Landslide Detection at the Mount Meager Volcanic Complex

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QSFP Final Report

8/16/2019

Abstract: In 2010, rock slopes above Capricorn Creek at the Mount Meager Volcanic Complex (MMVC) failed in what became the largest landslide in Canadian history. The event caused roughly $10,000,000 in damage, and while no lives were lost, the communities of Pemberton and Pemberton Meadows are still in significant danger of a large runout landslide (Friele et al., 2008). Recent research has identified multiple slopes on the MMVC that are in danger of failing, but one is of particular concern. This slope is approximately 10x the size of the source of the slide in 2010, and poses a significant danger to the communities of Pemberton Meadows and the Village of Pemberton (Roberti, 2019). Landslides are quite prevalent in the area, especially at loosely consolidated volcanic edifices like the MMVC. Just recently, a large landslide off of Joffre Peak made headlines (CBC, Global News). As we see increasingly warm weather and rapid snowmelt through the spring and summer, we will see an increase in large landslides (Petley, 2019).

We will be implementing the first rendition of a seismic monitoring system at the MMVC, using an industry-standard geophone and infrasound system, coupled with a weather station and a camera. Data will be transmitted to Quest via satellite and to an Innergex power plant via radio frequency transmission. This project is collaborative. Our main partner is Weir-Jones Engineering (WJE) out of Vancouver. This geophysical group has offered equipment and a small honorarium, and they will be using the system we helped design and install to create a landslide alarm system for an Innergex power plant at the base of the MMVC. The duration of the QSFP was spent organizing donors, securing helicopter time, designing the system, and planning the installation. Once we have installed (early September), we will be using the data to look for correlations between weather trends and landslides/rockfall.

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This document serves as a summary and interpretation of work completed during a 3 month summer fellowship between May and August in 2019. Though the fellowship window has passed, the larger project is still incomplete. This report does not follow a specific format- it combines narratives that re-tell experiences, as well as summaries of methods and background research. It will be centered around 2 questions: What did I do? What does it mean (what did I learn)?

Introduction

In September of 2018, I was driving through northern Nevada with 13 other students and Steve Quane, during the course Tectonics of Western North America. I was sitting in the front passenger seat of one of the Quest minivans, and Steve was driving. As a 4th year student with no clue what I wanted to do for a keystone, I used the opportunity to ask Steve if he had any projects that he hadn't yet had the chance to work on. I said that I did not want to work on an esoteric academic exercise, rather, I wanted to invest my time in something more tangible, something that others might use in the future.

Steve said that he had a colleague, Glyn at SFU, who was doing some work with newly discovered fumaroles on Mt. Meager. Maybe, Steve said, there was an avenue to pursue a keystone sized project working with Glyn. I was interested, but didn't think much more of it until November, when I was taking another of Steve's courses: Research in Earth and Environmental Science (REES). The main deliverable for the course was a mock grant proposal, so I decided to use the time to do some background research into Mt. Meager. What I found excited me... not only was Meager in a national spotlight because of the discovery of the fumaroles, there was also a significant gap in research relating to landslides in the area. I found that in 2010, there was a massive landslide (the largest in Canadian history) from the flanks of the volcano. No one was hurt, but the slide took out a bridge, cut off access to the hot springs, and dammed the Lillooet river. When the dam burst, the subsequent flooding caused damage in Pemberton Meadows, an important agricultural area.

Since that slide, there has been a significant amount of work done attempting to quantify the landslide risk in the area. Not surprisingly, the communities of Pemberton Meadows and Pemberton have been shown to be at significant risk of impact from landslides. Despite this finding, not a single risk management strategy has been taken, aside from some landslide awareness signage on the Lillooet Forest Service Road. So, in my mock grant proposal for REES (Appendix C), I came up with the idea of using low cost, easily deployable Raspberry Shake seismometers to create a landslide and rockfall inventory. The funding cap on the proposal was $2,500: enough for 3 instruments, some auxiliary gear, and travel time (driving). I ended the proposal by saying that the work could be easily expanded on to become a landslide early warning system (LEWS).

Regardless of whether or not I actually did the project, writing the grant proposal was a valuable experience. Steve sent it over to Glyn (SFU), asking if he had any ideas of avenues to take with it. We didn't hear back. The class ended, and I shifted my focus to other blocks. Finally, Glyn responded, and his response was an enthusiastic one. He said that the timing was right for a project like this, and that he had taken the liberty of pitching the idea to Weir-Jones Engineering (WJE), a geophysics firm out of vancouver. The president of that firm, Iain, responded rather quickly, and offered mentorship and an honorarium of $5000 to support the project. More importantly, they offered proprietary equipment and a communications system, meaning that I would be able to do the larger version of the project that I proposed- I would get to help create the alarm system that previous researchers had called for.

This was all very exciting. I quickly began applying for summer fellows, because I knew that if I wanted to fully devote myself to the project, I would need more support. Other than that, the news was a little premature. This was in December, and due to field conditions, it wasn't possible to work up at Meager until mid summer. In the interim, I put my focus back into my other classes.

Come April, Steve and I drove down to Vancouver to meet face to face with Weir-Jones and Glyn. We were prepared with a general idea of the system we wanted, and where we wanted to put it. Still, I was caught off guard when Iain, the president, asked: "So what do you want to do?"

It seemed as though I could dream big, and that somehow I had tapped into something that was much bigger than I initially imagined. I was excited, nervous, and felt ready to throw myself at the project.

Timeline

November 2018 - Preliminary research on landslides/risk management at the MMVC.
*
December 2018 - Offer of support from Weir-Jones Engineering (WJE), bedrock scouting via geologic map (Read, 1978). Gio Roberti (SFU) is finishing his PhD with Glyn, examining a massive slope facing the Job Glacier that is likely to fail.
*
March 2019 - Preparations for meeting with WJE - research into seismic volcano monitoring, landslide early warning systems. Preliminary site locations chosen based on bedrock scouting, line of sight (LOS) confirmed using ArcGIS viewshed tool.
*
April 2019 - Meeting with WJE. Offer of one station with geophone and RF communications, $5000 honorarium. Talk of getting further support from Innergex.
*
May 2019 - Joffre slide provides good public awareness. Fellowship begins.
*
June 2019 - Research on landslide triggers, LEWS. Offer from NuPoint Solutions for a camera and satellite telemetry, meaning more robust communications and visual confirmation of rockfall events. Small conference at UBC to bring all MMVC researchers up to date.
*
July 2019 - SLRD grant proposal for more helicopter time- application pending. First round of field work at MMVC assisted by Steve Grasby (NRCAN). Site locations confirmed, installation method decided.

August 2019- Present - Fellowship Write-Up
*

Future - Installation at MMVC - 3 sites over ~5 days. The most involved site will be the ridge requiring helicopter work. Data analysis.

Precursory Work

By the time the Summer Fellowship program began in late May, much work had already been done on this project.

Findings from Preliminary Research and Impetus for Study

The following is an excerpt from a grant proposal written in November (Appendix C) (Pitchel, 2018), prior to having support from WJE.

“Mt. Meager is known to be the most unstable mountain in Canada. Friele et al noted that poorly lithified and hydrothermally altered rocks create the potential for edifice collapse at volcanoes. The sources of the major edifice collapses at MMVC are hydrothermally altered rocks in the Angel, Devastation and Job Creek basins. Large masses of unstable volcanic rock still exist at MMVC. 8 years ago, Capricorn Creek (not identified by Friele) slid in a massive landslide, demonstrating that the warnings are real, and that events are unpredictable. Work was being done at the time with high resolution GPS imagery to identify slope stability and immediate dangers (Roberti, PhD Unpub., ~2008). More recently, heightened volcanic activity on the north flank of Mt. Meager has been observed. Glyn Williams-Jones of SFU reported 3 new fumaroles underlying a glacier, and has called for a landslide monitoring system at Meager.

With Williams-Jones’ recent work, MMVC was thrust into the public spotlight. News outlets such as CBC and the Vancouver Sun have published articles about the activity at MMVC. The articles mentioned the lack of necessary seismic monitoring.

Prior to the 2010 slide, work was done assessing the risk and hazard from landslides to the nearby communities. Many areas around the world have worked to quantify acceptable levels of risk from natural hazards. Pemberton Meadows (near Meager) is at risks 5.4x greater than deemed acceptable to areas that have risk management strategies in place (Friele et al., 2008). The risk management strategies that have been recommended for Meager Creek only pertain to zones in close proximity to the source. The village of Pemberton has no risk management strategies pertaining to landslides, and Friele et al. suggest that simple landslide detection via seismometers is the minimum requirement for responsible long term hazard and risk management.”

This was the first round of background research completed regarding this project. The impetus for this work was the distinct call from multiple sources (Friele et al., 2008, Williams-Jones, 2018, Roberti, 2018) for landslide monitoring at Meager. It was clear that there was a gap in the current body of knowledge, so the project seemed important and meaningful.

After this grant proposal was written, support for the project was offered by Weir-Jones Engineering. A meeting was arranged for late April, as the field season was later in the summer. Prior to the meeting, work was done to identify some preliminary site locations for seismic stations at the MMVC.

Peter Read, one of Canada's premier mapping geologists, made the most comprehensive map of the MMVC in 1979 (Figure 1).

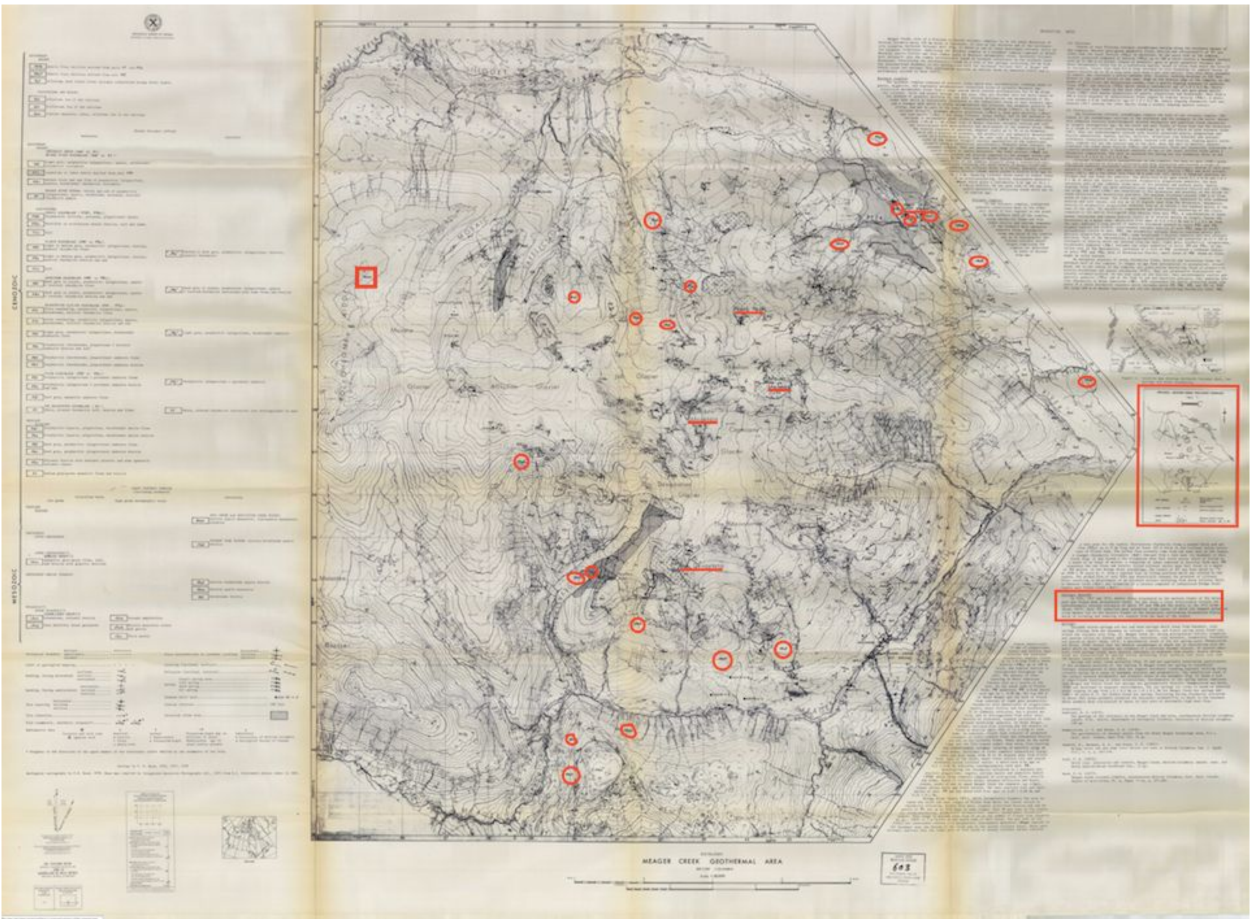
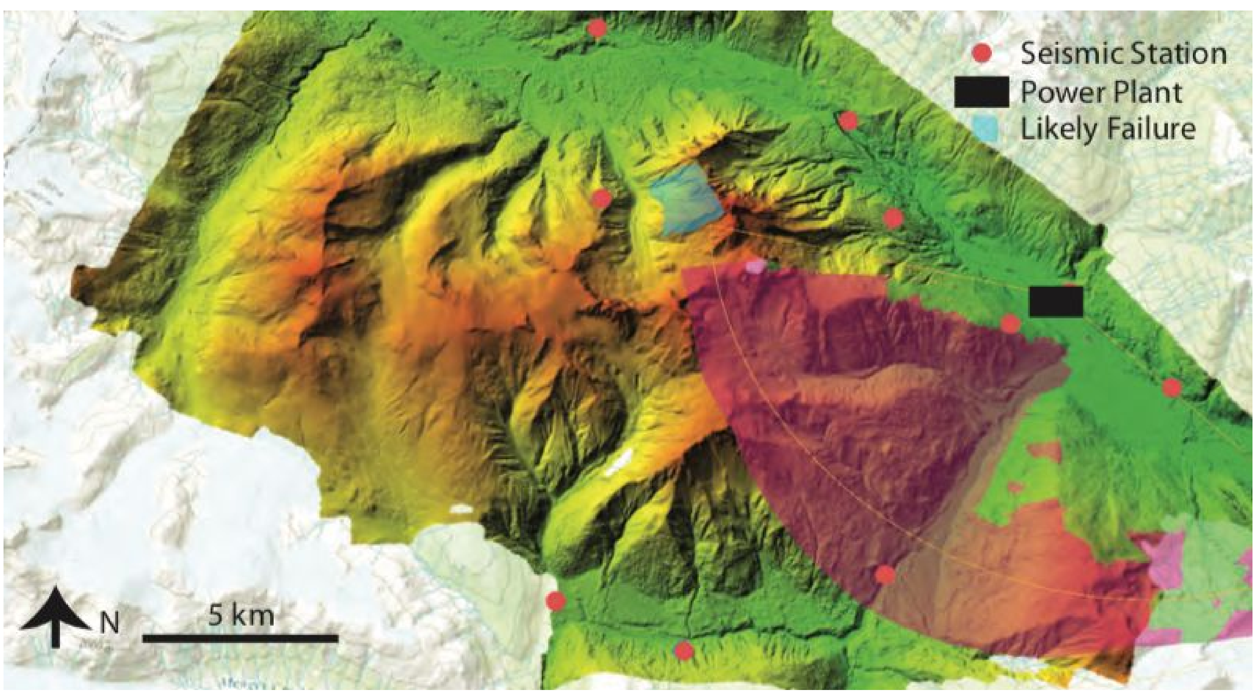


Figure 1: Geologic map of the MMVC (Read, 1979). Red circles indicate identified bedrock.

