LANDSLIDES IN THE KITIMAT-MORICE RIVER CORRIDOR, NORTHWEST BRITISH COLUMBIA, CANADA

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ABSTRACT
The 105-km long Kitimat-Morice River corridor features mostly interconnecting valleys linking the coastal community of Kitimat in northwestern British Columbia with the interior valley system of Morice River. Surficial geology, landslide inventory and terrain stability mapping were carried out for the corridor. Over 150 landslide deposits of various types have been identified in the study area. Moreover, InSAR monitoring of slopes west of Nimbus Mountain in Hoult Creek valley using RADARSAT-2 data tracked debris movement in debris flow channels over a 19 month period. The Flow-R Model was tested for these debris flow channels to assess their debris flow susceptibility. The main goal of this activity is to provide baseline geoscience information on landslides for potential infrastructure development (e.g., pipelines and all-season roads) to stakeholders and decision-makers.

RÉSUMÉ
Le corridor Kitimat-rivière Morice, d'une longueur de 105 km, comprend principalement des vallées interconnectées reliant la communauté côtière de Kitimat, dans le nord-ouest de la Colombie-Britannique, au système intérieur de la vallée de la rivière Morice. La cartographie des sédiments de surface et de la stabilité des pentes et la compilation des dépôts de glissements de terrain ont été réalisées pour tout le corridor. On compte plus de 150 glissements de terrain de types variables dans cette région d'étude. De plus, nous avons utilisé la méthode de surveillance InSAR à partir des données satellitaires RADARSAT-2 pour la région à l'ouest du Mont Nimbus, dans la vallée du ruisseau Hoult. Les données InSAR démontrent des accumulations de débris sur une période de 19 mois dans les chenaux en pente abrupte. La susceptibilité aux coulées de débris a aussi été calculée avec le modèle Flow-R. Bref, le but principal de notre étude est de fournir l'information géoscientifique de base aux intervenants et aux décideurs.

1 INTRODUCTION

In northwest British Columbia, several large historical landslides have caused fatalities and damaged infrastructure (Geertsema et al. 2009; Schwab 2011; Blais-Stevens et al. 2015). With increasing infrastructure development (e.g., pipeline routes, shipping terminals), concerns about slope stability are omnipresent. The Kitimat-Morice River corridor is a 105-km long mountainous corridor with interconnecting valleys from Kitimat at the head of Douglas Channel fjord, east to Morice River (Fig.1). An important role for the Geological Survey of Canada, part of Natural Resources Canada is to document baseline geoscience information to improve decision-making and inform the regulatory system.

The objectives of this paper are to: 1) present the compilation of surficial geology, landslide inventory and terrain stability mapping; 2) highlight preliminary results from InSAR monitoring; and 3) conduct Flow-R debris flow susceptibility mapping.

2 PHYSIOGRAPHIC SETTING

The corridor is located mainly within the Coast Mountains and the Hazelton Mountains, extending to the western edge of the Interior Plateau (Holland 1976). Kitimat is located at the southern end of the Kitimat-Kitsumkalum trough. Further east, the peaks and valleys are located within the Kitimat Ranges and the Bulkley Ranges (Holland 1976). Lowest elevation is at sea level at Kitimat at the head of Douglas Channel fjord, and the highest elevation is at Nimbus Mountain at 2319 m (Fig. 1).

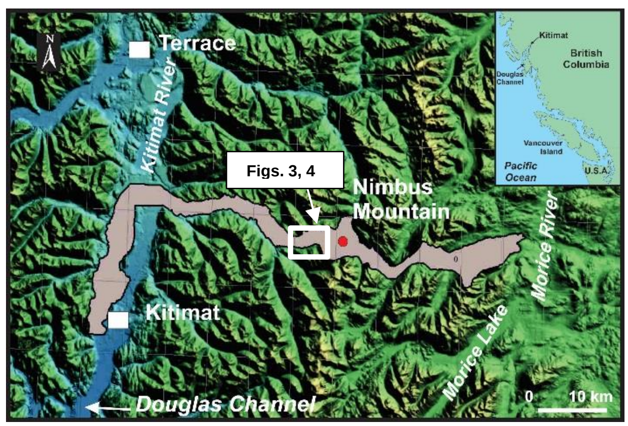

Figure 1. Location map of study area. Corridor (light brown polygon) is roughly 105 km from Kitimat to Morice River. The highest elevation is at Nimbus Mountain (2319 m; red dot).

