Comprehensive Volcanic-Hazard Map for Mount Meager Volcano, Southwestern British Columbia (Part of NTS 092J)

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Introduction

The Mount Meager Volcanic Complex, located in southwestern British Columbia (BC), has a 2 million year history of intermittent explosive volcanism (Read, 1990). It is currently in a state of quiescence, the last eruption having occurred 2360 calendar years BP from the Bridge River vent on the flank of Plinth Peak. It currently has an active hydrothermal system manifested by two fumaroles and multiple hot springs. The fumaroles were detected in 2016, breaching the surface of Job Glacier on the western flank of Plinth Peak (Venugopal et al., 2017; Roberti et al., 2018), indicating that the volcanic system is not extinct. A hazard and risk assessment was completed by Friele et al. (2008) and Friele (2012) to address the landslide risk at Mount Meager. Currently, there is no volcanic-hazard assessment outlining the multifaceted hazards to expect from the next phase of volcanic activity at this complex. This project, therefore, focuses on the volcanic hazards that are inherent to Mount Meager, exempting landslide hazards not directly related to eruptive activity.

Volcanic-hazard assessments are a principal resource that communities, policy makers and scientists use in an effort to understand the spatial and temporal scales of associated hazards (Calder et al., 2015). They are a useful tool for informing building codes and the development of community- and emergency-response plans that need to take into account mitigation strategies in the context of risk management.

Volcanic-hazard assessments are often based on the volcano's eruptive history, thus requiring accurate information about the hazard types, magnitudes and frequencies of eruption episodes (Stasiuk et al., 2003). For this project, however, a base level of knowledge for these characteristics is limited. The geological footprint of the last explosive eruption from Mount Meager has been well documented and mapped, and inferences have been made from the deposits from older volcanic activity throughout the complex (Read, 1990; Hickson et al., 1999). However, data from only one past eruption is insufficient to develop a volcanic-hazard assessment based purely on the geology of the system.

The aim of this project is to develop a numerical-modelling–based volcanic-hazard assessment informed by the documented deposits of the last eruption at Mount Meager, and analogous volcanic systems that have well-documented eruptions. While all volcanoes are unique, reasonable inferences can be applied to Mount Meager based on the studies of similar volcanic settings. For the most part, this will be a deterministic hazard assessment, meaning that hazards and scenarios will be categorized in accordance with the 'most likely' events to occur in a future eruption. Ideally, the approach would follow a probabilistic framework, given that a probability of occurrence does exist for multiple scenarios and hazard types (Rouwet et al., 2017). However, this requires in-depth knowledge of the volcano's history and a baseline understanding of its volcanic activity (Newhall and Hoblitt, 2002), which does not exist at Mount Meager. This project will provide insight into what can be accomplished and delivered in a volcanic-hazard assessment despite limited data on a volcano's geological history.

The completed volcanic-hazard assessment for Mount Meager will be of use to agencies and managers at regional, provincial and federal levels. This includes Squamish-Lillooet regional district managers, the Lil'wat Nation community, Emergency Management BC, and the Canadian Hazard Information Service (CHIS) and Public Safety Geoscience Program of Natural Resources Canada (NRCan). The hazard assessment will include estimated timescales of

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inundation and impact from the various likely hazards. This will inform emergency response plans, providing an advanced interpretation of the risks associated with this system. This preliminary assessment can be used to prioritize mitigation strategies and inform a monitoring program.

This paper presents the numerical modelling that has been undertaken to simulate the volcanic-debris–flow hazard, and tephra dispersal and deposition hazards stemming from an eruption of Mount Meager. Parameters incorporated into the models are based on three reasonable scenarios of eruption style, ranging from small-scale to large-scale eruption. Volcanic-debris flows and tephra have the potential to inflict the most damage across the largest area of all hazards expected from an eruption at Mount Meager. This paper describes the numerical models being used for the task and discusses the outcomes as they pertain to the impacts from any future eruption of this volcano.

Background

The Mount Meager Volcanic Complex, part of the Coast Mountains in British Columbia, is 150 km northwest of Vancouver. It is adjacent to the confluence of Meager Creek and the upper Lillooet River which flow along the base of the complex (Figure 1). The upper Lillooet River extends to Pemberton, the closest community, which is located 65 km to the southeast. The summit of Mount Meager, partially glacier clad, reaches 2645 m asl. It has been subjected to dynamic processes, such as dissection by glacier advance and retreat, during the Pleistocene Epoch (Clague and Ward, 2011), as well as extensive hydrothermal alteration (Venugopal et al., 2017).