Site locations were chosen by ease of access and known bedrock. The latter was crucial because equipment needed to be bolted into bedrock to ensure the best data. The stations also had to have LOS between each other, as the RF telemetry we would be using required it. Many volcanic monitoring programs took the route of surrounding the massif's with seismometers so as to best capture any seismic activity (Pacific Northwest Seismic Network). So, in choosing site locations, bedrock locations from the 1979 map were transcribed into Google Earth (Figure 2a) and ArcGIS, and efforts were made to surround the massif. LOS was confirmed using the ArcGIS viewshed tool (Figure 2b).


station 3
Station 1
Station 4
innergex boulder creek/home
rf link 3
station 6
rf link 2
station 5
RF link 1
Google Earth
Image © 2019 DigitalGlobe
© 2018 Google
Image © 2019 Maxar Technologies
N
7 km

A


Seismic Station
Power Plant
Likely Failure
N
5 km

B

Figure 2: (A) The first proposed station locations (from December) as visualized in Google Earth. Seismic stations are labeled "station" and RF repeaters are labeled "RF link." The Innergex hydro project is also indicated. (B) An example of the ArcGIS viewshed tool used to confirm LOS. Base map is LiDAR data (Roberti et al., 2018). LOS is shown from the power plant. Positive confirmation of LOS is indicated in green, while non-LOS is shown in red. Each station had at least confirmed LOS to its proximal stations.

In the interim, more prominent news publications were releasing articles (CBC, Globe and Mail, etc) about the risks associated with the MMVC. Ongoing projects were all rapidly picking up speed, and our monitoring initiative was gaining some recognition from other researchers at Meager.

Background Research Phase

The first month of the Summer Fellowship was spent conducting background research and reading. Prior to starting the fellowship, the project had been on hold for a few reasons- classes were running, and I had to give my focus to them. Also, the other players in this project (WJE, SFU, Innergex) had been working on other projects, and this monitoring system was on the backburner, or so we thought. So, the first step was to get back up to speed. The primary goal for the first few weeks was to get familiarized with landslide trigger mechanisms and LEWS. In order to stay organized and methodical, a literature review was conducted. The following are the findings from various sources on landslide triggers.

Landslide Trigger Mechanisms

A landslide is a broad term used to describe the general down-slope movement of soil, rock, and other organic material under the influence of gravity (Highland and Bobrowsky 2008). Landslides can therefore be classified under more specific criteria, typically relating to type of movement and composition. Movement is classified as fall, topple, slide, spread, or flow, and is synonymous with landslide type. The material is either rock, soil, or both. Soil is either earth (if composed of sand sized particles or smaller) or debris (if particles are more coarse).

There is a difference between a landslide cause and a landslide trigger. Causes of landslides take place on a longer time scale. Examples of causes include weathering and climate change. A trigger is an external, discernable stimulus such as heavy rainfall or ground-shaking. A slide can have multiple causes, but typically have only one trigger (Wieczorek 1996).

Broadly, landslides can be triggered by water, seismic activity, volcanic activity, and human activity.

Water: Landslides and water are closely linked. The saturation of a slope can directly trigger nearly all types of landslides. Rapid snowmelt, intense rainfall, changes in ground-water levels, and sea level rise (in coastal areas) can all cause landslide processes. An increase of water levels or saturation of soil can increase its pore pressure, which can in turn lead to landslides (Wieczorek 1996). Flooding can cause landslides, and landslides can cause flooding. If an area floods, banks may be undercut, causing instability and subsequent sliding. If a landslide blocks a waterway, it effectively creates a dam, which causes the area upstream to flood.

Seismic Activity: Earthquakes and ground-shaking can cause landslides and rockfall from steep slopes composed of loose, cohesionless, or saturated soil. Few slides caused by earthquakes reactivate old slide materials; most cause new material to slide. As all kinds of earthquake induced landslides can be caused by other triggers, very weak earthquakes could trigger a slide if the slide is already imminent (Keefer et al., 1984).

Volcanic Activity: Many volcanic edifices are made from loose and unconsolidated material, and thus are prone to collapse, causing rockfall, debris flows, and debris avalanches. Eruptions can melt snow incredibly rapidly, causing liquefaction of soils and landsliding. Volcanic seismicity can also induce slides (Highland and Bobrowsky 2008).

Human Activity: Human development can disturb or alter drainages, destabilize slopes, remove vegetation, and contribute excess water to the environment. These activities all have the potential to induce landslides (Highland and Bobrowsky 2008).

Table 1: Descriptions, velocities, and trigger mechanisms for landslide types deemed relevant to MMVC

Falls			
Type	Description	Velocity	Trigger
Rockfall	Abrupt movements of rock or earth that detach from steep slopes/cliffs. Typically impacts lower angle slopes and either breaks or rolls.	High	Undercutting of slope (stream/river, differential weathering), human activities, earthquakes

Slides			
Type	Description	Velocity	Trigger
Translational Landslide	Mass moves out or down along a planar surface with little rotational motion. Process may continue over long distances with sufficiently steep angles. Material ranges from loose soils to large rock slabs or both. Fails	Slow to moderate (can increase to high if mass becomes debris flow)	Intense rainfall, rise in groundwater, earthquakes.

	along faults, joints, bedding surfaces, etc.		

Flows			
Type	Description	Velocity	Trigger
Debris Flow	Rapid movement of slurry composed of loose soil, rock, organic material, and water that flows downslope. Can form from landslides that gain water. Often confined to the dimensions of gullies that facilitate movement. Can be thick, or more surficial.	Very high	Intense surficial waterflow (rainfall, snowmelt)
Lahar	Debris flows that originate on the slopes of volcanoes. Loosely consolidated volcanic matter mobilizes. Lahars can become larger as they accumulate debris.	Very high	Water: crater lakes, snow/ice melt, condensation from erupted steam.
Debris Avalanche	Large, sometimes open slope flows that form when an unstable slope collapses. Snow and ice can contribute to the movement, and debris avalanches can turn into flows or lahars with sufficient water. Common on steep volcanoes.	Very high	Cold vs Hot debris avalanches. Cold: Slope becomes unstable during a landslide or weathering processes, and transforms into an avalanche. Hot: Caused by volcanic earthquakes or the injection of magma.
Creep	An imperceptibly slow earthflow caused by internal shear stress	Very slow	Rainfall/snowmelt, and other kinds of physical weathering.

	insufficient to cause failure. 3 types of creep: Seasonal (changes in moisture content/temperature), continuous, and progressive (approaching failure). Difficult to discern the boundaries of a creep. Can progress to more rapid slides/flows.		

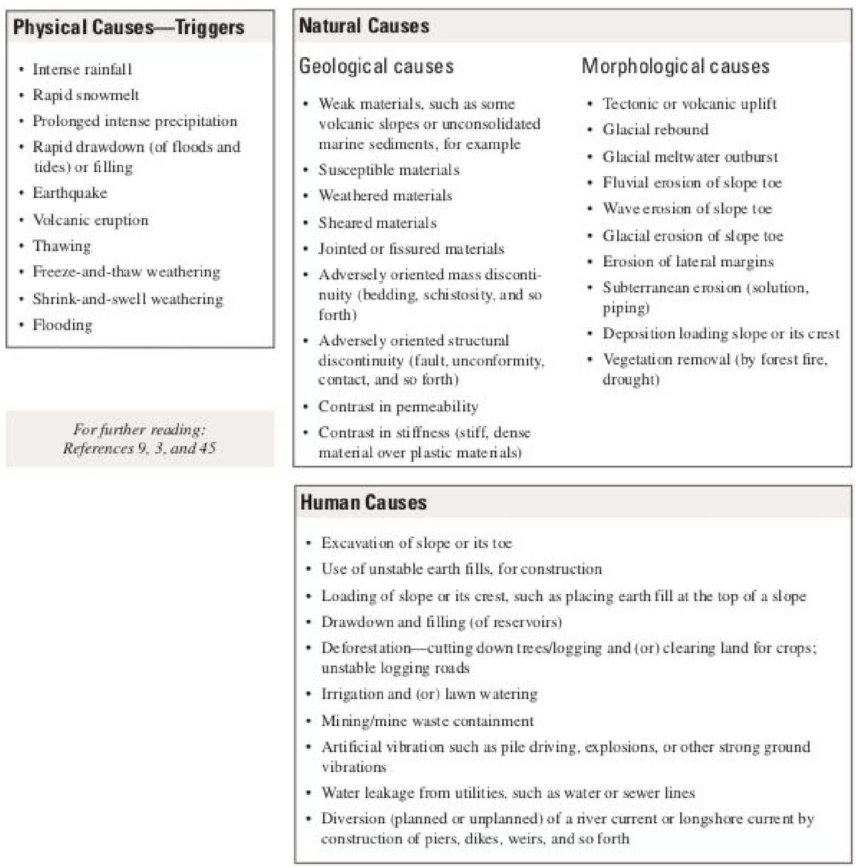


Figure 3: Landslide Causes and Triggering Mechanisms (Highland and Bobrowsky 2008).

Another crucial topic to read about were landslide early warning systems (LEWS). As a brief refresher - the initial proposal for this project was to create a LEWS for both Innergex and the village of Pemberton. After the meeting with WJE in april, the feasibility of creating such a system came down to funding. We had designed a 3 tiered proposal for WJE and Innergex (See appendix E). Innergex was bringing in the majority of the funding. The 3 tiers of the proposal were:

1. 1 station. Enough for an undergraduate thesis project (funded by WJE).

2. 3-5 stations. Enough for an alarm system for the Innergex power plant.

3. 10-12 stations. Enough for an alarm system for the village of Pemberton, and enough to create the first comprehensive volcano monitoring system in Canada.

We hoped to sell Innergex on the 3rd tier, and marketed it by portraying them as a good corporate citizen- both supporting science and a potentially life saving alarm system for Pemberton. However, we did not know what their response would be. So, while waiting to hear which project we would actually be working on, research had to be done on LEWS.

Landslide Early Warning Systems:

Intense rainfall (or other water added to a system) is the most common trigger of landslides (Posner and Georgakakos 2016, Vaz et al., 2018). Much work has been done surrounding the development of Landslide Early Warning Systems (LEWS) in relation to rainfall. Various studies and systems have examined different methods of landslide *prediction* based on rainfall thresholds, pore pressure (piezometry), and hydrological conditions of hillslopes (Segoni et al., 2018).

Schimmel et al (2013, 2014, 2017, 2018) have developed automatic landslide *detection* systems based on acoustic data (seismic and infrasonic). The following section reviews components of work done by Schimmel et al.

Alpine mass movements produce discernable seismic and acoustic waves at low frequencies (<30 Hz). As both seismic and acoustic monitoring have proven effective at detecting mass motion, Schimmel et al (2018) were able to combine the two techniques to create a detection system that minimizes false alarms. Their system uses one seismic and one acoustic sensor, allowing for a relatively low cost and easily deployable network.

For hardware, different infrasound sensors were tested, but all had common frequency ranges (<20 - 200 Hz). Different seismic sensors were also used: a sensor with a sensitivity of 28 V/m/s, and a geophone with a sensitivity of 80 V/m/s. Sensors were connected to analog to digital converters (ADC's), with the option of an ethernet connection. The system operated at 1.5 W, which makes it suitable for solar power.

They use a detection algorithm that overlaps data from the seismic and infrasonic sensors to eliminate error due to noise (infrasonic is susceptible to wind). Certain criteria must be met by the signals in order to trigger an alarm.

This is very similar to the system that we are implementing at Meager. At this time, we had also been offered satellite telemetry from NuPoint Systems, as well as a camera and a weather station. The following were my final recommendations for the system at Meager. Later, WJE expanded on this system to create a LEWS for Innergex. More on that in the next section.

Final Recommendations for Meager

Given the equipment and funding available, the focus should be on landslide detection rather than landslide prediction. Improvements and upgrades to this preliminary system can target prediction in the future. Detection is quite relevant to the region, because of Meager's long distance to habited areas (~75 km).