The bedrock geology of the Coast Mountains consists of Mesozoic to Cenozoic plutonic rocks, mainly granite, granodiorite, and quartz diorite along with some occurrences of older Paleozoic granodioritic plutons.

Volcanic assemblages are more common in the eastern part of the study area (Massey et al. 2005). Most mountain peaks have been glacially eroded in the form of domes (Clague 1984). The Kitimat-Kitsumkalum trough and surrounding valleys are filled with glacial and post-glacial sediments. In the lower Kitimat River valley, glaciomarine deposits are widespread at elevations below 200 m (Clague 1984).

2.1 Climate

In the Kitimat area (Fig. 1), climate is oceanic with average temperatures varying from -3° to 22°C. Based on Environment Canada's 1981-2010 climate data normals (Kitimat, Environment Canada, 2017), average precipitation values total 2700 mm per year, mainly in the form of rain, but with approximately 14% falling as snow.

In comparison, further inland, the Terrace area (Fig. 1) witnesses on average, 1500 mm of precipitation per year. Average minimum and maximum temperatures vary between 3°C and 10°C, respectively (Environment Canada, 2017). The area is part of the Coastal Western Hemlock biogeoclimatic zone (BC Ministry of Forests 1991).

3 METHODS

3.1 Surficial geology and terrain stability mapping and landslide inventory

The surficial geology and landslide assessment were carried out using 1:20,000 scale BC air photos taken in 2001 and 2013. The authors followed the Geological Survey of Canada (GSC) surficial geology model (Deblonde et al. 2012) combined with the BC Terrain Classification System (Howes and Kenk 1997). Some older, field-based mapping by the authors was incorporated into this mapping. The final five map products, at 1:25, 000 scale, each contain attribute tables of each model (Maynard et al. a,b,c,d *in press* and Weiland et al. *in press).* In addition, terrain stability mapping was also carried out following the method developed by BC Ministry of Forests for the Forest Practices Code (1999).

The approach is intended to qualitatively highlight the potential landslide sources based on slope gradient, surficial materials, material texture, material thickness, slope morphology, moisture conditions and ongoing geomorphic processes (BC Ministry of Forests, 1999). Terrain is classified from I-V, class V being the most unstable.

Interpreted air-photos were scanned, ortho-rectified, and digitized at the GSC. Ortho-rectification was carried out using the BC TRIM digital topographic maps at 1:20, 000 scale on an ArcGIS (v. 10.2) platform. Landslide polygons were mapped and tabulated according to type. The authors followed the Cruden and Varnes (1996) nomenclature.

3.2 InSAR monitoring

InSAR monitoring close to Nimbus Mountain (Fig. 1) was carried out following the methodology outlined in Singhroy and Li (2017). Differential synthetic aperture radar interferometry (DInSAR) is an advanced remote sensing technique for measuring ground deformation with sub-centimetre precision and high spatial resolution over a large area (Samsonov et al. 2011). For the conventional DInSAR processing, a differential interferogram is calculated from repeat SAR images acquired at two different times by performing the following processing steps: image co-registration, interferogram formation, removal of earth curvature and topographic components, filtering and phase unwrapping. Subsequently, the differential interferogram reveals the component of ground displacement towards or away from the satellite over the two observations.

In this study, interferograms were computed using the GAMMA Remote Sensing software. A 30 m resolution SRTM DEM was used for topographic correction. The flattened interferograms were filtered using an adaptive noise filter (Goldstein and Werner, 1998), unwrapped using a minimum-cost algorithm (Constantini, 1998), and geocoded (Pearse et al. 2014).