The complex is part of the Garibaldi volcanic belt, connected to the Cascade magmatic arc that extends into Washington State (Green et al., 1988; Read, 1990). Volcanism along this arc is related to subduction of the Juan de Fuca Plate beneath the North American Plate (Green et al., 1988). Unlike the American volcano counterparts, Mount Meager does not exhibit the recognizable conical peak associated with other stratovolcanoes. It has been suggested that tectonism in this section of southwestern BC has been driving rapid uplift for the last 10 m.y. (Farley et al., 2001). The high rate of uplift, coupled with dissection by glacier cover, has been balanced by high rates of erosion and con-

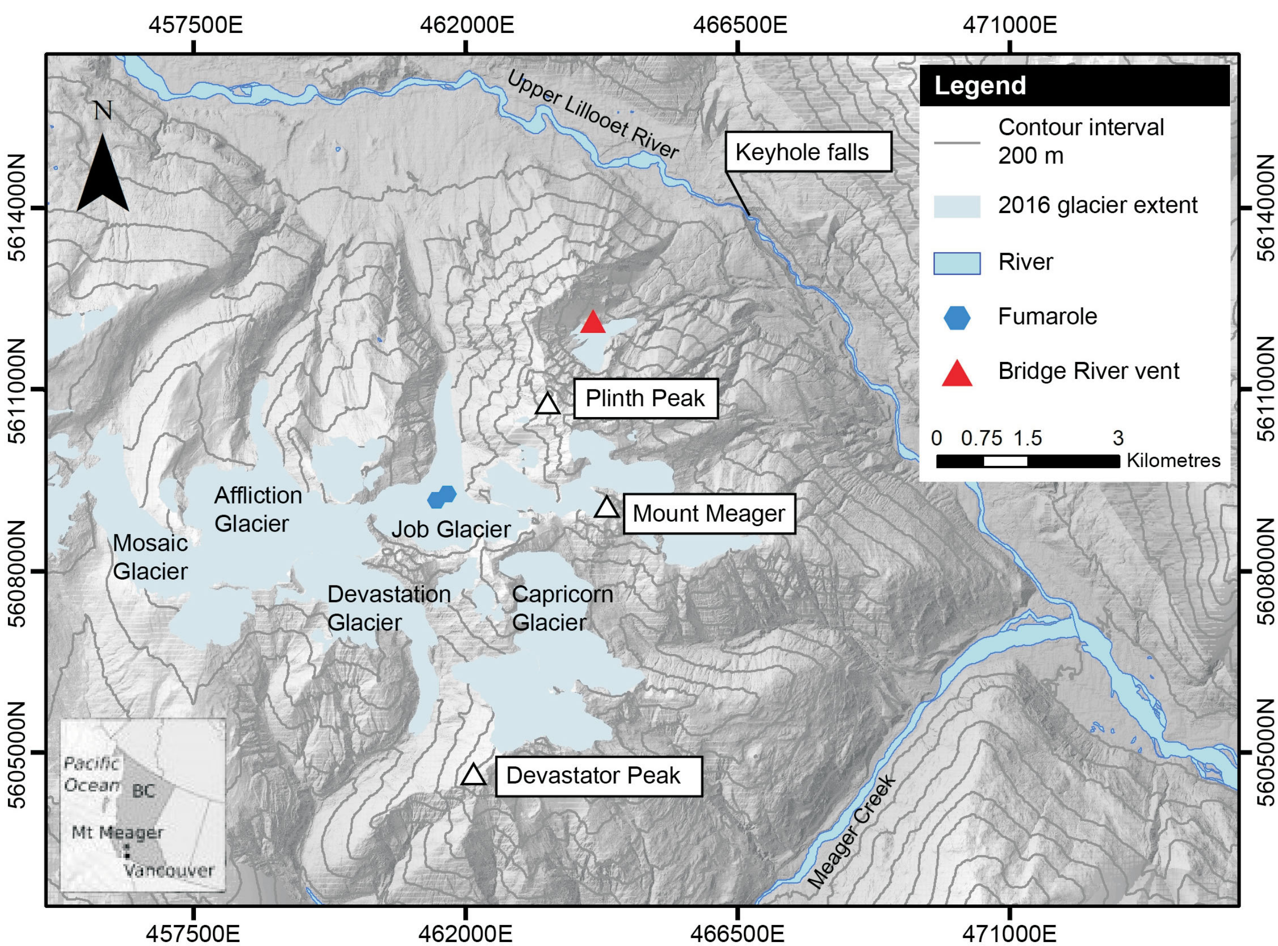

Figure 1. Overview of the Mount Meager Volcanic Complex, showing 2016 glacier cover and locations of the Bridge River vent and known fumaroles. Modified from Roberti et al. (2017). All co-ordinates are in UTM Zone 10, NAD 83.

tinuous mass-wasting events, resulting in a highly dissected morphology.

Despite being a large volcanic system, Mount Meager is far more recognized for its history of frequent, large-scale mass-wasting events. In 2010, the largest landslide in Canadian history (~53×10^6 m^3) was generated on the flanks of Capricorn Mountain, flowing into a portion of the upper Lillooet River, with a maximum path length of 12.7 km (Roberti et al., 2017).