Based on the work presented by Schimmel et al, I advocate for using a similar combination of seismic and infrasonic sensors.

A tri-axial geophone should be used as it will have less noise than an accelerometer. The geophone with the lowest frequency range should be chosen to accurately capture signals from landslides and other mass movements. Infrasound sensors can be purchased with Weir-Jones grant money, or SLRD money. Schimmel et al recommend a low cost infrasonic microphone, but the downside (as opposed to a higher quality sensor) is that it is more susceptible to noise[1] and must be calibrated[2]. GPS time synchronization seems to be a necessary component as well.

If possible, a weather station should be incorporated. This is beneficial for many reasons. Even though the focus is on seismic and acoustic detection, it is important to recognize the significance of rainfall/snowmelt as landslide triggers. A weather station can help monitor precipitation and solar radiation/temperatures, and rainfall thresholds in similar environments could be examined to help the systems accuracy. For a weather sensor, the Lufft WS700-UMB Smart Weather Sensor is a good option. It measures temperature, relative humidity, precipitation intensity, precipitation type, precipitation quantity, air pressure, wind direction, wind speed, and radiation. This sensor could be linked with a Remote Detect System from Nu-Point for visual surveillance, and RF data links from Weir-Jones for communications.

Once this recommendation for Meager was complete, and after a phone call with Tony Herunter from NuPoint Solutions, I created a final equipment wishlist to send to WJE. This can be found in Appendix F.

The next step, broadly, was to consider installation. Some barriers to installation are: snowpack, ground substrate (soil, bedrock, etc), access (road, helicopter, hike, etc), funding, and weather. One useful tool that was used to address the snowpack is called Planet Labs. The program functions similarly to google earth, but imagery is updated via satellite daily (Figure 4). Having more current imagery was critical to

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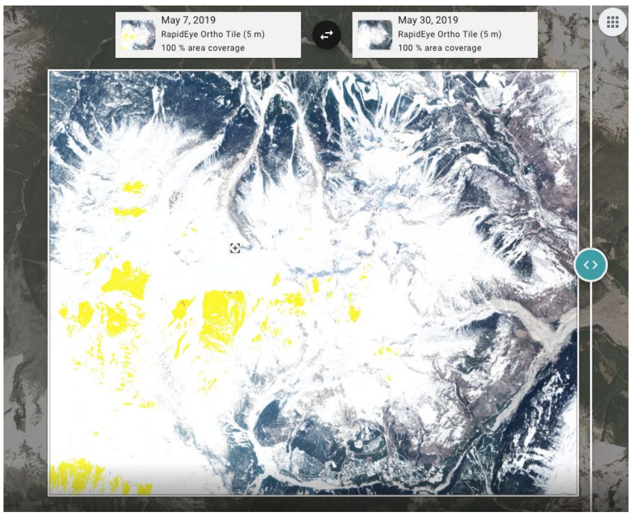
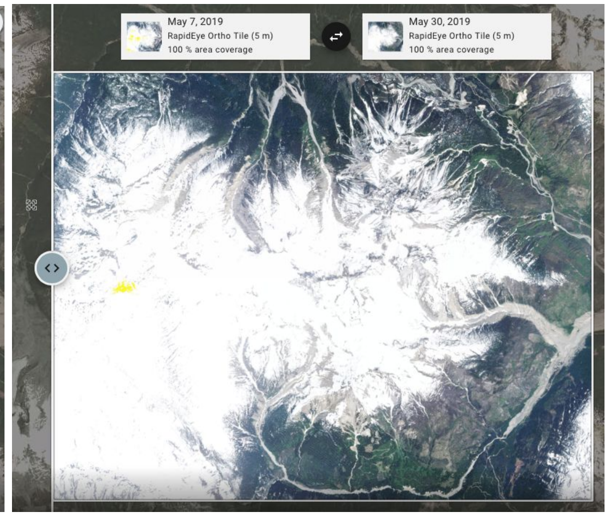
[1] For noise reduction, we are using roughly 5 ft of soaker hose x 4 attached to the infrasound intake, then the baseplate of the tower.

[2] The system is now using a small pressure sensor that is used in the Raspberry Boom infrasound sensor. By simply implementing a pressure sensor, rather than a full infrasound microphone, we were able to cut costs.

understanding the conditions we would be encountering without actually having to make a field trip up to the MMVC.





A. B.

C.

Figure 4: Planet Labs imagery comparison between (A) May 7, (B) May 30, and (C) July 29. All photos have 100% area coverage. Note the difference in snowpack.

With speculative site locations chosen, and an idea of current conditions, work had to be done to figure out how to install the equipment. Here, we turned to WJE for their field expertise. Up until this point, the project was already quite collaborative, and involved multiple players from different organizations all sharing resources to try to get the most robust body of research possible at Meager. The following section will address all of the different players, their roles, and the multi-level organization that this project adheres to.

Organization

The beauty of this project is that it is incredibly collaborative. Our monitoring system is a small piece of the larger research program that is taking place at the MMVC in the summer of 2019. This is the first large scale effort for a volcano monitoring system in canada.

Table 2: All parties peripherally involved in the monitoring project at the MMVC. All players also have other MMVC related projects they are involved in.

Players	**Affiliation**
Mason Pitchel, Steve Quane	Quest University Canada (QUC)
Glyn Williams-Jones, Gio Roberti	Simon Fraser University (SFU)
Iain Weir-Jones, Michael Trevorrow	Weir-Jones Engineering (WJE)
Tony Herunter, Wayne Carlson	NuPoint Solutions
Steve Grasby	Natural Resources Canada (NRCAN)
Wayne Russell	Innergex
Russell Mack	Squamish-Lillooet Regional District (SLRD)
Eric Dumerac (Guide)	Mountain Skills Academy
Marco Accurso, Denis Vincent	Coast to Coast Helicopters
Quest Summer Fellowship Program	Quest University Canada

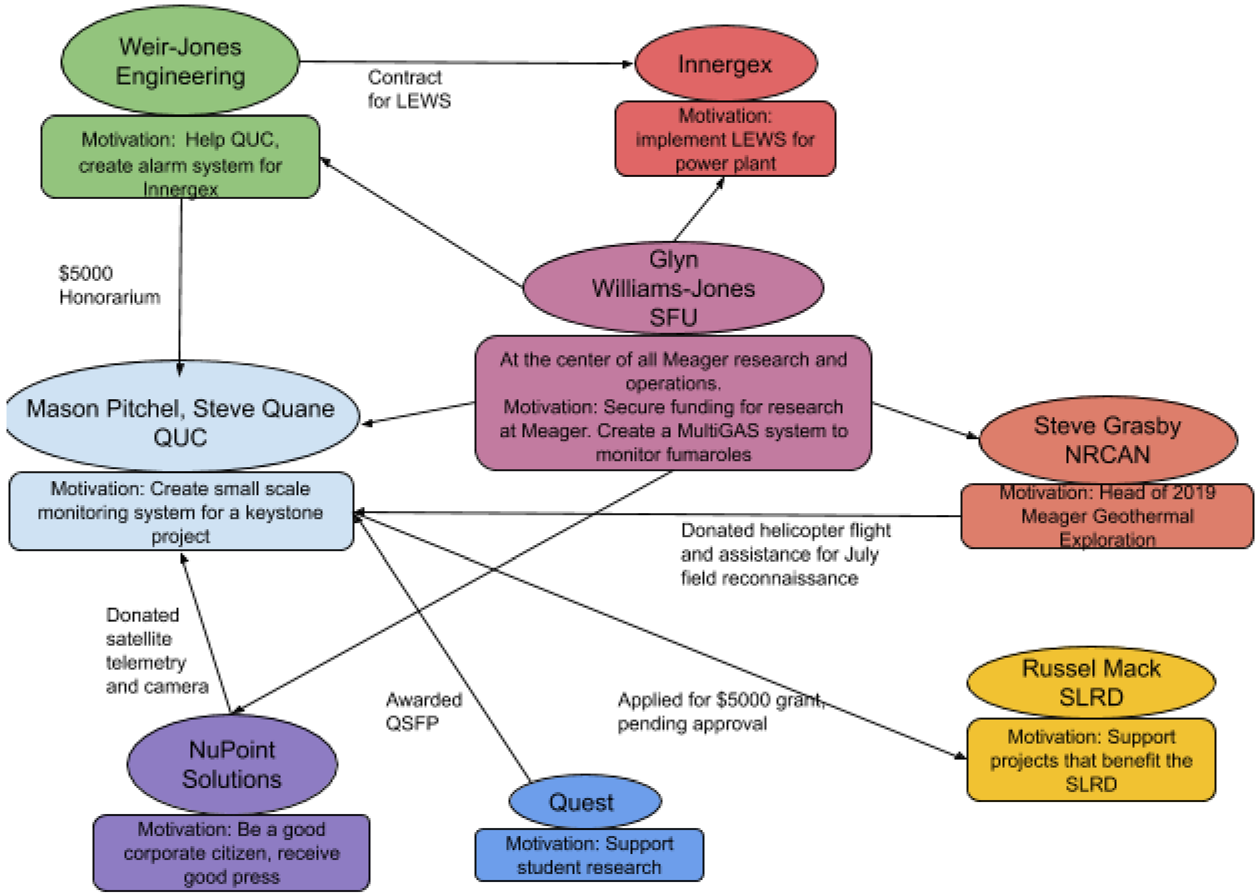


Figure 5: All major players, affiliations, and motivations for summer 2019 research at Mt Meager. Some names are not depicted, as they are subsidiaries of or related to these larger organizations.

In mid June, many of the parties involved gathered at UBC for a small conference to bring everyone up to speed with plans for the research window at Meager. The goal was to understand what others would be doing, so that resources and time could be shared and used as effectively as possible. The speakers and topics included:

Steve Grasby, NRCAN Calgary - *Project Overview*
Jeff Witter, Innovate Geothermal Ltd. - *Mining Historical Meager Data*
Nathalie Vigouroux - *Summary of the 1970s NRCAN Data* **(**for Yuliana Proenza)
Kelly Russell, UBC - *MMVC Orientation & Michelle Campbell's Subsurface Reconstruction*
Alex Wilson, UBC - *Results from Latest Mapping of MMVC*
Gio Roberti, Minerva Intelligence - *Slope Stability Hazards and AI Forecasting*
Steve Quane, Quest University - *Sea-to-Sky Initiatives*
Glyn Williams-Jones, SFU - *New Monitoring Initiatives*

At the meeting, Glyn released a pictogram from WJE (Figure 6) that detailed the different systems that would be installed at the MMVC. He also delivered the news that WJE had negotiated a contract to create an LEWS for Innergex. They would be using our equipment on the ridge as part of the LEWS. This pictogram serves as a good visual representation of many of the players at Meager.