Precision of the displacement measurements was improved by using radar image pairs from numerous scenes (>25), with similar viewing geometries, short perpendicular baselines (<100 m), short time intervals between acquisitions, and correcting for topographic and atmospheric conditions (Singhroy et al. 2012). To minimize the effects of atmospheric inaccuracies or lack of resolution in the DEM on the accuracy of DInSAR measurements, a new method known as the small baseline subset (SBAS) proposed by Samsonov et al. (2011) was used. The SBAS method can produce nonlinear time series of deformation over a long period of time using interferograms with short time spans, which are usually more coherent. In this method, a high-pass filtering with a Gaussian window was applied to remove the residual orbital and atmospheric signals. The interferograms were then calibrated against a chosen reference point assumed to be stable during the entire observation period. A Singular Value Inversion was applied to solve for individual deformation rates and any topographic error (Fig. 2).

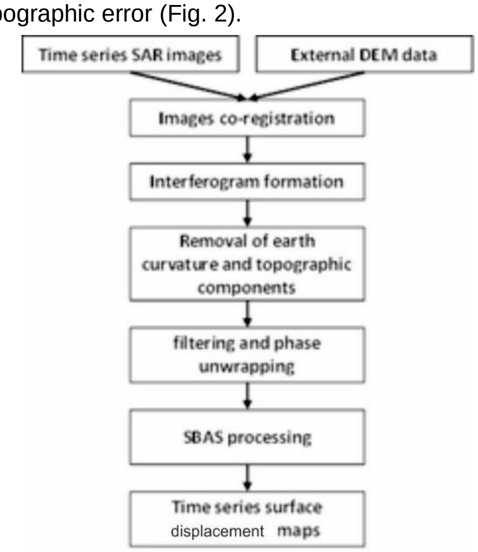

Figure 2. InSAR method flowchart (Singhroy and Li 2017).

Comparison with climate data (Kitimat station, Environment Canada 2016-17) was undertaken to establish whether there was a correlation of ground displacement with precipitation and temperature.

3.3 Landslide susceptibility mapping

Landslide susceptibility mapping was undertaken near Nimbus Mountain, the same area covered by InSAR monitoring. A qualitative heuristic method (cf. Blais-Stevens and Behnia 2016) and the Flow-R method (Horton et al. 2008; 2013) were applied in the recognition of debris flows.

4 RESULTS AND DISCUSSIONS

4.1 Surficial geology, landslide inventory, and terrain stability mapping

Five adjoining surficial geology maps were compiled for the 105-km long corridor. Each map includes a landslide inventory table and an inset figure showing the terrain stability interpretation. These inset maps are colour-coded from green to red (i.e., classes I-V, stable to unstable, respectively; Maynard et al. a,b,c,d, *in press* and Weiland et al. *in press*). Figure 3 shows portions of a surficial geology map (Fig. 3a) from the corridor with a terrain stability map (Fig 3b). This area is located just west of Nimbus Mountain where InSAR monitoring took place (discussed in section 4.2; see Figure 1 for location). The surficial geology map (Fig. 3a) displays very steep channels up to the height of land on the deeply-incised north valley wall of Hoult Creek. The peaks consist of bare bedrock, some containing remnant glaciers with increasing amounts of colluvium downhill. Farther downhill exposures of till exist on the more moderate-gradient slopes. Debris flow fan deposits are found at the base of the steep mountain streams.

Figure 3b displays a terrain stability map of the area shown in Figure 3a. It is mainly interpreted as an area with low to high likelihood of landslide initiation, especially within the steep streams (units IV and V=orange and red, respectively). This area has also previously been documented as an active landslide area (Schwab 2011; CEAA 2012). The presence of debris flow fans at the base of the streams validate the terrain stability mapping. It is important to remember that the terrain stability map reflects potential zones of initiation of landslides and not zones of accumulation, thus it is not a true landslide hazard map. For example, some areas on Figure 3b shown as having no significant problems existing (i.e., class I=green zone) represent fans where debris flows are deposited downhill from a steep zone where there is high likelihood of the initiation of landslides (class V=red zone).