Geological History

The 2 million year eruptive history of Mount Meager has constructed several peaks, resulting in the complex that stands today (Read, 1990; Farley et al., 2001). Mapping by Read (1990) and supported by Hickson et al. (1999) shows that volcanism at this complex can be split into three periods: early- and late-stage rhyodacite, and a middle stage of andesitic activity. The eruptive suite includes pyroclastic deposits, overlapping andesite and rhyodacite flows, and dacite domes, as well as peripheral basaltic flows (Read, 1990; Hickson et al., 1999). The volcanic deposits, which, on average, form the upper 600 m (topographic) of the complex, overlie Mesozoic plutonic and metamorphic basement rocks (Read, 1990; Roberti, 2018).

Extensive work by Simpson et al. (2006), Friele et al. (2008) and Friele (2012) has documented the long record of landslides and established a hazard assessment based on the large-scale and frequent landslides prevalent throughout the complex. Work has continued to document recent mass-wasting events and identify unstable slopes throughout the massif (Hetherington, 2014; Roberti et al., 2017, 2018). Only one of the documented debris-flow events has been directly associated with the last eruption (Simpson et al., 2006). A question remains regarding what relationship might exist between a deep-seated mass-wasting event and the depressurization of the underlying volcanic system, possibly triggering an eruption.

Summary of Past Volcanic Hazards

A number of hazards associated with the last eruption of Mount Meager have been discerned from the mapped deposits of this event. These deposits exhibit eruption characteristics that suggest an initial phase of sub-Plinian activity that transitioned to a Vulcanian eruptive episode. Welded block and ash-flow deposits form the banks of the upper Lillooet River directly below the 2360 BP eruptive vent. This deposit is the remnant of an impermeable dam that blocked the upper Lillooet River, creating a temporary lake with a volume of $0.25–1.0 \times 10^9$ m^3 that eventually failed catastrophically (Stasiuk et al., 1996; Hickson et al., 1999; Andrews et al., 2014). The failure produced an outburst flood that is associated with a volcanic debris-flow deposit identified 42–47 km downstream beneath present-day Pemberton (Simpson et al., 2006; Friele et al., 2008). A short lava flow stemming from the Bridge River vent is also associated with this period of volcanic activity (Hickson et al., 1999). Thin layers of tephra attributed to this particular eruption have been identified in Alberta, 530 km from the Bridge River vent (Nasmith et al., 1967; Mathewes and Westgate, 1980; Leonard, 1995; Jensen and Beaudoin, 2016).

Likely and Expected Volcanic Hazards

The likely and expected hazards resulting from an explosive eruption at Mount Meager can be organized based on the area of land they may impact and their potential to reach populated areas. Firstly, the propagation of an ash cloud and subsequent tephra fall are likely to affect the largest area due to their ejection into the atmosphere and transport by wind. Volcanic debris-flows are also expected to occur, given the large volume of ice (a potential supply of water) overlying the heated system; this particular hazard is both primary and secondary in nature, in that it can be triggered by an eruption or occur at a different time. All of these can impact areas up to 100 km from the source volcano (Pierson et al., 2014). Next, pyroclastic flows may occur, given the likely development of an eruption column that would eventually collapse once the energy of the eruption subsided. Field evidence suggests that a dome collapse likely triggered the welded block and ash-flow deposits blanketing the river valley below the Bridge River vent (Michol et al., 2008). Finally, a lava flow is also likely to occur within the timeframe of an eruption; however, given the dominant geological characteristics of the system, the lava flow would be highly viscous, travelling only a short distance and affecting only the topography of the volcano flank. It should be noted that basaltic lavas have also been documented around the periphery of the complex (Hickson et al., 1999), which suggests potential for less viscous and farther reaching lava flows, thus increasing the inundation footprint; however, this is not the dominant rock type of the complex.

Methods

Numerical modelling was undertaken to examine potential inundation zones and timescales of propagation of the hazards that are explored in this paper. The choice of numerical-modelling programs used for each type of hazard was based on ease of use, open access and applicability to the specific hazard being investigated. These are important characteristics to consider for volcanic-hazard numerical models due to the reality that actual volcanic eruptions can be crisis events where the development of hazard maps and assessments needs to be rapid. Identifying the numerical models that are suggested as the best-practice programs for the Canadian context will provide the best support in the event of a volcanic-eruption crisis.