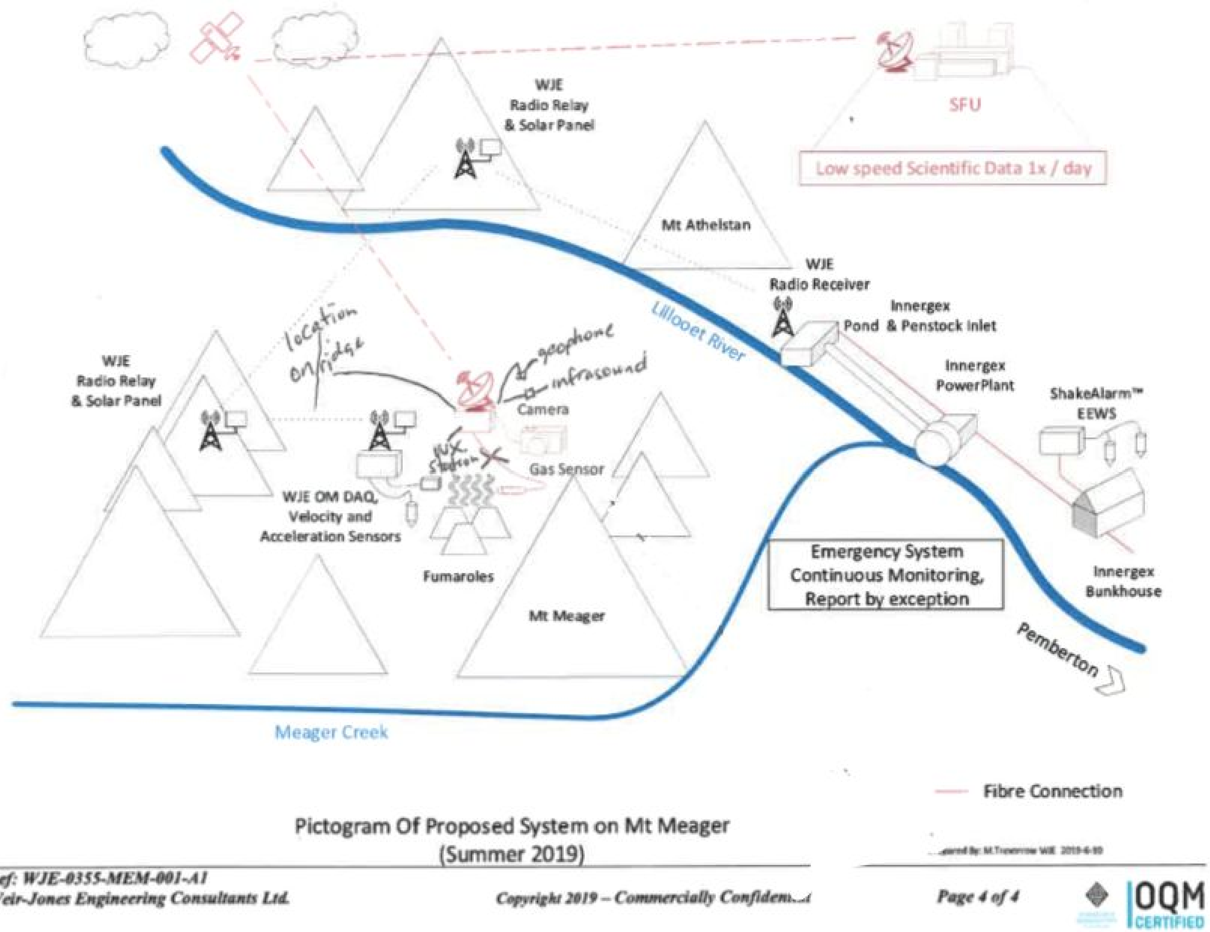
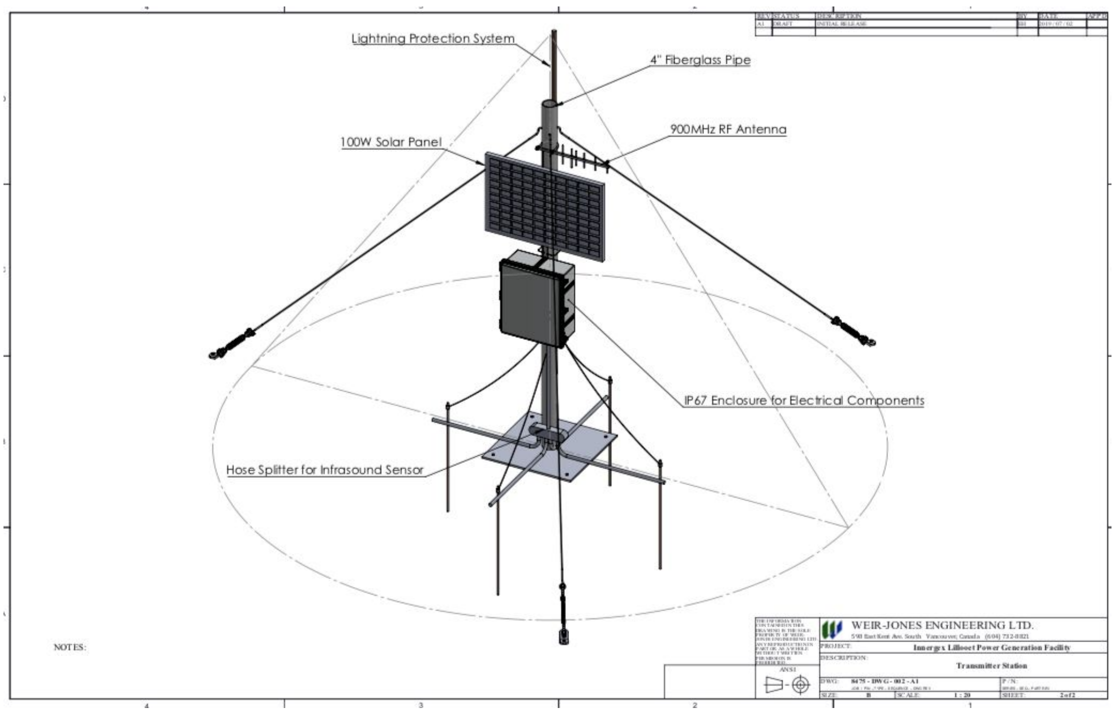


Figure 6: System Pictogram from WJE, with markups by QUC. QUC system is in red.

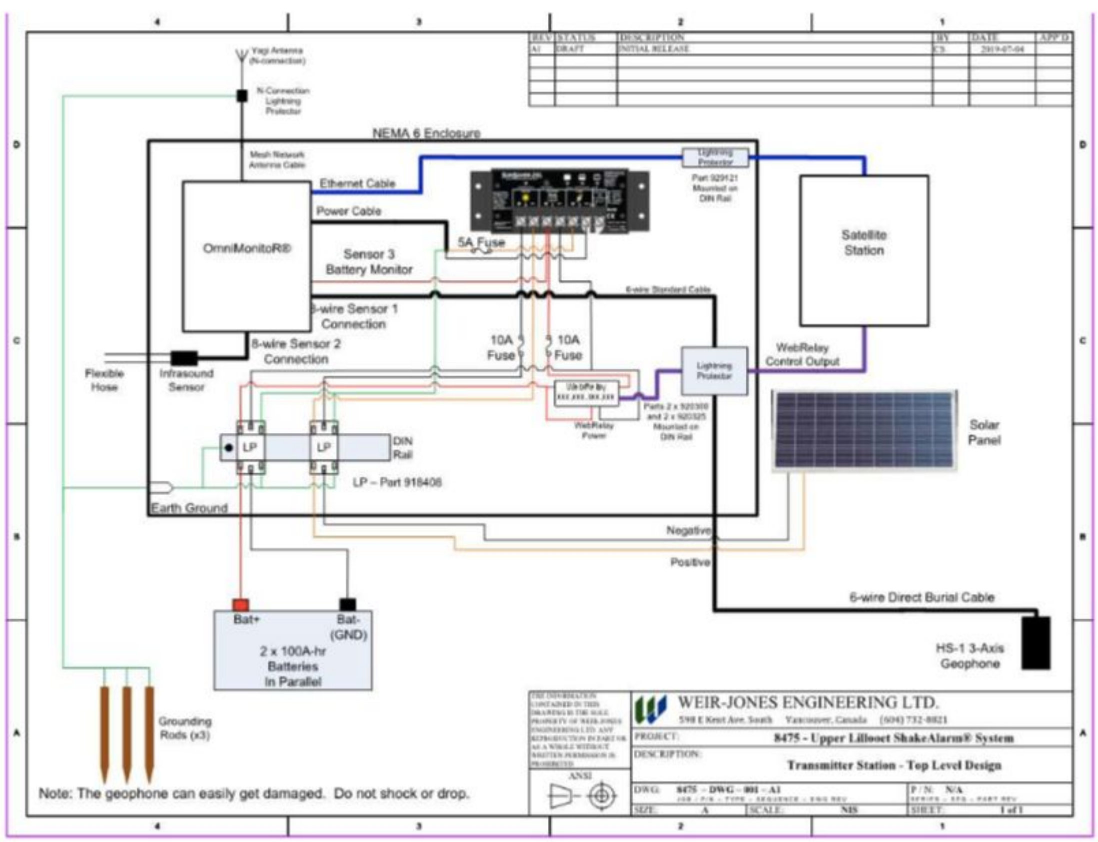
Summary of Work Done/Final Rendition of the System

The bulk of the work done during the duration of the Quest Summer Fellowship Program was in the realm of organization, liaising, and trying to secure funding. The reason for this was that when it comes to actually creating a monitoring system or an alarm system, the people who agreed to help with the project were far better equipped to actually design the componentry, theorize the installation, etc.

Much of what was produced took the form of grant proposals, equipment wishlists, and background research. One field excursion was made, with the purpose of finding ideal locations for the installation of the system depicted in figures 7a and 7b. The results of the field work changed our installation plans slightly, and these results can be found in Appendix E.


Lightning Protection System
4" Fiberglass Pipe
900MHz RF Antenna
100W Solar Panel
IP67 Enclosure for Electrical Components
Hose Splitter for Infrasound Sensor
NOTES:
WEIR-JONES ENGINEERING LTD.
Innergex Lillooet Power Generation Facility
Transmitter Station

A.


Yagi Antenna (N-connection)
N-Connection Lightning Protector
NEMA 6 Enclosure
Mesh Network Antenna Cable
Ethernet Cable
Power Cable
OmniMonitoR®
5A Fuse
Sensor 3 Battery Monitor
8-wire Sensor 1 Connection
8-wire Sensor 2 Connection
6-wire Standard Cable
10A Fuse
10A Fuse
Lightning Protector
Part 929121 Mounted on DIN Rail
Satellite Station
WebRelay Control Output
Lightning Protector
WebRelay Power
Parts 2 x 920300 and 2 x 920325 Mounted on DIN Rail
Solar Panel
Flexible Hose
Infrasound Sensor
LP
LP
DIN Rail
LP – Part 918406
Earth Ground
Negative
Positive
6-wire Direct Burial Cable
Bat+
Bat- (GND)
2 x 100A-hr Batteries In Parallel
HS-1 3-Axis Geophone
Grounding Rods (x3)
Note: The geophone can easily get damaged. Do not shock or drop.
WEIR-JONES ENGINEERING LTD.
598 E Kent Ave. South Vancouver, Canada (604) 732-8821
8475 - Upper Lillooet ShakeAlarm® System
Transmitter Station - Top Level Design

B.

Figure 7: (A) Design of the structure to be located on the ridge facing the Job Glacier and the slope of concern (appendix B, fig. 2, appendix E, fig. 1). Included on the 10 ft pole are a geophone, an infrasound sensor, a camera, a weather sensor, a solar panel, and lightning protection. The pole will be bolted to a concrete block buried in soil. (B). Electrical componentry to be mounted on the pole. Source: Weir-Jones Engineering.

The system in figure 7 is what we will be installing on Meager. At the time of writing, the componentry has been assembled and is being tested. It is based on the work presented in a study by Schimmel et al (2018). They note that alpine mass movements produce discernable seismic and acoustic waves at low frequencies (<30 Hz). As both seismic and acoustic monitoring have proven effective at detecting mass motion, Schimmel et al (2018) were able to combine the two techniques to create a detection system that minimizes false alarms. Their system used one seismic and one acoustic sensor, allowing for a relatively low cost and easily deployable network.

In addition to a geophone and an infrasound sensor, we are including a camera and a weather station. Water is widely recognized as the most common landslide trigger, so we hope that by including a weather station, we will be able to track correlations between mass movements and weather patterns.

There will be 2 modes of telemetry (Figure 6). At Quest, we will receive data at slower speeds through the satellite telemetry from NuPoint systems. WJE will receive near real time data via radio-frequency data links. WJE requires faster transmission speeds because they are using the system as part of an alarm system for Innergex.

We have encountered some difficulty with installation plans- initially, we had planned to install the pole depicted in figure 7 by drilling the baseplate to bedrock, along with the guy wires. However, the field excursion yielded results that were not conducive to that method of installation. On the ridge where equipment will be installed, there is no bedrock to be found. Fortunately, there is an abundance of diggable soil, which will allow us to install by pouring concrete, bolting the base plate to it, then burying it (appendix E).

Complete records of other work completed can be found in the appendices of this report. Documents included are:

- Grant Proposals (WJE, QSFP, SLRD)
- Equipment/componentry requests
- Field work findings

Not included, but relevant are:

- Full literature reviews
- Work/figures done by WJE
- Results of phone calls and in-person meetings

Takeaways

The 3 month window of the QSFP was a small portion of the time that will be spent working on this project. The benefit of having the support of Quest was mainly that it allowed for my concentrated effort on the project during a time that such effort was critical.

I have learned valuable skills and lessons through the fellowship. Because it has been an exercise in organization and interagency communication, I have made leaps and bounds in my abilities to collaborate and liaise with a variety of different groups.

Also, I've witnessed firsthand the beauty of public-private partnership (PPP). We have worked with numerous organizations including universities, private companies, and government agencies, all of whom are committed to making this project happen.

The initial timeline that was proposed was to be determining installation methods in June, installing in July, then analyzing data in August. That timeline elongated to the one shown in the introduction. Though it was meant to be a "research fellowship," reality quickly dictated that the fellowship would be spent setting up the research methods: organizing different people (donors, engineers, helicopter pilots, etc), designing the system, determining the mode of installation, and reading. Analyzing data is yet to come.

So, the first lesson learned was:

"*Plans change, and you will adapt.*"

The initial plan was too ambitious for the amount of work that had to be done, and for the expectations/schedules of the other parties working on this project.

Once I realized that I would not be analyzing data during the fellowship window, I committed fully to helping design the best possible system. This involved a significant amount of collaboration with (and some healthy reliance on) the kind folks at Weir-Jones Engineering and NuPoint Systems. In particular, there were many phone calls with Michael Trevorrow (WJE), Wayne Carlson (NP), and Tony Herunter (NP). As with most of the interactions surrounding this project, I was far and away the least experienced person in the group. I took several things from this dynamic- the first:

"Check your ego."

It can be a little embarrassing to be the least prepared person in the room. That's ok. I learned that hierarchies exist in the world of academia for a reason- all of the people who have helped me have also been in my position. It is one of the big reasons that they were willing to help me in the first place. The other takeaway from this dynamic was:

"Be explicit about what you don't know."

This was critical. From the beginning, I tried to make it very clear that I am a liberal arts student, with good foundational knowledge, but no geophysical background. Despite my initial attempts to make this known to the folks I am working with, there were still several instances in which I had to *check my ego* and simply admit that I felt lost in the discussion. I even went as far as to set up a conference call between WJE and NP, so that they could talk to each other about equipment requirements, and so I wouldn't have to be a go-between.

To me, the biggest takeaway from this project is as follows:

"If you want something, ask for it."

I have been blown away by the support for this project so far. That being said, almost all of the support has been given because we asked for it. Our primary supporter, Weir-Jones Engineering, gave us money and equipment partially because they were interested in the project, but also for more philanthropic reasons. The founder and president, Iain, saw the value in supporting undergraduate research.

The helicopter time that was used for the reconnaissance mission in August was donated by Steve Grasby of NRCAN, and he donated it because we asked.

The QSFP offered support because I took the time to convince them that the project was worthwhile. Through this *"just ask"* mantra, I have had a fair bit of practice in writing the kind of documents that aim to convince folks to support a project such as this. I've written several grant proposals and applications, as well as countless emails asking people for help. There is an art to showing people that your work is worthwhile, and I believe that I am a few steps closer to mastering it.