Table 1 shows the total number of landslide and colluvial deposits for the entire corridor. There are 58 debris flow fans, 79 rockfall/scree deposits and roughly 25 other landslide deposits, i.e., rock avalanches, slumps and slides, and earthflows. There are close to 1200 smaller landslides that are too small to outline as polygon, but that indicate downhill sediment transport direction. Colluvial deposits occurring as either veneers or blankets are abundant (found in roughly 842 polygons) but not assigned to a specific landslide process.

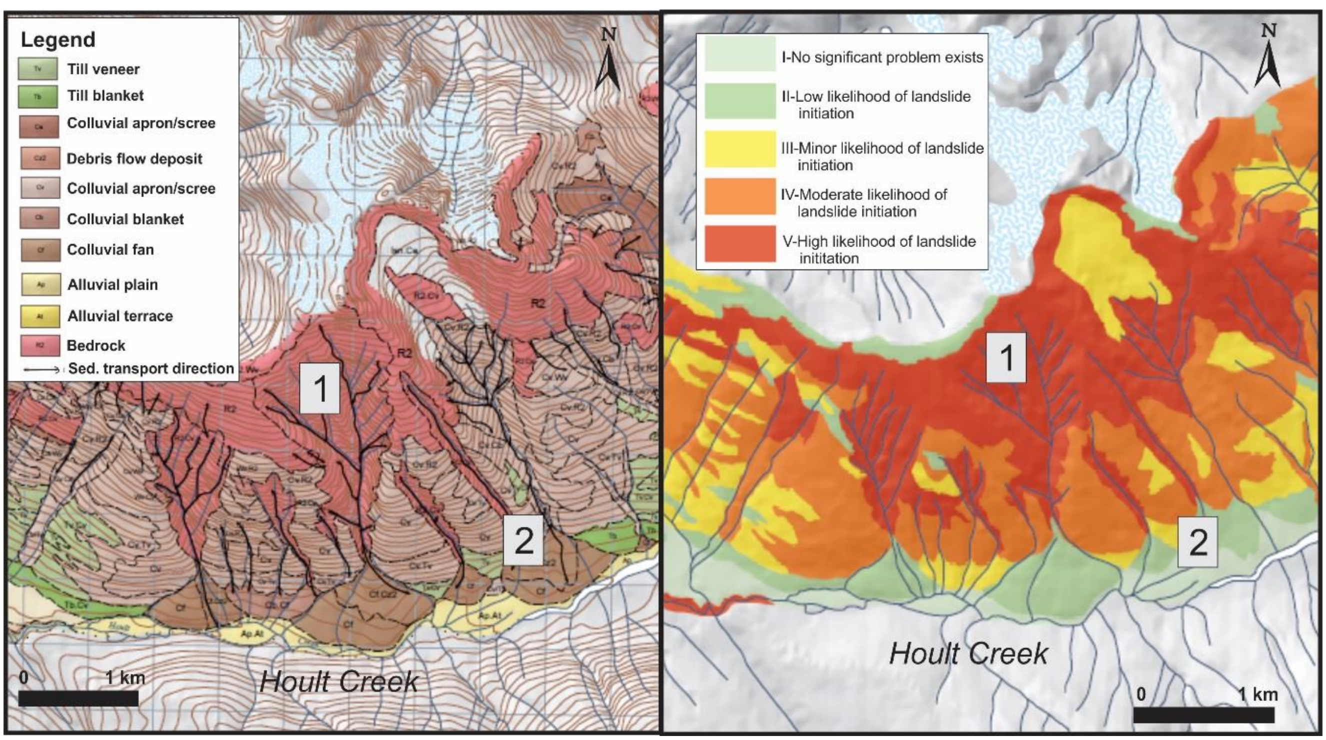

Figure 3.a) Portion of surficial geology overlain on a topographic map (Maynard et al, c *in press*), west of Nimbus Mountain see Fig. 1 for location). b) Terrain stability map colour-coded from green to red (classes I-V; stable to unstable).

