1- How does uplift and glacial erosion influence the stability and longevity of volcanic edifices?

<u>*Overview*</u>

It is well known that changes in the height, composition and structure of a volcanic edifice through growth, eruption or erosion can influence whether and when an eruption might occur through their effects on the crustal stress regime (van Wy de Vries and Matella 1998, Borgia and van Wyk de Vries 2003, Karlstrom et al. 2009; Karlstrom et al., 2014). Furthermore, depending on the rate of change of crustal stresses, periodic forcings from alpine glaciations (Jellinek et al., 2004), global glaciations (Watt et al., 2013) and climate change (Huybers and Langmuir, 2009) can influence the frequency, composition and spatial distribution of volcanism. In addition to this periodic forcing, intermittent forcing of the crustal stress regime can also occur through catastrophic slope failures leading to landslides or total flank collapses (e.g. Silitoe 1994). Moreover, as volcanoes age, hydrothermal alteration of the rocks forming their flanks causes them to weaken and to fail more frequently, in turn (van Wyk de Vries and Francis, 1997).

The Northern Cascade Arc volcanoes have been modified by both glaciations and by landslide events (which can occur in concert) and both of these surface processes may influence local edifice loads and contribute to the structure of the eruption history. In contrast to current efforts to understand effects of climate variability on all time scales on volcanism, there is little work on how flank collapse events might be expressed in the volcanic record from a given volcano. To build understanding of explicit links between, say, the record of catastrophic erosional changes in an edifice and fluctuations in eruption rate and magma supply requires a thorough characterization of the history of such events, which is challenging, and requires a clear picture of the mechanics governing edifice stability (Borgia et al 2000). Mt Meager is an exceptional site for studying the dynamics of a glaciated, uplifted volcanic edifice, and the research questions identified during the recent Vancouver meeting are wide ranging.

Mt Meager presents an opportunity of study edifice evolution and stability at a higher rate than ususal due to a combination of rapid uplift, high erosion and vigorous hydrothermal activity. This high rate makes such volcanoes a particular challenge for risk analysis, because they are hard to constrain, and may alter rapidly their hazards. Mt Meager is a complex geological environment consisting of a magmatic system, at an unknown depth, a fragmentary edifice, standing on a complex metamorphic basement (Read 1990, Hickson 1999, Simpson 2006, Friele et al 2008). Meager is an uplifted, very steep volcano with 2500 m of topography. It has a strong hydrothermal system, is tectonically faulted, has deep glacial and fluvial erosion. It's flanks are scarred by gravity-related faults and it has frequent large-scale landslides. Eruptions are accompanied by collapse of the steep slopes, but many landslides happen outside eruptive periods (Hickson 1999). It is renowned for being the most landslide prone massif in Canada, possibly the world, with numerous major historical events that have included fatalities and severe infrastructure impact.

This combination makes it a type volcano for extreme topographic processes. It exemplifies, in the extreme, other volcanoes of the northern Cascades, of Alaska, the Andes, as well as other volcanic areas with high erosion rates. Mt Meager thus serves as a perfect natural laboratory for gravity and topographic processes on volcanoes. While Meager is an extreme topography, the lack of vegetation on the high slopes and freshness of the landslide deposits in the valleys make it highly accessible to low level fieldwork and perfect for remote sensing investigation.

Gravitational spreading linked to landsliding (e.g. van Wyk de Vries and Francis 1997, Borgia et al 2000) is a fundamental edifice process that controls the stress- strain-environment in which both the hydrothermal and magmatic systems operate. At Meager the uplift, high erosion rates and glacial loading and unloading provide a highly dynamic environment, that can be used to test ideas about edifice deformation, stability and the relationship between loading, unloading and volcanism.

Key outstanding questions that this PhD project will explore include:

- What is the structural response of the edifice to rapid topographic change and what structures are formed, in what arrangement?
- How fast do structures develop and evolve?
- Does the stress relaxation lead to landsliding or stabilisation of slopes, and what is the rate of stress change that could be applied to the deeper magmatic system?
- What effect does the deformation and landsliding have on removal of edifice, and thus pressure changes on the magmatic system under the edifice?
- How does the edifice deformation constrain the type of landslide produced?

Existing knowledge and critical gaps

We know only fragmentary information about the eruptions and evolution of the Mt. Meager complex; however, some windows exist into specific events. The volcanic history of the Mt Meager complex (Hickson et al 1999) and the Holocene landslide history have been documented (Simpson 2006, Friele et al 2008) and there are general studies describing the most recent landslides (Guthrie et al 2012). However, the detailed Holocene glacial history of Mt Meager is not known in any detail. We do know that Mt Meager is cut by many faults (these are visible on high resolution Google Earth images, and from previous publications on small areas). Also, we do know that slopes on Mt Meager are in a critical condition (MSc, Heatherington 2013). However, the detailed structure has been mapped in only a very few small sites and no measurements of any rock mechanical properties are available. The hydrogeological system in the volcano is not known to any detail, nor are rates of erosion by landsliding nor glacial, nor fluvial erosion known. These cannot be estimated without detailed morphological mapping as proposed here. There is a known landslide that accompanied the 2350 BP eruption (Hicks et al 1999), but it is not clear if any other large landslide has accompanied any other eruption. Such information would be accessible if the massif was better mapped, something that is possible with high resolution aerial and satellite imagery.