Another big skill that I had the chance to practice was public speaking. A month into the fellowship, I gave a 45 minute talk to the other fellows and the Quest Faculty. This was beneficial for a few reasons- I got valuable feedback about the project, but it was also the first time I had prepared a presentation of that length. I was able to get into the details of the project, which forced me to synthesize and organize my thoughts. I will definitely be pursuing more presentation opportunities as they can provide helpful deadlines and decentivize procrastination.

Moving Forward

Though the fellowship is ending, the project itself is still in formative stages. The next academic year will be dedicated to the completion of this project, and it will ultimately form my Keystone.

The next immediate step is to install the equipment at Meager. This will involve several separate efforts. The first is a dry run of the install down in Vancouver at the WJE office. This will ensure a smooth and efficient installation on the mountain. The actual installation will be comprised of several days of work. The mountaintop installation will be over 2 or 3 days, though the actual work will not take as long. It is important to leave a weather window when working with helicopters. Once the site on the mountain is finished, the equipment that will be informing my system is finished. However, I will also be assisting

WJE in installing their equipment at the Innergex bunkhouse and at the repeater sites. These sites, along with mine, will provide the data and communications necessary for the Innergex alarm system.

Once everything is up and running, I will begin looking at data. I am taking two independent studies in the fall- one in September to allow for installation and plenty of reading, and one called "Digital Techniques in Geoscience" in November. I plan on using the second IS to help me begin understanding how to unpack my data.

After that, broadly, I will be writing my keystone.

Overall, the fellowship (and more broadly this project) has been far and away the most rewarding academic experience of my life. I have been stimulated and pushed to exercise my mind at all times, and that feels wonderful.

Sources

Allstadt, K. (2013). Extracting source characteristics and dynamics of the August 2010 Mount Meager landslide from broadband seismograms. Journal of Geophysical Research: Earth Surface, 118(3), 1472-1490. doi:10.1002/jgrf.20110

CBC. (2018, November 5). Over the volcano [Press release]. Retrieved from https://newsinteractives.cbc.ca/longform/mount-meager-eruption-risk

Friele, P. (2012, March 10). Volcanic Landslide Risk Management, Lillooet River Valley, BC: Start of North and South FSRs to Meager Confluence, Meager Creek and Upper Lillooet River. (Canada, Ministry of Forests, Lands and Natural Resource Operations).

Friele, P., Jakob, M., & Clague, J. (2008). Hazard and risk from large landslides from Mount Meager volcano, British Columbia, Canada. Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, 2(1), 48-64. doi:10.1080/17499510801958711

Government of Canada, N. R. C. (n.d.). How can we tell when a volcano will erupt and how do we prepare for an eruption? Retrieved February 8, 2019, from http://chis.nrcan.gc.ca/volcano-volcan/how-comment-en.php?wbdisable=true

Highland, L., Bobrowsky, P. (n.d.). USGS Circular 1325: The Landslide Handbook—A Guide to Understanding Landslides. Retrieved May 30, 2019, from https://pubs.usgs.gov/circ/1325/

Keefer, D. K. (n.d.). *Landslides caused by earthquakes*. 16.

Landslide at Joffre peak, no injuries or fatalities reported | Watch News Videos Online. (n.d.). Retrieved June 22, 2019, from Global News website: https://globalnews.ca/video/5273224/landslide-at-joffre-peak-no-injuries-or-fatalities-reported/

Manconi, A., Coviello, V., Galletti, M., & Seifert, R. (2018). Short Communication: Monitoring rock falls with the Raspberry Shakes. Earth Surface Dynamics Discussions, 1-12. doi:10.5194/esurf-2018-62

Noel, A. (n.d.). Risk rising. Retrieved January 24, 2019, from https://www.piquenewsmagazine.com/whistler/risk-rising/Content?oid=10617939

Petley, D. (2019, May 21). Joffre Peak: Temperature and satellite data suggest progressive failure. Retrieved June 22, 2019, from The Landslide Blog website: https://blogs.agu.org/landslideblog/2019/05/21/joffre-peak-temperature/

Posner, Georgakakos. An Early Warning System for Landslide Danger. (n.d.). Retrieved June 4, 2019, from Eos website: https://eos.org/project-updates/an-early-warning-system-for-landslide-danger

Read P B, 1978. Meager Creek geothermal area. *Geol Surv Can, Open-File 603*, 1:20,000 geol map and text.

Retrieved from https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/natural-resource-use/resource-roads/local-road-safety-information/sea-to-sky/volcaniclandsliderisk management.pdf

Roberti, G. (n.d.). (PDF) Landslides and glacier retreat at Mt. Meager volcano: hazard and risk challenges. *Geohazards*. Retrieved from https://www.researchgate.net/publication/325582001_Landslides_and_glacier_retreat_at_Mt_Meager_volcano_hazard_and_risk_challenges

Schimmel, A., & Hübl, J. (2015). Automatic detection of debris flows and debris floods based on a combination of infrasound and seismic signals. *Landslides*, *13*. https://doi.org/10.1007/s10346-015-0640-z

Segoni, S., Piciullo, L., & Gariano, S. L. (2018). Preface: Landslide early warning systems: monitoring systems, rainfall thresholds, warning models, performance evaluation and risk perception. *Natural Hazards and Earth System Sciences*, *18*(12), 3179–3186. https://doi.org/10.5194/nhess-18-3179-2018

Statistics Canada. 2017. Pemberton [Population Centre], British Columbia and British Columbia

[Province] (table). Census Profile. 2016 Census. Statistics Canada Catalogue no. 98-316-X2016001. Ottawa, ON. Released November 29, 2017.

Vaz, T., Zêzere, J. L., Pereira, S., Oliveira, S. C., Garcia, R. A. C., & Quaresma, I. (2018). Regional rainfall thresholds for landslide occurrence using a centenary database. *Natural Hazards and Earth System Sciences*, *18*(4), 1037–1054. https://doi.org/10.5194/nhess-18-1037-2018

Westen, C. J., Castellanos, E., & Kuriakose, S. L. (2008). Spatial data for landslide susceptibility, hazard, and vulnerability assessment: An overview. Engineering Geology, 102(3-4), 112-131. doi:10.1016/j.enggeo.2008.03.010

Wieczorek, G. F. (n.d.). *LANDSLIDE TRIGGERING MECHANISMS*. 15.

Appendices

Appendix A

Summer Fellows Proposal

In 2010, rock slopes above Capricorn Creek at the Mount Meager Volcanic Complex (MMVC) failed in what became the largest landslide in Canadian history. The event cause $10,000,000 in damage, and while no lives were lost, researchers have postulated that the communities of Pemberton and the Lillooet Valley are still in significant danger of a large runout landslide (Friele et al., 2008).

I propose building, implementing, and networking a seismic monitoring system at the MMVC, using an industry-standard geophone, accelerometer, and infrasound system. Along with collecting and analyzing seismic data, we will create an event detection system that will function as a landslide early-warning system for Pemberton and the Lillooet Valley, and an Innergex run-of-the-river (ROR) power plant.

This project has two main goals: a) academic advancement of our knowledge of the geologic hazards at the MMVC and b) societal awareness of the hazards present at the MMVC and early-warning during potentially catastrophic events. Academically, the design, testing and installation of this system will comprise the majority of the Quest Summer Fellowship time period. Upon successful installation, I will begin analysis of the ongoing seismicity of the area, to understand the distinction between typical seismic signatures for landslide events and volcanic activity. The format and structure of seismic system maintenance, data collection and analysis will be a template for future teams to monitor and analyze this seismic data in a continued effort to prepare for rockfall and landslides, and to monitor volcanic unrest at the MMVC. We are partnering with the Weir-Jones Group, a geophysics firm based in Vancouver who will provide state of the art seismic detection and communications equipment. The primary societal goal of this project is to raise awareness, educate the public in the surrounding area, and involve community in the creation of a comprehensive early-warning system for landslides, rockfall, and volcanic activity in Pemberton, the Lillooet Valley, and the Innergex plant. Our partnership with the expertise at Weir-Jones will allow us to utilize the network we design and implement to create the early-warning system, based on their proprietary Shake-Alarm system.

Seismic detection at the MMVC is needed for several reasons. Heightened volcanic activity in the area coupled with receding glaciers has produced conditions that are likely to increase the frequency of landslides and rockfall at the MMVC, and as a result, Employees stationed at an Innergex ROR power plant face a very real danger. Recent research has identified 27 potential large landslide sites at the MMVC. One site of particular concern is the East flank of Devastation Creek, which is the largest potential damage source identified, and is actively deforming at a rate of approximately 30 mm per month (Figure 1). On a geologic scale, this amount of motion is alarming, and indicates that catastrophic failure of the slope is imminent (Roberti et al 2018). The ROR project is situated directly in the flow path of this slide source. Innergex has 4-5 employees stationed at the plant at any given time, and estimates give the plant approximately 2 minutes before impact once the slope fails. With the new information about the inevitability of massive landslides at the MMVC, Innergex has a responsibility to protect the lives of its employees. Senior management at the corporation recognizes and are committed to addressing this issue, and also have financial incentive to do so. By supporting scientific research and development, they become eligible for a tax credit.

Communities down valley from the MMVC are at risk as well. The populations of Pemberton and the Lillooet Valley are steadily rising (Statistics Canada 2017). Many areas around the world have established acceptable standards of risk pertaining to landslides, and, according to Friele et al., 2008, Pemberton and the Lillooet Valley (near the MMVC) are at risks that far exceed these standards (Friele et al., 2008). Despite this finding, and despite the 2010 damage, the village of Pemberton has no risk management strategies pertaining to landslides. Friele et al., 2008 suggest that simple landslide detection via seismometers is the minimum requirement for responsible long term hazard and risk management.

When Glyn Williams-Jones of Simon Fraser University (SFU) reported three new fumaroles underlying a glacier at the MMVC, the area landed in the media's spotlight. News publications including the *CBC, Pique Magazine,* and the *Vancouver Sun* have published articles in the last five years about activity at the MMVC. Williams-Jones has called for a landslide monitoring system at the MMVC, and the articles mention the lack of necessary seismic monitoring.

While the scope of this project is larger than a typical Quest Summer Fellowship, the support offered by the Weir-Jones group will allow me to scale my involvement to an appropriate level. Weir-Jones are professionals committed to the long-term goals of the project. My main tasks are to assist with siting of the seismic stations, installing and testing the stations and conducting preliminary analysis on the data.

Station locations are being determined by the existence of known bedrock outcrops (mapped by Read et al, 1978), confirmed accessibility to each site (via helicopter or 4-x-4 vehicle), and established line of sight between stations (confirmed using the LiDAR data and the ArcGIS Viewshed tool) (Figure 1).

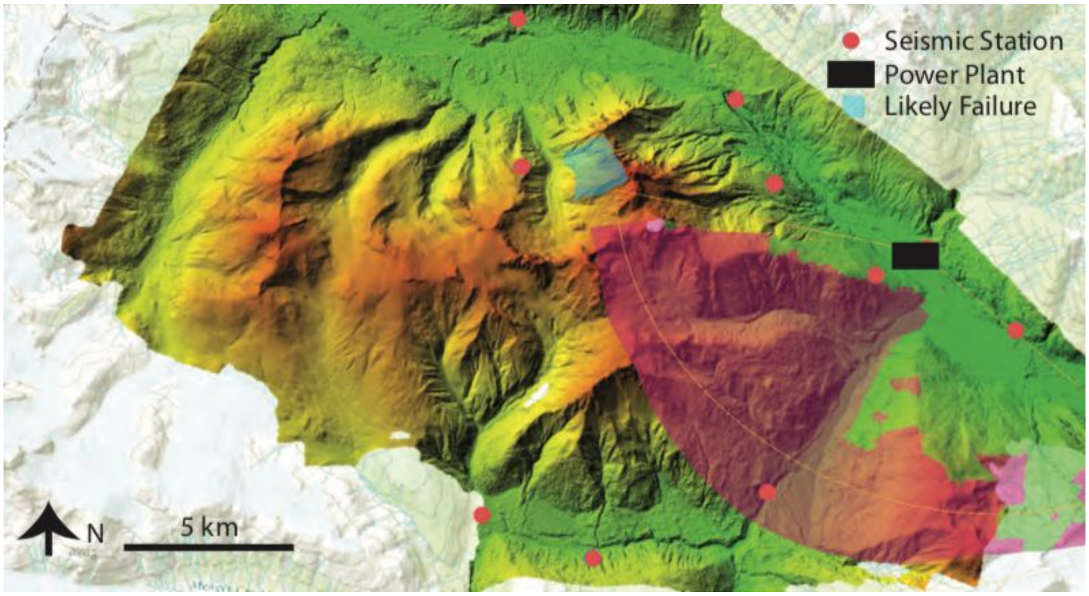


Figure 1: LiDAR Map of the MMVC Monitoring Network. Preliminary Locations of seismic stations were chosen based on known bedrock (Read et al., 1978), and confirmed line of sight. Line of sight was confirmed using the ArcGIS Viewshed tool (example in bottom right displays areas that have line of site (green) and those that do not (red) looking from near the Innergex plant to the Southwest). Stations need to have line of sight to at least one other station in order to complete a radio frequency daisy chain link for communications..

Stations will consist of data collection units (accelerometer, infrasound microphone and geophone), memory cards, reserve batteries, a 6 meter solar tower, and a radiofrequency (RF) data link. Stations will communicate with each other via RF data links, and the data will ultimately be sent to a "home" at the Innergex plant. The plant is equipped with high-speed internet, and will export near-live data. Data will be collected and transmitted on a two tiered system based on importance. Seismic signals of a certain size will trigger an event detection, and will thus be given priority. These signals will transmit immediately to home for use in the early warning system for the Innergex plant and the surrounding communities. All other data is considered non-essential to the early-warning system, and in order to economize bandwidth, it will lag behind several minutes . This data will still be collected, transmitted, and analyzed to explore academic questions about the long-term behavior of the MMVC.