Unit*	Description	No. of occurrences
	Landslide depostis and tracks	
Cf; Cf.Cz2; Cz2	Fan sediments deposited by debris flows	58
Ca	Apron and cone talus scree deposits derived from rockfall	79
Cz	Landslide deposits: undifferentiated, relict to recent bedrock slumps, slides, topples, and/or spreads	8
Cz1	Landslide deposit derived from relict rock avalanches	2
Cz2	Earthflow deposits derived from dissected, fine textured glaciomarine-marine deposits	6
Cz4	Landslide deposits associated with relict bedrock slumps-slides	5
Cz5	Landslide deposits associated with shallow, translational sliding from headwalls	4
	Sediment transport direction	1182
	Colluvial deposits	
Cv	Veneer derived from underlying weathered bedrock	688
Cb	Blanket derived from underlying weathered bedrock	145
C	Variable thickness, undifferentiated deposits derived form underlying weathered bedrock and/or small mass movements	9
** From GSC model (Deblonde et al. 2012) and BC Terrain Classsification System (Howes and Kenk 1997)*		

Table 1. Compilation of landslide deposits and tracks and colluvial deposits for the entire Kitimat-Morice corridor.

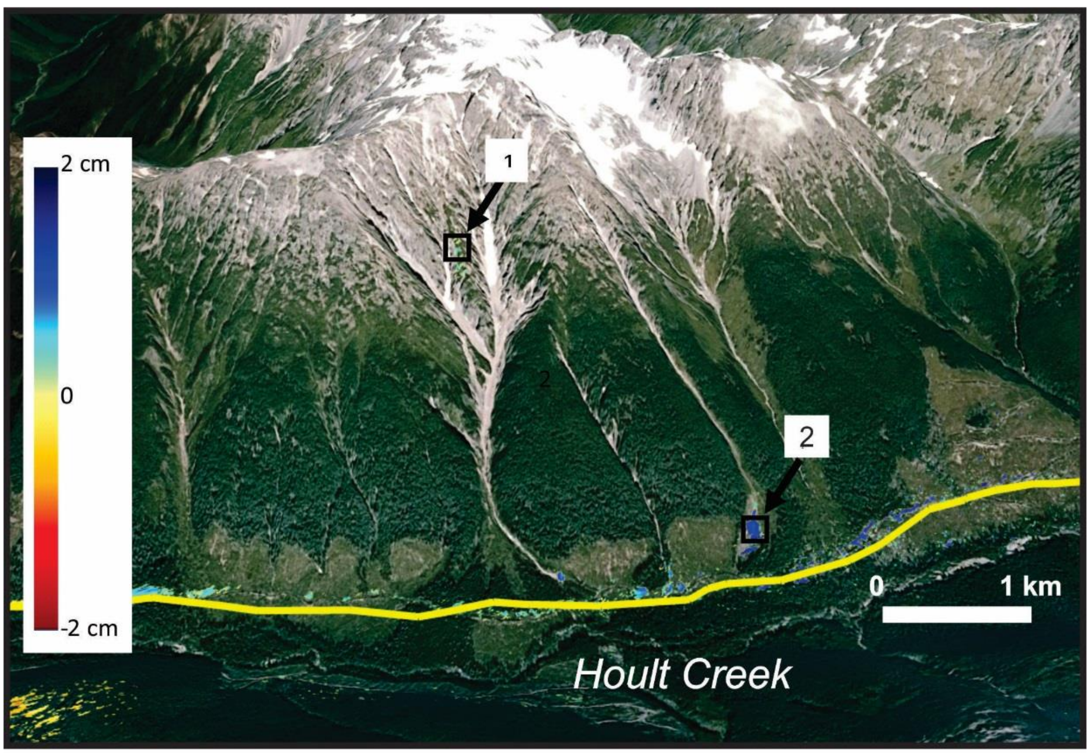

Figure 4. Ground displacement results from InSAR monitoring of slopes at Hoult Creek, west of Nimbus Mountain (see Figure 1 for location). Blue tones indicate accumulation of sediment and red tones, depletion (e.g., 1 and 2, also shown in Figs 3a and b). Points 1 and 2 also reflect active debris flow channels. Yellow line shows a proposed pipeline route.