The input parameters chosen for each numerical-model simulation were divided into three conceivable scenarios. To represent a large-scale scenario, the 1980 eruption of Mount St. Helens, an ice-clad volcanic system in Washington State, was chosen. This case study was chosen due to its well-documented, large-magnitude eruption (Wolfe and Pierson, 1995) and its occurrence in the Cascade magmatic arc, which is closely associated with the Garibaldi volcanic belt that includes Mount Meager. The mid-range scenario is based on the eruption of Nevado del Ruiz in 1985, which resulted in the propagation of a volcanic-debris flow originating from snow and ice melt that resulted from an eruption onto the volcano's glacier (Herd et al., 1986; Voight, 1990). Finally, the small-scale eruption was based on a 2015 eruptive event at Cotopaxi volcano in Ecuador, which resulted in an eruption of ash and a small volume of volcanic-debris flows (Global Volcanism Program, 2016). This latter case study was chosen because Cotopaxi is a well-monitored and documented volcano with similar geological characteristics to Mount Meager (e.g., rhyolitic and andesitic eruption compositions; Hall and Mothes, 2008). Table 1 shows the scenarios and the corresponding numerical-model input parameters used in Ash3d and LAHARZ, two numerical models described below.

Modelling Tephra Hazards

The United States Geological Survey (USGS) program Ash3d was used for tephra deposition and dispersion. This program is actively used by several volcano-monitoring agencies, such as Instituto Geofisico (IGEPN) in Ecuador and the USGS in their response to volcanic eruption crises around the world. It is an atmospheric model for tephra transport, deposition and dispersion run on a web interface (Schwaiger et al., 2012; Mastin et al., 2013). The atmosphere is divided into a 3-D grid and flow of mass is calculated through each grid cell. Considering the wind field taken from a weather-forecast model, ash particles fall in the model depending on their settling velocity in air (Schwaiger et al., 2012). A limitation of this program is that vent location is not user-defined but rather a predetermined general location of the volcano itself defined by the USGS. At the moment, this is not a concern for Mount Meager, as there have been no studies to determine future vent locations. Furthermore, tephra dispersion and deposition are more dependent on wind direction at the time of eruption, which ASH3d does consider. See Table 1 for the input parameters used in the development of the scenario-based simulations.

Modelling Volcanic-Debris Flows

Two numerical-model programs have been used to investigate the volcanic-debris flow hazard at Mount Meager: the USGS-developed LAHARZ and VolcFlow.

LAHARZ is a readily available program run within a Geographic Information System (GIS) that is widely used by many volcanologists (Muñoz-Salinas et al., 2009). It is a semi-empirically–based program designed to estimate potential zones of inundation based on specified debris-flow volumes (Schilling, 2014).

VolcFlow is a depth-averaged approach intended to model geophysical flows and has the ability to manipulate rheological-flow parameters (Kelfoun et al., 2009; Kelfoun and Vargas, 2016). In practice, VolcFlow requires a steeper learning curve than LAHARZ, based on the user interface. However, VolcFlow allows the user more opportunity to place constraints on flow parameters, thus providing more opportunity to simulate realistic flows. Table 2 displays the input parameters that were used for the simulation of two volcanic-debris flows in VolcFlow. Table 1 includes the volume chosen for the simulation of volcanic-debris flows in LAHARZ, which is the only physical input parameter required by that program.

In this paper, only volcanic-debris flows originating from Job Glacier have been presented. This point of origin was chosen to start this research due to the presence of active fumarolic activity within the complex. Other points of origin around the complex will be investigated at a later date using the same scenario parameters described in Tables 1 and 2.

Table 1. Three eruption scenarios and the corresponding parameter values used in numerical models. Abbreviation: VEI, Volcano Explosivity Index.

Scenario	Tephra characteristics	Volcanic-debris–flow characteristics
Cotopaxi volcano, Ecuador, 2015 eruption, VEI 1-2	Plume height: 27 km asl Erupted volume: 0.0390 km^3 Eruption duration: 45 minutes	Volume: 1–3 × 10^6 m^3 Runout length: 15- 18 km
Nevado del Ruiz, Columbia, 1985 eruption, VEI 3	Plume height: 5 km asl Erupted volume: 0.0001 km^3 Eruption duration: 1 hour	Volume: 5 × 10^7 m^3 Runout length: 60–100 km
Mount St. Helens, U.S.A., 1980 eruption, VEI 5	Plume height: 24 km asl Erupted volume: 1.4 km^3 Eruption duration: 9 hours	Volume: 5 × 10^8 m^3 Runout length: 80–100 km

Table 2. VolcFlow input parameters.