The significance of this project is multi-faceted—tackling fascinating academic questions as well as tangible societal impacts. There is no current monitoring of an active volcano in Canada, due to infrequency of eruptions. (NRCAN, 2018). However, the increased volcanic activity at the MMVC and its recent media attention indicate pressing need for a monitoring network. The seismic monitoring system I plan to implement at the MMVC would become the only monitoring system at an active volcano in Canada, and could serve researchers for years to come.

Current Supporters and Media Opportunities

We have been offered support from the Weir-Jones Group out of Vancouver, who have agreed to provide proprietary equipment (seismometers, RF data links, solar panels, etc), mentorship, and a small honorarium to cover costs such as helicopter time. Additionally, in light of the risk to the ROR plant, senior management at Innergex has indicated that they are supportive of the project, and committed to the safety of their employees. My faculty host, Steve Quane has worked in the MMVC for over 20 years and Glyn Williams-Jones of SFU is at the helm of current research at the MMVC. Steve and Glyn are working together on several natural hazard related projects in the Sea-to-Sky corridor and Glyn has committed to collaborating with us. We have met with Williams-Jones and Weir-Jones, and are currently developing a proposal to present to Innergex for support beyond that being provided by Weir-Jones.

The depth of my involvement with this project would be significantly increased were I to receive support from the Summer Fellowship Program. It would allow me to fully commit myself to the work at the MMVC, but more importantly, it promises to provide substantial future opportunities for Quest. The project will bring media attention to the university, and would be a sustainable opportunity for future students. The MMVC has recently fallen under local and national media spotlights. Given the publicity and Williams-Jones connections, the project promises to draw attention to all involved. The future academic applications of the monitoring network will serve Quest for years to come. The collaborative nature of this project could pave the way for collaboration with graduate students at SFU. The relationships formed could serve students by way of experiential learnings, exchanges, and other research projects. Professors could use data for class projects, students could use the network for future keystones—all while the network serves the public as an active early-warning system for Innergex, Pemberton, and the Lillooet Valley.

Appendix B

Mason Pitchel and Steve Quane
Quest University Canada

Landslide Monitoring at the Mount Meager Volcanic Complex: A Pilot Study

Amount Requested: $5000

Introduction:

In 2010, rock slopes above Capricorn Creek at the Mount Meager Volcanic Complex (MMVC) failed in what became the largest landslide in Canadian history. The event caused roughly $10,000,000 in damage, and while no lives were lost, the communities of Pemberton and Pemberton Meadows are still in significant danger of a large runout landslide (Friele et al., 2008). Recent research has identified multiple slopes on the MMVC that are in danger of failing, but one is of particular concern. This slope is about 10x the size of the source of the slide in 2010, and poses a significant danger to the communities of Pemberton Meadows and the Village of Pemberton (Roberti, 2019). Landslides are quite prevalent in the area, especially at loosely volcanic edifices like the MMVC. Just recently, a large landslide off of Joffre Peak made headlines (CBC, Global News). As we see increasingly warm weather and rapid snowmelt through the spring and summer, we will see an increase in large landslides (Petley, 2019).

Research Plan:

We will be implementing the first rendition of a seismic monitoring system at the MMVC, using an industry-standard geophone and infrasound system, coupled with a weather station and a camera (Figure 1). Data will be transmitted via satellite. Through this project, we will be looking for correlations between weather trends and landslides/rockfall. The primary purpose of this project is academic, but the implications for the SLRD are significant. Our system, based on the work of Schimmel et al (2018), will serve as a proof of concept for an event detection system for landslides at Mount Meager, as well as for the rest of the SLRD. Eventually, this work could be expanded upon to become a Landslide Early Warning System (LEWS).

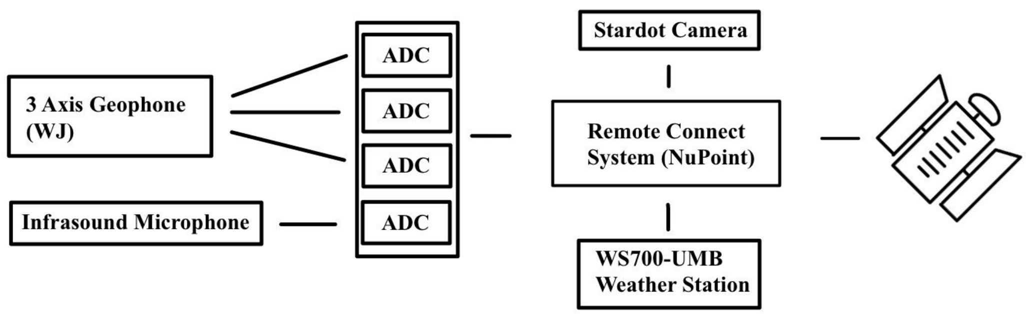


Figure 1: Approximation of componentry of the MMVC monitoring project.

We are partnering with the Weir-Jones Group, a geotechnical engineering firm out of Vancouver. They are providing seismic and acoustic sensors, as well as 5000 dollars to cover extra equipment, and part of the cost of deployment. NuPoint Solutions out of Delta has agreed to donate a camera coupled with a satellite data transmission system. As a separate project, researchers from SFU and UBC will be implementing a MultiGAS system to monitor off gassing from newly discovered fumaroles on the Job Glacier. Their system will share data transmission with ours. Our equipment will be deployed on a ridge facing the slope of concern (Figure 2).

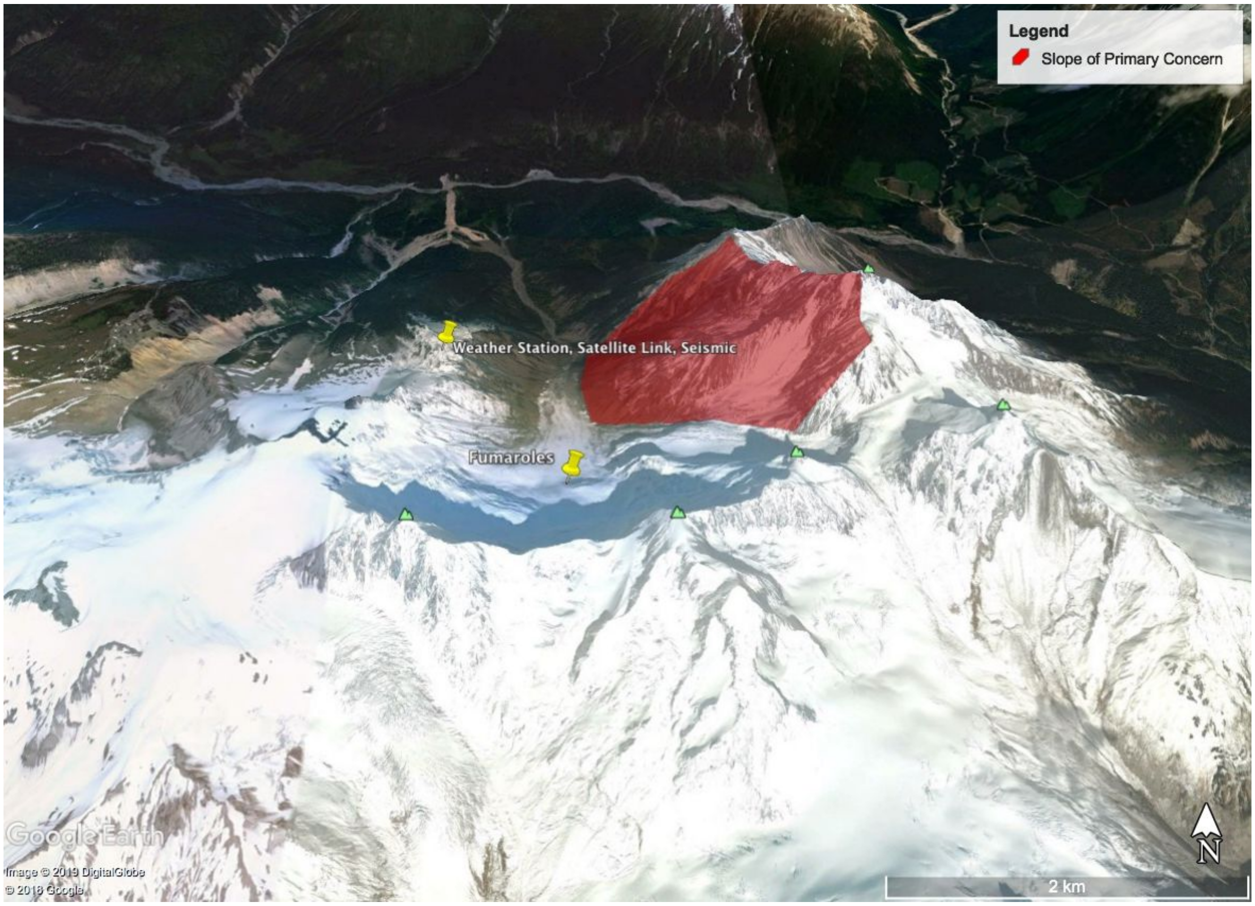


Figure 2: Site Location and Slope of Primary Concern, MMVC. The slope is located on the North-West Flank of Plinth Peak.

Benefits to the SLRD:

The benefits of this project are multifaceted. Aside from tackling fascinating academic research questions, the monitoring system proposed could directly benefit the SLRD. Friele et al., 2008 suggest that simple landslide detection via seismometers is the minimum requirement for long term hazard and risk management. Our system can inform future, more advanced systems that will lead to risk management policies and procedures. While in its current form, the sensors will not support an alarm, this system could be expanded upon to eventually create a landslide alarm for the communities of Pemberton and Pemberton Meadows. This will be the first tangible step towards such an alarm system that the region has seen.

Additionally, research at the MMVC is in a period of rapid growth. The region has seen significant press in recent years. When Glyn Williams-Jones of Simon Fraser University (SFU) reported three new fumaroles underlying a glacier at the MMVC, the area landed in the media's spotlight. News publications including the *CBC, Pique Magazine,* and the *Vancouver Sun* have published articles in the last five years about activity at the MMVC. Williams-Jones has called for a landslide monitoring system at the MMVC, and the articles mention the lack of necessary seismic monitoring. With all of the press, the region has become a literal and figurative hotbed for research in the Sea to Sky. There are a number of exciting new initiatives planned this summer, that will all work in conjunction with each other to get an inside look at what is going on at the active volcano.

With all of the work being done in the area, the time is now to get involved. Not only will this research provide tangible risk management opportunities for the district, it also promises good PR. There is a wonderful opportunity for press around academic, private, and public collaboration. Local and national news has already shown interest in Meager, and the new initiatives promise to bring more attention to the area.

Request and Current Supporters:

We are requesting CAD 5000$ from the SLRD. Currently, we have been granted $5,500 from Weir-Jones and Quest University. This is enough for roughly one helicopter flight into the MMVC with all of our gear and personnel, with a bit extra for necessary instrumentation such as a weather station. We anticipate that this funding will cover the cost of deployment, but it does not leave us any room in our budget for equipment retrieval, repair missions should something become damaged, or any sort of preliminary reconnaissance. The money contributed by the SLRD will ensure a more complete project long term.

Appendix C

Mason Pitchel
11/20/2018

GSA Student Research Proposal

This section should present the problem, hypotheses, and the overall objectives of the project. Please be sure to discuss your figure here, if applicable. (1,000 character limit, including spaces).

I am proposing the implementation of a seismic monitoring system (SMS) at the Mount Meager Volcanic Complex (MMVC) using low cost Raspberry Shake 4D Seismometers (RSS). I hypothesize that heightened seismic activity in the area, coupled with global climate change, will increase the frequency of landslides and rockfall at the MMVC. Capricorn Creek at the MMVC was the site of the largest landslide in Canadian history in 2010. The event cause $10,000,000 in damage, and while no lives were lost, researchers have postulated that the communities of Pemberton and Lillooet are still in significant danger of a large runout landslide (Friele et al., 2008). A comprehensive landslide inventory is necessary in order to be able to quantify both landslide hazard and risk (Van Westen et al., 2008). The goal of this project is to install a seismic monitoring system at MMVC that will record all of the seismic data in the area. The data will be analyzed for trends between earthquakes and landslides, with consideration of the implications for local hazards and risks.

Upload a pertinent, well-organized figure that enhances the proposal. Successful figures will be referenced in the proposal text and include at least: title, stand-alone caption, and a citation if not the original work of the student. If you already have an image on file and upload a new image, the new image will overwrite the old image. Applications without a figure will not be reviewed.