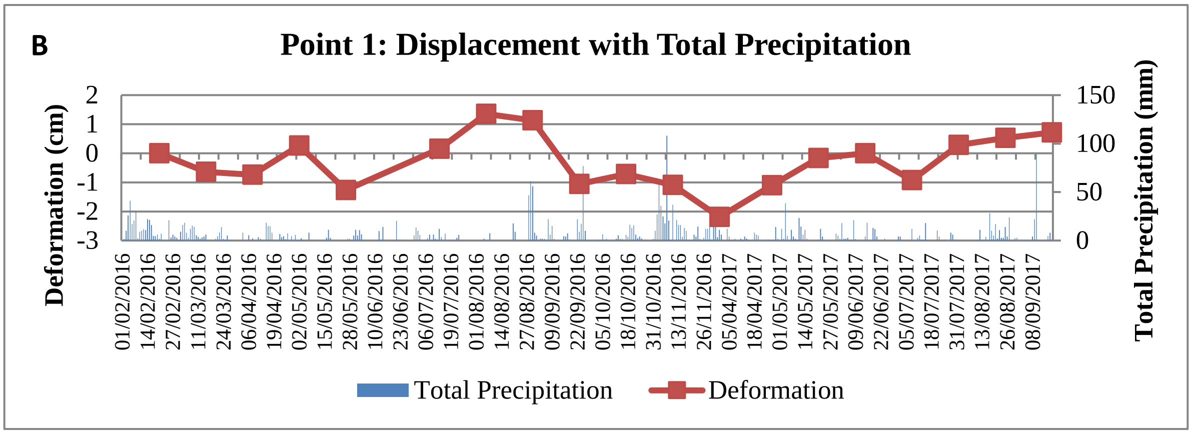

Figure 5. Ground displacement measured from InSAR with total precipitation from Feb. 2016-Sept. 2017); Point 1 (see Fig. 4 for location).

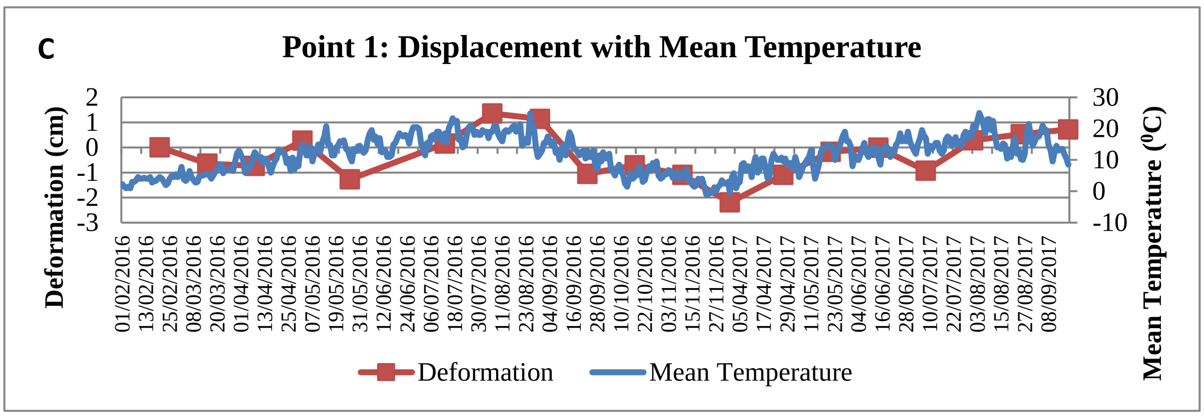

Figure 6. Ground displacement measured from InSAR with mean temperature from Feb. 2016-Sept. 2017; Point 1, see Fig. 4 for location).

