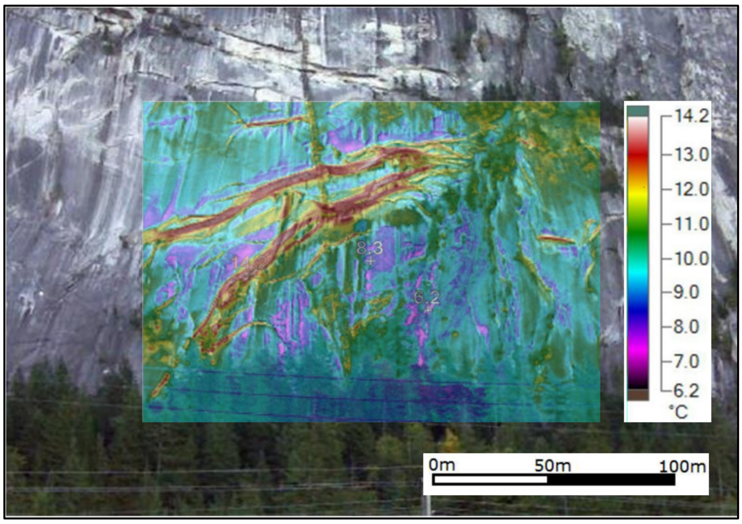

Figure 4. Thermal image overlaying a photograph of the Grand Wall. Note the higher temperature concentrations on the partially detached overhangs. Modified from Vivas 2014.

5 CONCLUSIONS

Rockfalls are a natural phenomenon known to occur in granitic domes around the world (Stock et al. 2013). With increased visits to areas such as Stawamus Chief Provincial Park, people are increasingly exposed to these hazards. Understanding the rockfall failure processes and the factors controlling instability in these terrains is essential in mitigating the risk to the public. The volume of the 2021

Grand Wall and North Wall failures have been well constrained to 2607 m^3 and 3642 m^3 respectively. Analysis of pre- and post-source zone geometries suggest that rockfall risk factors on the Grand Wall remain, and future rockfalls are possible. In contrast, the immediate vicinity of the North Wall failure is now in a more stable configuration. Slope damage on the North Wall from the 2015 failure appears to have contributed to the instability that led to the 2021 failure. A record-breaking heat wave was likely an important trigger for the 2021 Grand Wall failure due to cyclic thermal expansion. The overhanging, partially separated geometry of the Grand Wall source zone led to temporal heat fluctuations focused in this area. It is also possible the heat wave that affected the Grand Wall contributed to the failure at the North Wall. While ascribing single trigger mechanisms to spontaneous rockfall events is difficult, the triggers described here are the most evident. Future rockfalls would most likely be associated with climactic triggers such as an extreme heat wave or freeze-thaw cycles. Multi-instrument remote sensing analyses such as the one carried out here enables improved understanding of these slope failures. Future studies at the Chief will expand upon this work to monitor and inform mitigation approaches at this location and similar sites world-wide.

REFERENCES

BC Government News. 2022. 2022 season sets BC Parks reservation record. url: https://news.gov.bc.ca/27587

Brend, Y. Sept. 2021. Rock slides that shook B.C. community linked to climate change, expert says. CBC News. url: https://www.cbc.ca/news/canada/british-columbia/stawamus-chief-rock-slides-webcam-climate-change-rain-heat-granite-rock-fall-1.6184534

CloudCompare. 2021. CloudCompare 3D point cloud and mesh processing software Open Source Project. url: http://www.cloudcompare.org.

Collins, B. D., Stock, G. M. 2016. Rockfall triggering by cyclic thermal stressing of exfoliation fractures. Nature Geoscience 9, 395–400.

GeoPacific Consultants Ltd. 2015. Preliminary Geotechnical Review, Angels Crest Rock Fall, Stawamus Chief, Squamish, BC. 12942.

Hencher, S. R., Lee, S. G., Carter, T. G., and Richards, L. R. 2011. Sheeting joints: Characterization, shear strength and engineering. Rock Mechanics and Rock Engineering 44, 1–22.

Mathews, W. H., Monger, J. 2005. Roadside geology of southern British Columbia. Roadside Geology.

Philip, S. Y, et al. 2021. Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada June 2021. Earth System Dynamics Discussions, 1–34.

Riquelme, A.J., Abellán, A., Tomás, R., Jaboyedoff, M., 2014. A new approach for semi-automatic rock mass joints recognition from 3D point clouds. Computers & Geosciences, 68, 38-52.

Sampaleanu, C. 2017. The role of intact rock fracture in rockfall initiation. M.Sc. thesis. Simon Fraser University.

Stead, D., Donati, D., Wolter, A., Sturzenegger, M. 2019. Application of remote sensing to the investigation of rock slopes: Experience gained and lessons learned. ISPRS International Journal of Geo-Information 8, 296.

Stock, G. M., Martel, S. J., Collins, B. D., and Harp, E. L. 2012. Progressive failure of sheeted rock slopes: The 2009-2010 Rhombus Wall rock falls in Yosemite Valley, California, USA. Earth Surface Processes and Landforms 37, 546–561.

Stock, G.M., Collins, B.D., Santaniello, D.J., Zimmer, V.L., Wieczorek, G.F., Snyder, J.B. 2013. Historical Rock Falls in Yosemite National Park, California (1857-2011). US Department of Interior, US Geological Survey.

Struik, B., Adam, P. 2021. Risky Ground 2021 Fall Edition. Risky Ground Newsletter. url: https://www.sfu.ca/content/dam/sfu/cnhr/news_events/newsletter/RiskyGround_News_2021-09-21.pdf.

Tuckey, Z. 2012. An Integrated Field Mapping-Numerical Modelling Approach to Characterising Discontinuity Persistence and Intact Rock Bridges in Large Open Pit Slopes. M.Sc. thesis. Simon Fraser University.

Turner, B., Kelman, M., Ulmi, M., Turner, T., and Franklin, R. 2010. Sea to Sky GeoTour: geology and landscapes along Highway 99 from Vancouver to Whistler, British Columbia. Natural Resources Canada.

Vivas, J. 2014. Groundwater Characterization and Modelling in Natural and Open Pit Rock Slopes. M.Sc. thesis. Simon Fraser University.