<u>Raspberry Shake Sample Data and Deployment Method</u>

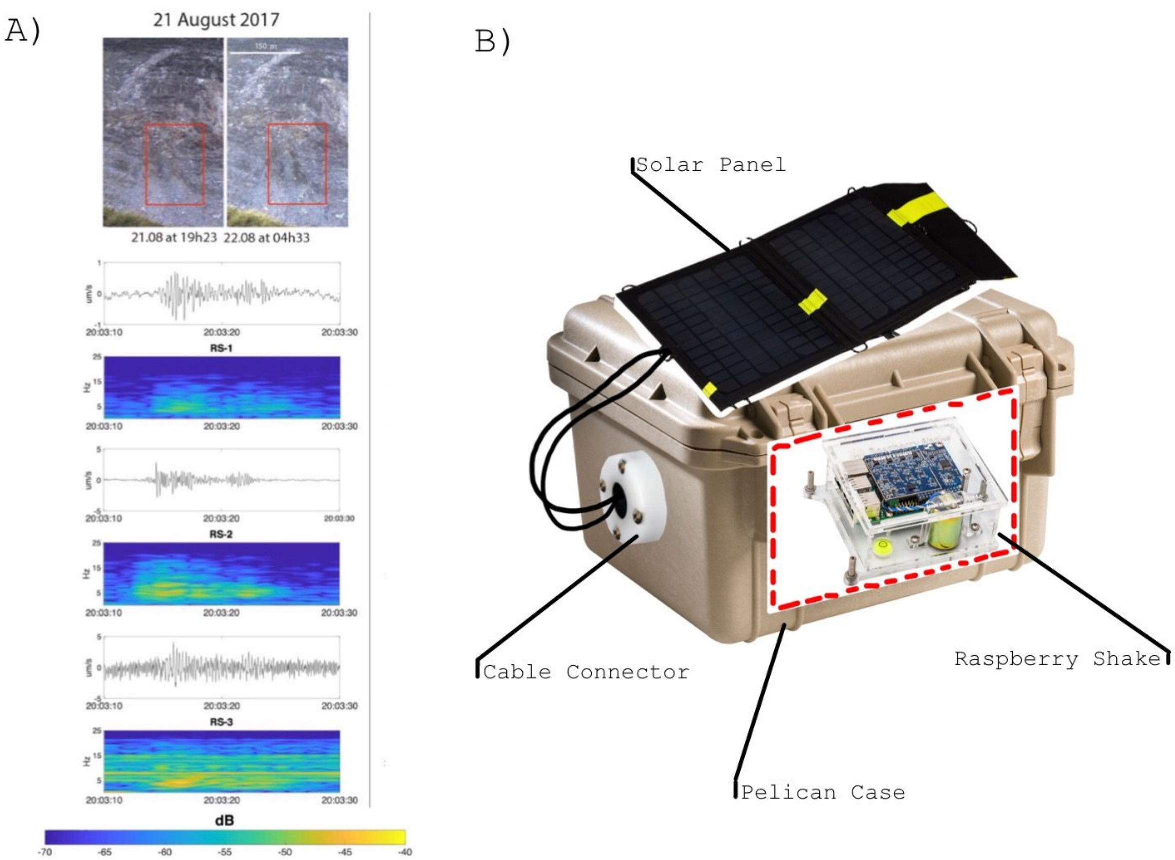


Figure 1A: Signal associated with rockfall event. Signal is band-pass filtered (Butterworth) between 0.5 and 15 Hz. Time is in UTC. Note the large noise level at the station RS-3 caused by the cable car operations mainly during the day of 21 august 2017. Pictures acquired from the webcam before and after are shown at the top of the event. Red rectangles indicate alocations of rock fall events in the imaged slope area. (Manconi et al., 2018). I chose this figure from Manconi's work because of its' clear representation of data obtained via RSS. Figure 1B: Field deployment strategy of RSS.

This section should discuss the scientific and societal significance; what is the importance of this project? Please be sure to discuss your figure here, if applicable.(2,500 character limit, including spaces).

Mt. Meager is known to be the most unstable mountain in Canada. Friele et al note that poorly lithified and hydrothermally altered rocks create the potential for edifice collapse at volcanoes. The sources of the major edifice collapses at MMVC are hydrothermally altered rocks in the Angel, Devastation and Job Creek basins. Large masses of unstable volcanic rock still exist at MMVC. 8 years ago, Capricorn Creek (not identified by Friele) slid in a massive landslide, demonstrating that the warnings are real, and that events are unpredictable. Work is currently being done with high resolution GPS imagery to identify slope stability and immediate dangers (Roberti, PhD Unpub., 2008). More recently, heightened volcanic activity on the north flank of Mt. Meager has been observed. Glyn Williams-Jones of SFU has reported 3 new fumaroles underlying a glacier, and has called for a landslide monitoring system at Meager.

With Williams-Jones' recent work, MMVC has been thrust into a public spotlight. News publications such as CBC and the Vancouver sun have published articles about the activity at MMVC. The articles mention the lack of necessary seismic monitoring.

Prior to the 2010 slide, work was done assessing the risk and hazard from landslide to the nearby communities. Many areas around the world have worked to quantify acceptable levels of risk from natural hazards. The Lillooet Valley (near Meager) is at risks 5.4x greater than deemed acceptable to areas that have risk management strategies in place (Friele et al., 2008). The risk management strategies that have been recommended for Meager Creek only pertain to zones in close proximity to the source. The village of Pemberton has no risk management strategies pertaining to landslides, and Friele et al. suggest that simple landslide detection via seismometers is the minimum requirement for responsible long term hazard and risk management.

According to Van Westen et al., landslide inventory is absolutely essential for quantifying landslide hazard and risk. A complete record at MMVC does not exist. While high resolution imagery is the best option for landslide mapping, the high costs of such systems can be limiting for certain study areas. Using Raspberry Shake seismometers is a low cost, easily deployable, modular system for monitoring which can detect landslides, and could provide a landslide catalogue in the future. A framework for monitoring and deployment has already been developed by Manconi et al.

This section should concisely state your research plan and how it will test your hypothesis stated above. Please be sure to discuss your figure here, if applicable. (2,500 character limit, including spaces).

I will deploy an array of weatherproofed RSS at Mt Meager with the goal of monitoring all seismic activity in the area. The location of deployment will be determined by on-going research by Gioachino Roberti, as well as previous work by Friele et al. Potential locations currently identified are the Angel, Devastation and Job Creek basins, and the North flank of Mt. Meager. Locations chosen must be accessible and conducive to easy retrieval, on stable ground (i.e. bedrock), and have minimal tree cover. The RSS will be powered with Solar panels and contain memory cards to record data (Figure 1b).

This is a pilot study, and the first rendition of a monitoring system at Mt Meager. The goals of this study are to create an accurate catalogue of landslides during the data collection window, and to answer the question: "Does an increase in volcanic seismicity lead to an increase of landslide events at MMVC?" This will be answered by monitoring for all seismic data, and analyzing trends from different signatures recorded.

Seismicity is typically considered to be ground vibrations caused by earthquakes, but as Manconi et al note, landslides and rockfall can register on seismometers as well (Figure 1A). They state that recognizing the seismic signature of an earthquake is important, as an earthquake can trigger rockfalls and landslides. As earthquakes, landslides, and rockfalls all produce different seismic signatures, seismic monitoring is an important method of understanding the interplay between them, and thus the associated risks and hazards of living in seismically active areas.

Though the RSS will not live-update data, the comprehensiveness of the system will be an improvement from point-in-time field observations used today. The data will also be cross referenced with publicly accessible local climate data, which is a contributing factor to slope failure.

The nature of this system allows for it to include live data in the future, and could be used as an early detection system for landslides, serving the residents of Pemberton and Lillooet. More funding and infrastructure is needed. Another improvement would be to incorporate imaging technology, such as webcams or cameras set on timers, to visually confirm whether or not a rockfall or slide actually occurred (before/after images).

RSS will be deployed at the beginning of the summer 2019, re-visited midsummer, and data will be collected in the fall for analysis before access becomes too difficult.

Budget Justification: In this section, explain the need for each item in your budget for which you are requesting funding from GSA. Also, be sure to provide a specific cost breakdown for each item. For example, if you are including the cost of food needed in the field, specify the number of days food would be needed and the daily cost of the food ("10 days at $12/day, for a total of $120"). (1,200 character limit, including spaces):

- Turnkey IoT Home Earthquake Monitor RS 4D: USD $499.99 x 3. Primary component of monitoring system.
- Pelican 1300 Protector Case: USD $70 x 3. Used for weatherproofing RSS.
- Goal Zero Nomad 7 Plus: USD $99.95 x 3. Used to power RSS.
- Blue Sea 1001 Waterproof Cable Clam: USD $24.95 x 3. Used for weatherproof connection of RS and Solar.
- Petzl Irvis Crampon: USD $122.86. For safe glacier travel.
- Petzl Summit Evo Ice Axe: USD $140. For safe glacier travel.
- Gas Money Return to Mount Meager: $50 x 3. 3 trips needed to Meager for set up, check in, and break down.

Total: USD $2497.53

Duration of investigation:

June 2019 - September 2019

Amount and nature of other available funds, facilities, materials, etc. (1,200 character limit, including spaces):

Available: Necessary backcountry gear, vehicles, gps, tools needed for assembly and installation of RSS.

Abbreviated resume. List education, major positions held, and significant accomplishments. Provide information relevant to your qualifications to undertake proposed research. List up to 5 of your publications and presentations (2,500 character limit, including spaces):

EDUCATION

Quest University Canada, Bachelor of Arts and Sciences (2015-Present)
Relevant Courses: Earth Systems and Human Impacts, Experiments in the Physical Sciences, Earth Materials, Field Geology, Volcanology, Plate Tectonics of Western North America, Research in Earth and Environmental Science.

OTHER
10+ years technical experience in backcountry settings including hiking, backpacking, class 5 rock climbing, rope systems, etc.
Attended GSA annual meeting in Indianapolis, 2018.

Appendix D

Preliminary Technical Requirements Assessment for Seismic Monitoring at Mt. Meager

Steve Quane and Mason Pitchel

Introduction

This report comprises a preliminary assessment of the technical requirements for a seismic network at Mt. Meager Volcano, British Columbia. It is in response to the initial meeting for the joint project between Wier-Jones Engineering Consultants (WJEC), Quest University Canada (QUC) and Simon Fraser University (SFU). To date, the principles for the project are Iain Weir-Jones, Chris Sellathamby and Anton Zaicenco (WJEC), Steve Quane and Mason Pitchel (QUC) and Glyn Williams-Jones (SFU). At our initial project meeting, it was decided that we wanted to develop a multi-tiered project proposal. The rationale for such a proposal is two-fold. First, we want to guarantee that some preliminary seismic work gets done this summer at Mt. Meager as part of Mason Pitchel's undergraduate degree project (tier 1), we also want to propose an event-detection system to Innergex that included the minimum necessary for them to develop an event-detection, early-warning system for their run-of-the-river facility at Pebble Creek (tier 2) and a robust seismic monitoring system for the Mt. Meager area that will monitor all seismic activity whether generated by landslide, tectonic movement or volcanic activity (tier 3). Here, we present preliminary locations and system requirements for each of the three tiers in order for further technical analysis, siting and costing decisions to be made by the team. Please note that the suggested components and siting locations for each tier are preliminary and meant as the start of a discussion as we determine the best setup for each tier based on technical requirements and limitations.

Seismic Station Locations

Our preliminary sites for locations of seismic stations are seen in Figure 1. They are numbered 1-10 or reference (note: these are not priority distinctions). Our preliminary site decisions were based on a combination of the following: a) location of exposed bedrock (mapping by Read et al., 1978), access by either helicopter or 4x4 vehicle c) proximity to potential landslide events d) coverage of areas that will most likely affect the Innergex run-of-the-river plant and e) line of sight access between stations in order to relay signals to the Innergex plant building. It should be noted here that site locations are preliminary, and more work needs to be done in terms of line of sight viewsheds (ArcGIS) and in field site verification. Due to the rugged terrain and limited access to the area, it is expected that the locations of most of the sites will be modified to meet the criteria necessary for proper function (proper access, solid bedrock platform, line of sight to either Innergex plant or other station). It is expected that in-field site adjustments will need to be done prior to deploying the network. Nine of the ten stations (1-9) are proposed to be stationed on bedrock with line of sight to at least one other station, while station 10 will be on glacial ice or at the head of the Job glacier. A weather station is proposed at site 1 which is located across the valley from the slope that is deemed most likely next to fail in the region. The slope has shown ~3 cm per month movement in recent summer seasons (Roberti et al., 2018; Figure 1).

Seismic Station Components and Data Transfer Requirements

In this project, we propose to use the following componentry: 3-axis geophone, 3-axis accelerometer, infrasound microphone, GPS and broadband seismometer. The amount of componentry at each location will be determined by project tier choice and funding priorities. The mass movements that we want to detect in order to create an event-detection/alarm system emit seismic and acoustic waves of <50 Hz (e.g., Schimmel et al, 2018). Therefore, we propose a sampling frequency of 100 Hz to ensure full spectrum detection during mass movements. Figure 2 outlines a partial system setup and components to help determine the data transfer requirements in order to build a real-time event-detection/alarm system. Different data transfer requirements will be needed based on the chosen tier for the monitoring system. Assuming 24- bit analogue to digital conversion (ADC), each channel will need 2400 bit/s. For a full seismic station with all the components sampling channels at 100 Hz, it is possible to need 24,000 bits/s data transfer. It should be noted, however, that not all data needs to be transferred immediately. Only data within a given time of an event (i.e., 10s before and after a magnitude trigger) are necessary immediate transfer to the event-detection algorithm. Other data, used for research purposes, can be sent at slower rates.

Project Tiers

Here, we present three tiers of project for discussion. Ultimately, the choice for deployment f a tier will be determined by project needs and funding.

Tier 1

This tier is designed to be the minimum project that will be deployed in Summer, 2019. If chosen, this tier can serve two main purposes; a) provide an undergraduate research experience for Mason Pitchel and b) serve as a proof-of-concept for seismic monitoring and event detection at Mount Meager to be used in further proposals to Innergex and the village of Pemberton. This tier will consist of two seismic stations. Site 1 from Figure 1 will be included. It will comprise a 3-axis geophone, infrasound microphone, GPS and weather station. Sampling at 100 Hz the maximum data rate needed will be 14,400 bits/s for real time data collection. The other station will comprise a 3-axis geophone, infrasound microphone and GPS. These stations can potentially be sited and deployed in June, 2019. Alongside each station, we propose to place a low-cost Raspberry shake style seismometer to test their viability in mountainous terrain under relatively harsh conditions (note: these would be removed in September, prior to snowfall).

Tier 2

This tier is designed to be the minimum deployment needed for event-detection for the Innergex plant, focusing on potential failure from the slope identified by Roberti et al., 2018. We propose stations at sites 1-5. The setup is modelled after that of Schimmel et al., 2018. All sites will have 3-axis geophone, infrasound microphone and GPS. Sampling at 100 Hz, the event-detection system will require 14,400 bits/s of data transfer.