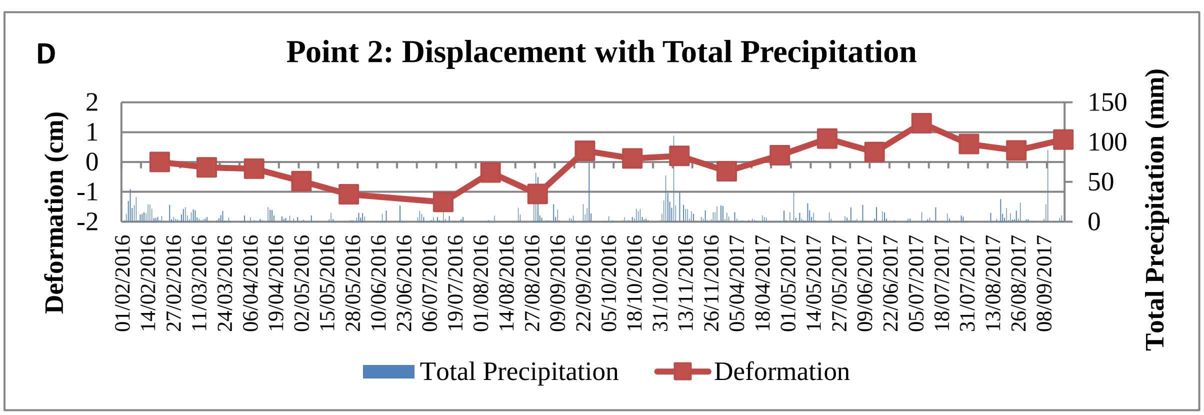

Figure 7. Ground displacement measured from InSAR with total precipitation from Feb. 2016-Sept. 2017; Point 2 (see Fig. 4 for location).

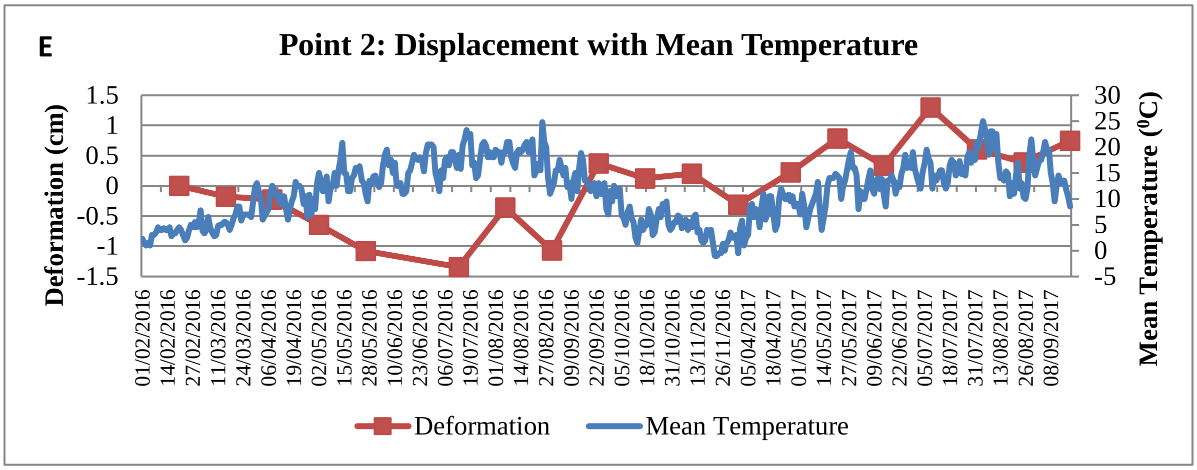

Figure 8. Ground displacement measured from InSAR with mean temperature from Feb. 2016-Sept. 2017; Point 2, see Fig. 4).