Goals

1. Characterize the structure, architecture and stability of the Meager edifice through detailed geological mapping with remote sensing, topographic data and specific fieldwork campaigns to the accessible parts. Also, change detenction using Radarsat can document movement before specific landslides, such as the 2010 landslsie and this can help predict future landslides.
2. Refine the landslide history by detailed mapping of the more recent events, that are still well exposed and preserved in the valley bottoms or in large outcrops along the rivers.
3. Characterise the glacial history with detailed mapping of glacial features alongside the other mapping, and use the history to explore glacial retreat-related landslide activation.

4. Carry out analogue models to explore the deformation related to different rheology layers in a fast eroding massif, and to explore the link between groundwater, deformation and erosion. Analogue models using granular materials to build the edifice, combined with syrups and silicones for magma and ductile layers, gas and water for hydrothermal effects are powerful tools to explore rapidly the multiple parameters involved in the Mt Merger situation. Specifically non-eroded models can be built to define and end member situation, backing up the extensive model base already available from LMV work. Erosion can be induced either in saturated models or by vacuum removal of dry material, to create topography. Conversely material can be added to simulate eruption or glaciation. Dimensional analysis then allows the characterisation of the main parameters influencing the system.

5. Models will be run to follow the structural development of landslides from slow deep seated deformation, through landsliding to collapse (e.g. Shea et al 2008, Andrade, 2009, Paguican 2012)

6. To use the Mt Meager results to understand other volcanic environments, by comparison and contrast: other volcanic systems, such as the Sancy (France), Tutupaca (Peru) and Apo (Philippines) are the targets for comparison. These are sites of sister projects where exchange of data for comparison will be easily done.

Proposed work

- Remote sensing: use visual satellite, radar and aerial imagery to map the edifice (*SFU*)
- Field campaign to characterize structure of edifice at high resolution, plus ground based LiDAR (SFU)
- Analogue Modelling at LMV (Edifice stability + mass movement kinematics (LMV)

Major outcomes

- Characterisation of the architecture of an uplifted, glaciated volcano.
- Determine the balance of environmental, gravitational and tectonic processes in the volcano-magmatic system.
- Understand landslide emplacement from high volcanoes, including triggering and development, emplacement and secondary hazards.
- Provide type example of High Mountain volcano architecture and dynamics to apply globally.

Timeline

	2014	2015	2016	2017
Remote sensing analysis: LMV				
Field trips	Fall	Fall		
Aerial data acquisition: SFU	Fall			
Analogue+Numerical modelling: LMV		+ remote use of numerical methods (SFU)	+Summer Flume models (UBC)	
GSA Conference, Vancouver	Fall			
AGU Conference			Fall	
Write and submit PHD				
Write and submit papers				
Principal university for student	SFU+LMV	LMV	LMV	SFU

2- Description of the two laboratories and the thesis supervisors

The Laboratoire Magmas et Volcans and the Quaternary and Geotechnical groups at Simon Frazer will be the main operators in this project. Magmas and Volcanes brings the expertise in analogue modelling, tectonic field analysis and photogrammetry. En counterpart Simon Frazer brings expertise in quaternary studies and geotechniques, as well as extensive experience already on Mt Meager and the Cascades.

The thesis supervisors will be Benjamin van wyk de Vries for LMV/UBP and Brent Ward for Simon Frazer.

Synergy: There is already a close collaboration between SFU and UBP on Mt Meager: field campaigns, MSc field studies and exchange visits have been made. There is an established complementarity in approach: B Ward provides the Quaternary, J Clague the Landslide and technicality, and B van Wyk the structural – volcano-tectonic aspect, plus the kinematics of landslides. The PhD student will fit into an already cemented team. Numerical Geotechnical modelling with Doug stead, and the UBC Engineering unit would be an extension of this collaboration. Models of Dam break and landslide reworking would be best done in Hassan's large flume lab at UBC. Our results will be used to define related projects in the Main Stage and northern Cascade arcs as well as at Auvergne region volcanoes.

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ANNEXE 1: Demonstrated collaborative success to date: Existing joint publications
Papers in preparation, submitted and published by LMV, SFU and UBC project members

Carpentier M., **Weis D.**, Chauvel C., (2014), Mineral sorting fractionates Sr and Hf isotopes in Cascadia Basin terrigenous sediments. Chem. Geol. (accepted April 2014).

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Nauret F., Snow J.E., Hellebrand E., **Weis D.**, (2011). Non-peridotitic source in mid-ocean ridge melts from Lena Trough, Arctic Ocean. Jour. Petrol., 52, 1185-1206.

Debaille V., **Doucelance R.**, **Weis D.**, **Schiano P.**, (2006). Multi-stage mixing in subduction zones: Application to Merapi Volcano (Java island, Sunda arc). Geochim. Cosmochim. Acta, 70, 723-741.

Bernard K, **Friele P, van Wyk de Vries B**. Textural and sedimentological evolution of the Mt Meager Landslide (in preparation).

Jessop, D. E., **O. Roche**, et al., (2012). LiDAR derived morphology of the 1993 Lascar pyroclastic flow deposits, and implication for flow dynamics and rheology. J. Volc. Geotherm. Res. 245: 81-97.

Jessop, D. E., and **Jellinek, A. M.**, (2014) Effects of particle mixtures and nozzle geometry on entrainment in volcanic jets", Geophys. Res. Lett. (in review)

Jessop, D. E., and **Jellinek, A. M.**, Catestrophic sedimentation from the corner region of volcanic ash clouds (in preparation).

Clague J., **van Wyk de Vries B.** Detailed structural and morphological analysis of the 2009 Mt Meager Landslide (in preparation).

Zurek, J., Moune, S. Williams-Jones G., Magmatic sources of Masaya volcano, Nicaragua (in preparation).