Tier 3

This tier comprises a robust event-detection/alarm system for the Mt. Meager area (beyond the slope identified by Roberti et al., 2018) as well as broader scientific monitoring of landslides as well as tectonic and volcanic earthquake activity. We propose deployment at sites 1-10 including a weather station at site 1 and an on-ice station at site 10. We propose each site have a 3-axis geophone, 3-axis accelerometer, infrasound microphone and GPS. In addition, we propose two broadband seismometers in order to detect lower frequency, volcano seismicity. For event-detection, each station would have a maximum data transfer rate need of 19,200 bits/s.

Discussion

What we present above is meant to be the basis of discussion for our ongoing project collaboration. Indeed, the technical specifications above need to be affirmed by other members of the team. It is likely, that efficiencies can be made in data transfer by combining signals in the ADC conversion or using smaller bits conversions (GPS, for example). In addition, the tiers are suggestions and can be modified to meet project needs as they develop and mature.

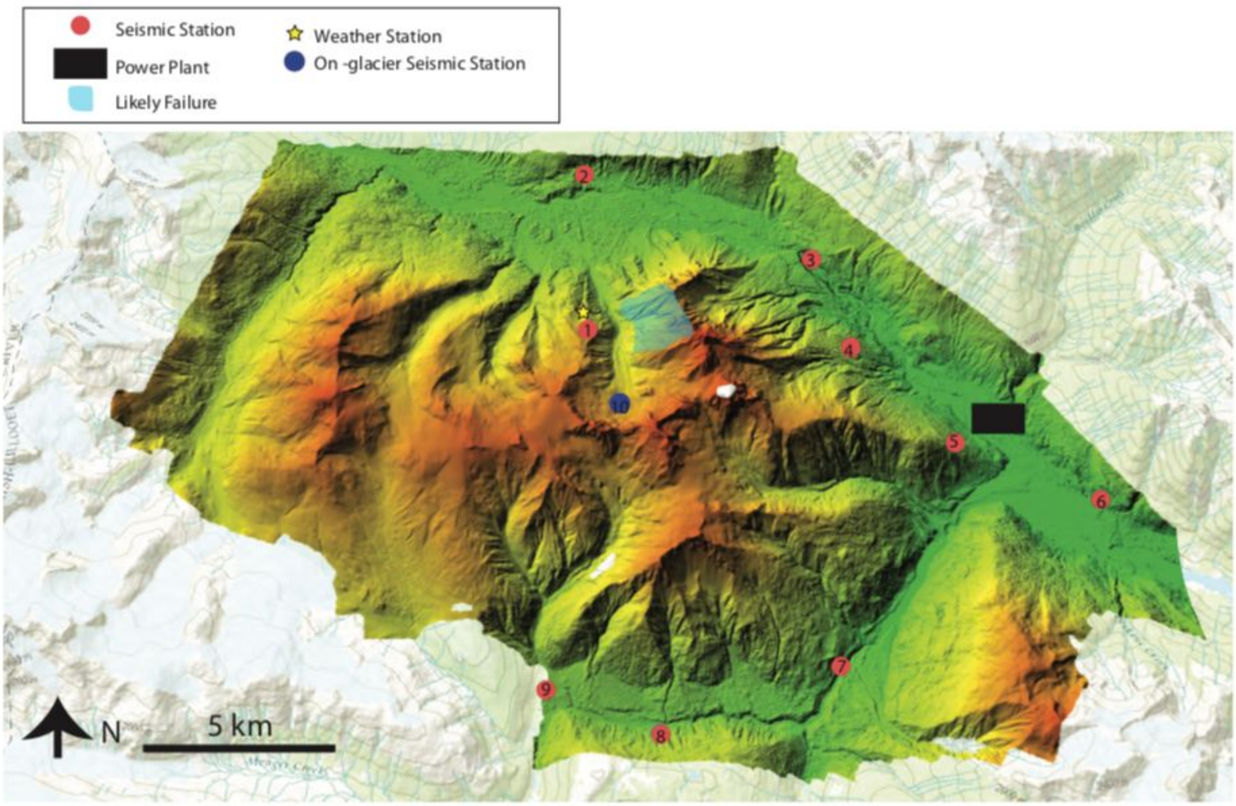


Figure 1: LiDAR Map of the MMVC Monitoring Network. Preliminary Locations of seismic stations were chosen based on known bedrock (Read et al., 1978) and preliminary line of sight analysis.

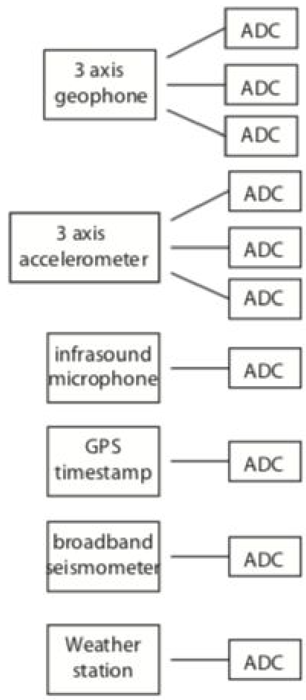


Figure 2: Overview of potential components and data transfer specifications. ADC are 24 bit and proposed sampling rate is 100 Hz.

Appendix E

Meager Field Work Summary

On July 20th, 2019 Mason Pitchel (QUC) and Steve Grasby (NRCan) flew from the Innergex base camp to the ridge on the western flank of the Job Glacier with the goal of siting a location to deploy a camera, weather station, geophone, and infrasound sensor. The ideal location would have line of site to both the slope of concern and to a repeater location located in the Lillooet River valley. It would also have ample bedrock to allow the equipment to be bolted in place.

Line of sight proved to be a non-issue, while bedrock was determined to be wholly absent from the location.

An alternative was established: diggable soil, with buried concrete or a metal plate (similar to a snow anchor). With this new criteria, 3 potential locations were identified. The characteristics of each are displayed in table one. 2 of 3 locations have adequate line of sight, while one had several large boulders that could potentially serve as anchors.

	Location 1	Location 2	Location 3
Pros	Best Line of Sight. Diggable Soil. Relatively wind protected. Flat ground.	Diggable soil. Relatively wind protected. Boulders could provide anchors.	Good LOS. Diggable Soil. Could be less snowpack.
Cons	No bedrock, few boulders.	No bedrock, No clear LOS for KMZ option 3.	Steeper, windy.

Table 1: Pros and cons of Locations

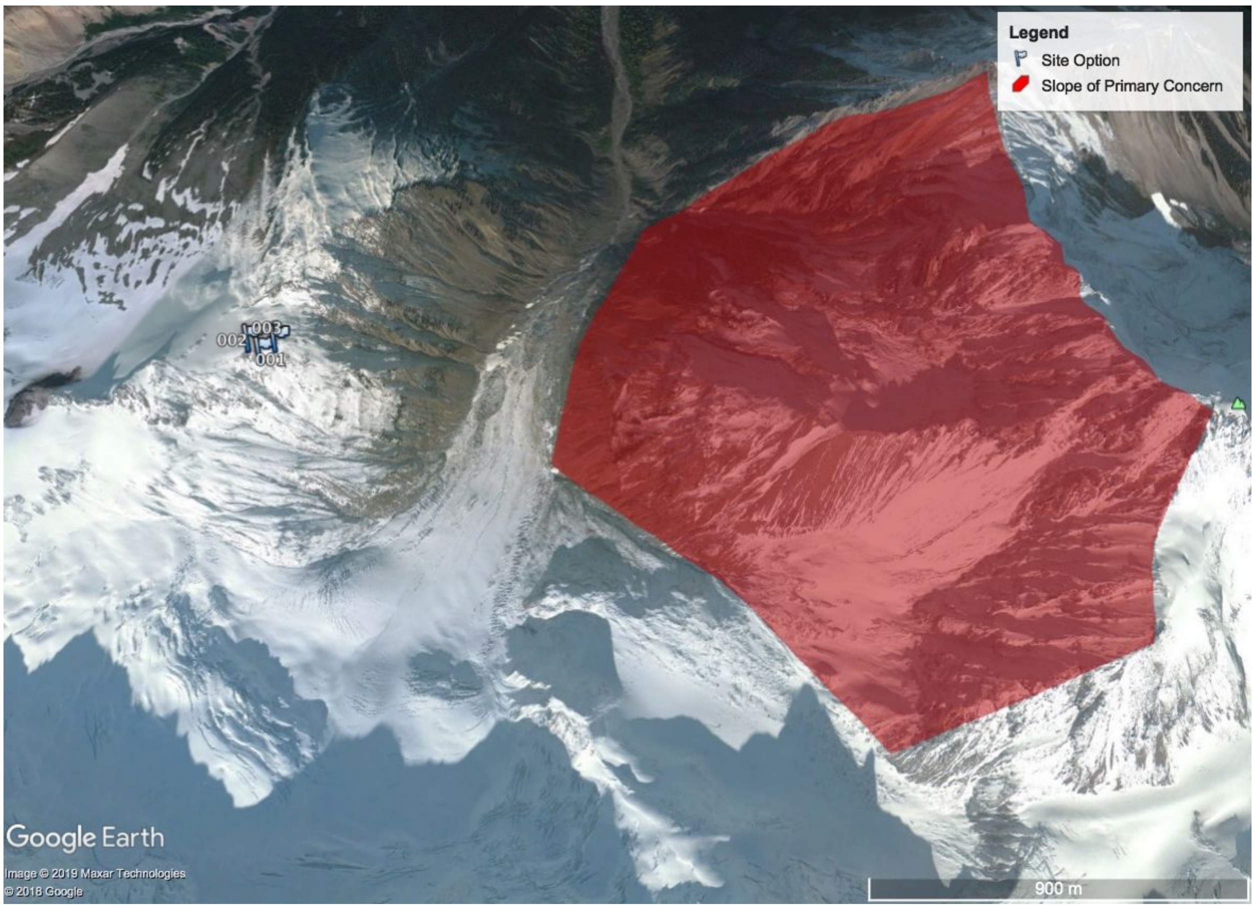


Figure 1: Site Options.

Location 1 seems to be the best combination of relatively sheltered with a flat aspect and diggable soil.

Location 1:

Steve Grasby holding a shovel to give an idea of what a 10 foot pole would look like. Slope of concern to the right hand side of the photo, good LOS to valley bottom on the left.

Decent wind shelter provided by small ridge.

Location 2:

(Poor Image Quality): An idea of the welded material that the boulders on site are composed of.

Slightly poorer line of sight.

Perfect view of Slope of Concern.

Location 3:

Good LOS, good view of slope, More wind exposed.

Appendix F

Weir-Jones Equipment / NuPoint Equipment Wishlist

Alpine mass movements produce discernable seismic and acoustic waves at low frequencies (<50 Hz). As both seismic and acoustic monitoring have proven effective at detecting mass motion, Schimmel et al (2018) were able to combine the two techniques to create a detection system that minimizes false alarms. Their system uses one seismic and one acoustic sensor, allowing for a relatively low cost and easily deployable network.

The focus of the Quest research at Mt. Meager should be on landslide detection rather than landslide prediction. Improvements and upgrades to the system proposed here can help inform prediction in the future. Detection is quite relevant to the region, because of Meager's long distance to habited areas (~75 km).

Based on the work presented by Schimmel et al (2018), I would advocate for using a similar combination of seismic and infrasonic sensors.

From Weir-Jones, we are requesting a tri-axial geophone, 4 ADC's, and an infrasound microphone. The geophone with the lowest frequency range should be chosen to accurately capture signals from landslides and other mass movements. The infrasound microphone should be in the range of ≤ 20 Hz - ≥ 100 Hz. We are also requesting GPS time synchronization.

Ideally, the data from the WJ equipment will be linked with data from a camera and weather system linked with satellite telemety donated by Nu-Point systems, to allow for several angles of monitoring. The NuPoint equipment will be ready at SFU in early July.

The NuPoint Remote Connect satellite link system is compatible with SDI-12 over RS485 connections.

The componentry could be linked as shown in figure 1.

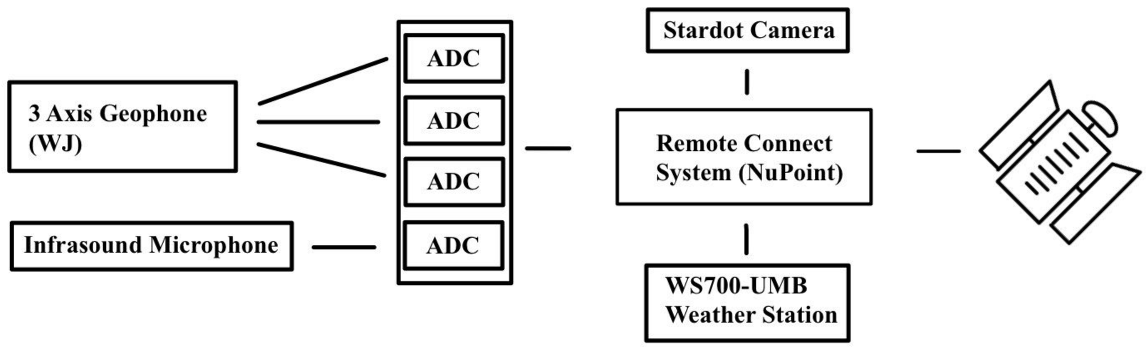


Figure 1: Proposed componentry for the QUC-MMVC landslide monitoring system

The mass movements that we want to detect emit seismic and acoustic waves of <50 Hz (e.g., Schimmel et al, 2018). Therefore, we propose a sampling frequency of 100 Hz to ensure full spectrum detection during mass movements. Assuming 24- bit analogue to digital conversion (ADC), each channel will need 2400 bit/s.