Input parameters	Value
VEI 1–2 volume	5×10^6 m^3
VEI 5 volume	5×10^8 m^3
Viscosity	25 Pa•s
Density	1500 kg/m^3
Yield strength	1500 kPa
Internal and basal-friction angle	0

Results

Tephra Dispersion and Deposition with Ash3d

Simulations using Ash3d were run on a nearly daily basis from June 2 to August 17, 2018 for the three scenarios. Both the Nevado del Ruiz and the Mount St. Helens scenarios were simulated to track tephra for 24 hours after the start of an eruption. This was also followed by the Cotopaxi case partway through the investigation. However, the Cotopaxi-based scenario was initially set to track tephra for only 6 hours after a simulated eruption. Within this time frame Ash3d reported no cities being affected by tephra deposition for the majority of the simulation runs. From August 2 onward, additional runs were set up to simulate the distribution of tephra 24 hours after the eruption in order to obtain observable results. The following results are based on only 46 runs during the June 2 to August 17 time period.

A majority of the simulations showed tephra being dispersed and deposited to the east and northeast of Mount Meager. For the Mount St. Helens scenario, Kamloops and Williams Lake are most often in the path of tephra dispersion, relative to any other city in BC, in 40 of 46 runs. Port Hardy, northwest of Mount Meager, is simulated to receive tephra in 32 of 46 runs. Vancouver, south of Mount Meager, received tephra in 22 of 46 simulated runs. Similar outcomes occur with the Nevado del Ruiz scenario. However, a difference is that Port Hardy is the city in the path of tephra dispersion most frequently, in 45 of 46 runs.

Regarding the Cotopaxi-based scenario for observations over 24 hours, only one or two cities are shown to be impacted by tephra. Based on 8 runs over a 24-hour period, the communities impacted by tephra dispersion are Kamloops (3/8), Kelowna (2/8), Merritt (2/8), Duncan (1/8) and Williams Lake (2/8).

Isopleth maps were generated using data extracted from tephra deposition generated in Ash3d (Figure 2). Different outcomes are displayed using the Mount St. Helens and Nevado del Ruiz scenarios. The map displaying the Cotopaxi scenario is based on the most likely occurrence 6 hours after a simulated eruption.

Volcanic-Debris Flow with LAHARZ

All three scenarios result in a volcanic-debris flow reaching the upper Lillooet River, which runs along the eastern base of Mount Meager. The simulated runout length differs for all three scenarios. Given a failure volume of 1×10^6 m^3 for the smallest eruption scenario, a runout length of 9 km is simulated. A volume of 5×10^7 m^3 equates to a runout length of 34 km and the largest failure volume of 5×10^8 m^3 generates a debris-flow runout of 65 km, which reaches the town of Pemberton. All three debris-flow simulations show that the failure follows the confines of the river channel (Figure 3).

Volcanic-Debris Flow with VolcFlow

Two scenarios using the VolcFlow program are presented here. The first involves a debris-flow–failure volume of 5×10^7 m^3, representing a scenario between the small- and mid-scale eruption scenarios. The runout length for that failure is 6 km. The simulation representing a large-scale eruption with a failure volume of 5×10^8 m^3 results in a runout length of 13 km. Both simulations show that even a small-volume failure would reach the upper Lillooet River. The VolcFlow program simulates the mass of both failures dispersing across the floodplain that exists at the bottom of the watershed holding the Job Glacier, rather than strictly following the gradient of topography propagating to lowest elevation points. The large-scale eruption scenario shows the failure stopping at Keyhole falls, which is a location of significant elevation drop. The VolcFlow program may be unable to solve for significant changes in elevation inherent in the pixels of the Digital Elevation Model used for the simulation. Further research will be required to determine whether the simulated failure would travel farther without the significant elevation drop. Figure 4 displays the outcomes obtained using the VolcFlow program. In both cases, the program calculates the propagation of failure across 20 minutes (1200 seconds).

Discussion and Conclusions

The results of these simulations offer an example of the benefits of using numerical-modelling tools in the absence of in-depth geological information in a volcanic-hazard environment. The three numerical models displaying two types of volcanic hazards likely for Mount Meager exemplify the varying spatial scale of impact possible from an eruption.

Tephra dispersion is a regional scale hazard that has the potential to impact communities beyond the borders of British Columbia. Volcanic-debris flows are a proximal/local hazard capable of impacting industrial activities at the base of Mount Meager, given a small-scale eruption, and additionally impacting the community of Pemberton, given the large-scale scenario.

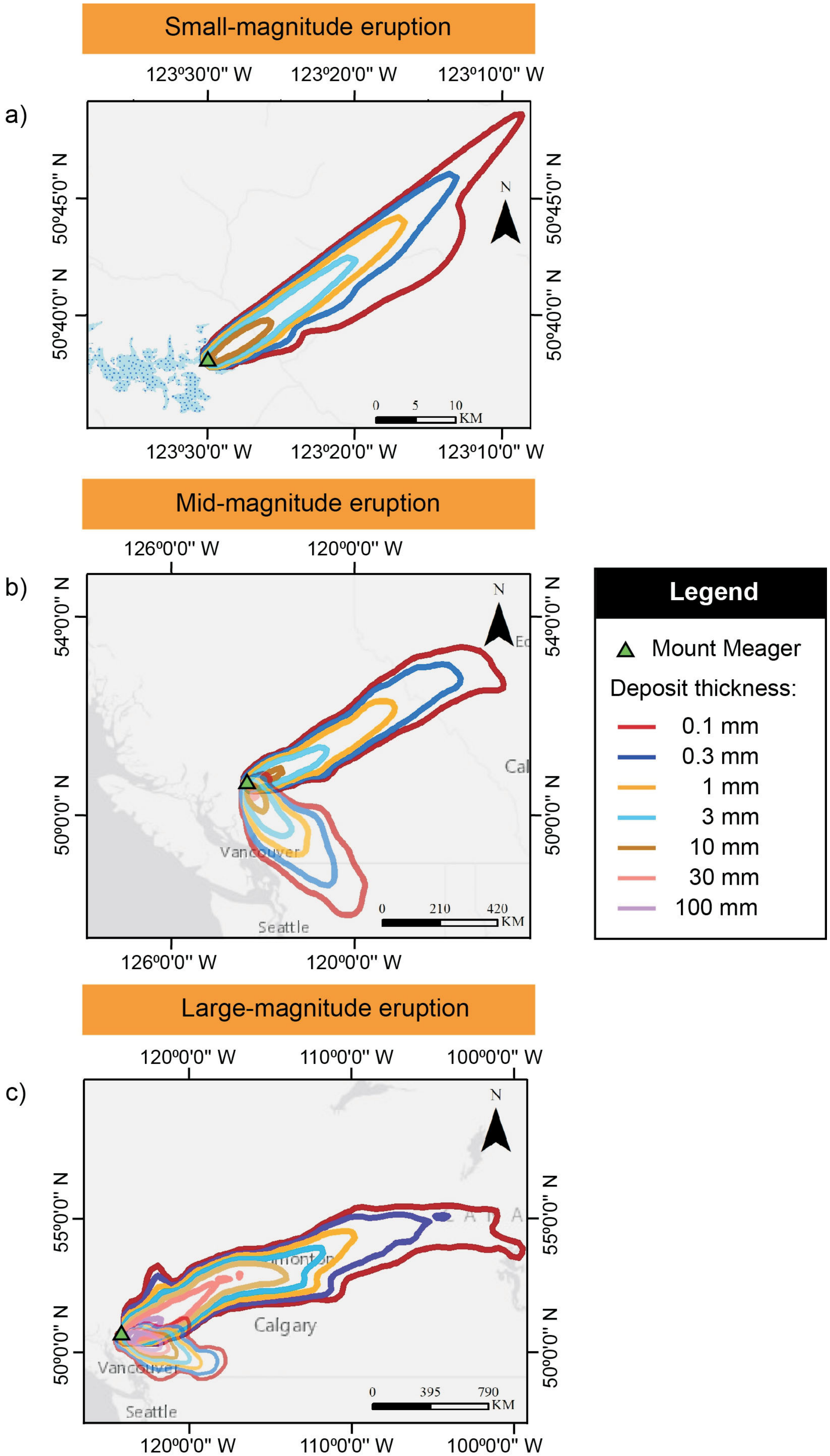

Figure 2. Surface distribution of tephra, showing variations in direction of deposition based on different possible wind patterns: **a)** Cotopaxi eruption characteristics 6 hours after eruption,(**b)** Nevado del Ruiz eruption characteristics 24 hours after eruption, and **c)** Mount St. Helens eruption characteristics 24 hours after eruption.

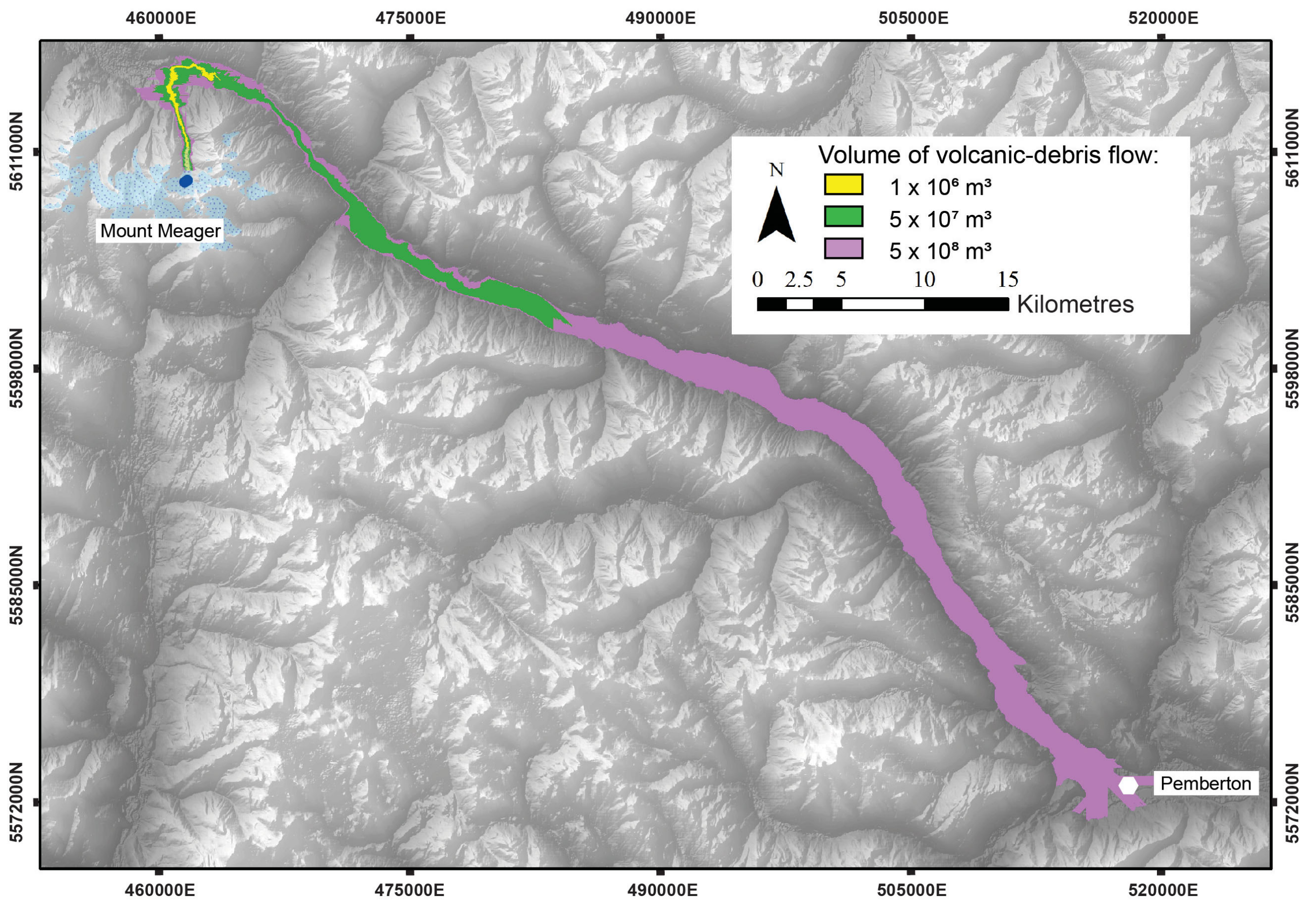

Figure 3. Surface expression of the inundation zones from simulated volcanic-debris flows as modelled by LAHARZ. Co-ordinates are in UTM Zone 10, NAD 83.

Results show that an eruption above Volcano Explosivity Index 2 (the smallest scale eruption scenario) is likely to impact multiple cities in southern British Columbia and beyond. The exact trajectory of tephra dispersion is dependent on wind patterns. Although westerly wind patterns are the dominant prevailing winds across BC, any direction of wind pattern is possible. A large mass of erupted material that is able to reach several kilometres into the atmosphere equates to more distant tephra dispersion.

The results of simulating volcanic-debris flows with the LAHARZ program versus the VolcFlow code are different. Using the same failure volume for the worst-case eruption scenario, the LAHARZ program models a runout length 52 km greater than those from VolcFlow. However, LAHARZ is limited by the simplistic functions. The rheological characteristics of the flow cannot be manipulated and the program only propagates the failure mass down gradient. VolcFlow is flawed by its inherent inability to solve for significant changes in the elevation profile of the environment. At Mount Meager, this is a significant problem given the existence of Keyhole falls in the path of likely failure propagation. However, results showing that the failure mass of a large-scale eruption reaches Keyhole falls are of significance nonetheless, suggesting that failure material may possibly propagate farther or at least form a dam, given the constricting nature of the valley at that point along the river. The dam would be inherently unstable and could pose a secondary hazard of outburst flooding, similar to the events of the last eruption 2360 years BP (although that dam was created from the welded block and ash-flow deposit rather than from debris-flow material). It is important to note that the development of a dam created from the material of the volcanic-debris flow was not actually intended or simulated with VolcFlow; it is merely a hypothesis for the outcome of a buildup of material being confined at the location of Keyhole falls.

This paper outlines the preliminary investigations of two likely hazards generated from an eruption at Mount Meager. It is a scenario-based approach to simulate the propagation of these hazards and is limited in scope to just three scales of eruption: small, medium and large. This paper should not, therefore, be used as a forecast or prediction of the events that will occur during the next eruption at Mount Meager. Rather, it serves to display the preliminary results of three conceivable outcomes of future volcanic activity.

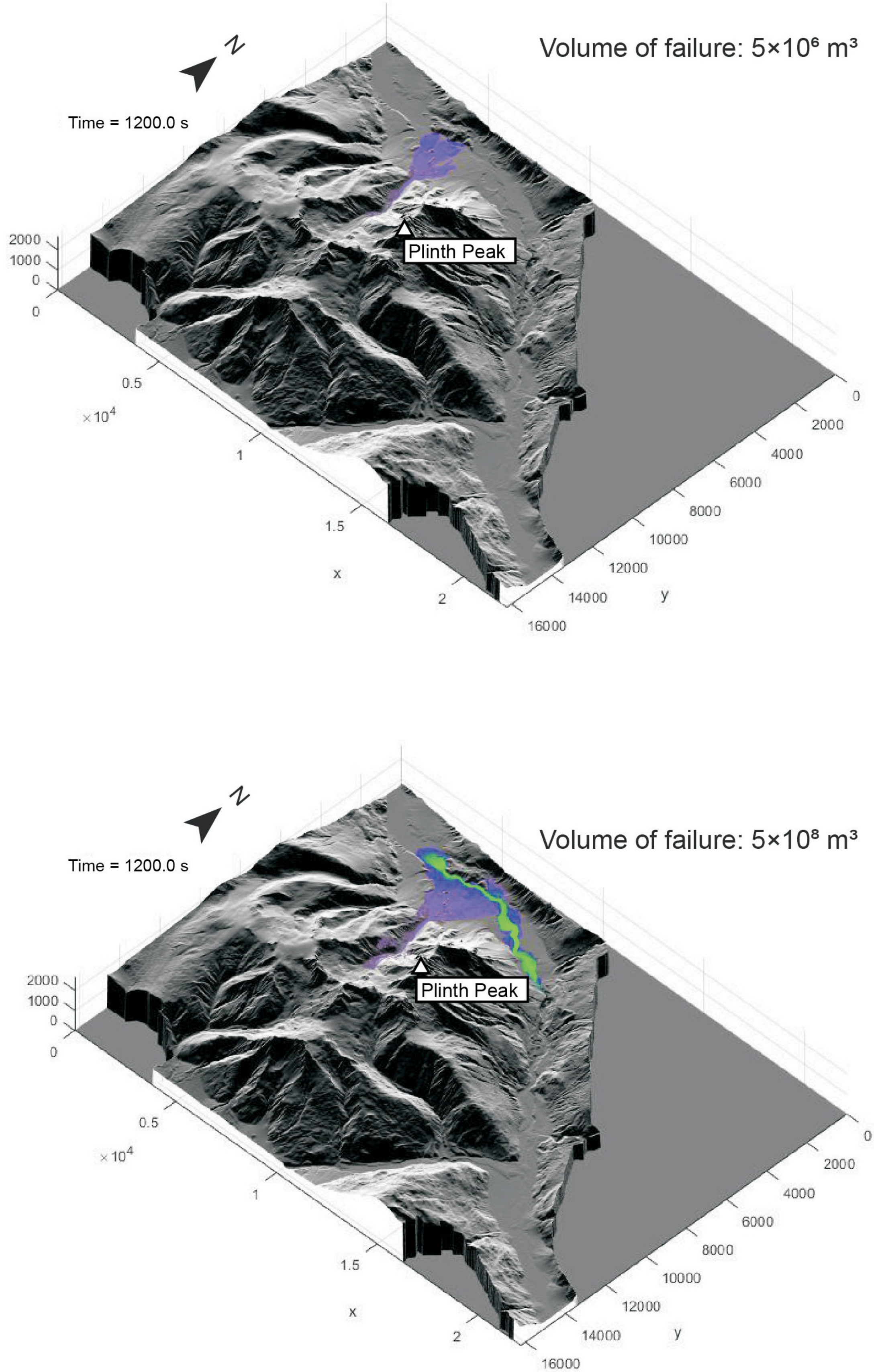

Figure 4. Surface expression of the inundation zones from simulated volcanic-debris flows as modelled by VolcFlow, assuming initial volume of failure of **a)** 5×10^7 m^3, and **b)** 5×10^8 m^3. Axes show distance in metres.

Future Work

This paper presents the findings of numerically modelling the tephra hazards and volcanic-debris flow hazards from Mount Meager. Future work will expand on the possible hazards stemming from an eruption to include lava flows and pyroclastic flows, both of which are considered proximal hazards. Numerical models for volcanic-debris flows, lava flows and pyroclastic flows will be applied to multiple locations around the complex, which is necessary given the uncertainty in vent location during any future eruption. This paper does not comment on the time frames of inundation expected from the volcanic-debris flow hazard, but this will be addressed with further research. Ultimately, the results of numerical-model simulations for each type of hazard will be combined and included in a comprehensive volcanic-hazard map and assessment for Mount Meager.

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