4.2 InSAR monitoring of slopes

InSAR monitoring of the area just west of Nimbus Mountain (Fig. 4) took place from February 2016 to early September 2017 (roughly 19 months). We also compared the InSAR with climate data results for the same period of time. The closest station was roughly 50 km away at Kitimat (Fig. 1). Although the time period of monitoring is short, some preliminary observations can be made. At point 1 in the upper reaches of a debris flow channel, there is no direct link between precipitation over time and surface displacement (Figs. 4 and 5). This is expected as it is in the upper slope where you normally see denudation rather than sediment accumulation. InSAR data appear to reflect increasing negative surface displacement in some of the smaller channels during the summer months when it is dryer (less precipitation), but also when snow is melting at higher elevations. There is an apparent link between temperature and surface displacement (Fig. 6). Changes in deformation in the upper slope appear to reflect seasonal trends, correlating especially well to increasing and decreasing temperature (Fig. 6).

Point 2 at the base of the slope is on a debris flow fan (Figs. 3a, 4) where surface displacement, i.e., sediment accumulation, increases over time (Figs. 7 and 8). It does not, however, directly reflect changes in precipitation (Fig. 7). Through time there is a cumulative positive surface displacement/sediment accumulation which can reflect sediment deposition because of higher precipitation in the fall and winter months, but also during spring freshet. In any case, if a channel slightly alters its course, some areas may witness periods of erosion (i.e., negative surface displacement) and thus would not necessarily directly correlate with temperature and precipitation. Perhaps if climate data were available from a weather station closer to the site and observations were made for a longer period of time, linkages would be clearer.

The InSAR results have captured active surface displacements in the upper and lower slope of debris flow channels. This is something to consider when routing and building pipelines, roads or any other linear infrastructure at the base of steep slopes. In addition, in a very short period of time, InSAR data have demonstrated a useful remote method of monitoring steep mountainous terrain.

4.3 Debris flow susceptibility using Flow-R

Debris flow susceptibility was calculated using Flow-R (Horton et al. 2008; 2013). Figure 9 shows Flow-R results for the area west of Nimbus Mountain where there is high probability of propagation in each of the mapped debris flow fans. This includes the fan with active surface displacement (sediment accumulation) monitored with InSAR (Fig. 4, point 2; Fig. 9, white arrow). Moreover, all the steep channels indicate high probability of debris flow occurrence. This is observation is validated by the debris flow fans mapped, in addition to transport direction arrows shown in Figure 3a.

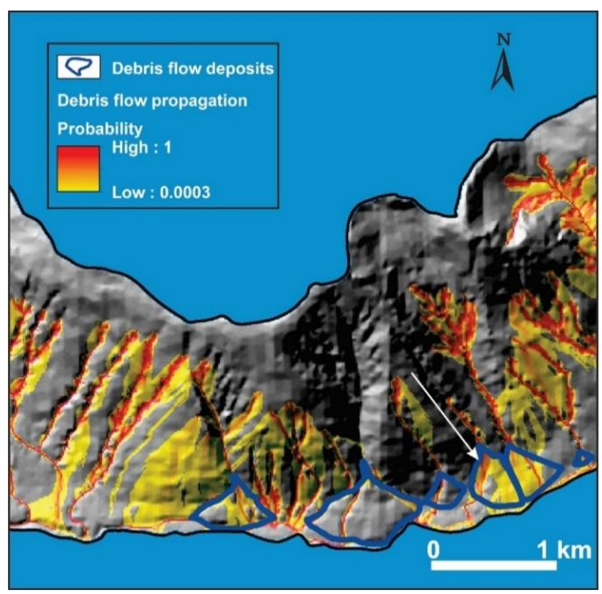

Figure 9. Debris flow susceptibility calculated with Flow-R. White arrow points to channel with high probability of occurrence and sediment accumulation from InSAR monitoring.

5. CONCLUSIONS

Surficial geology and landslide inventory of the 105-km long Kitimat-Morice River corridor have identified a total of 162 landslide deposits of various types . Debris flow deposits (=59) and scree and talus deposits from rockfalls (79) make up 85% of the landslides. In addition, landslide tracks and deposits that were too small to outline as polygons were also compiled at a total of 1182 features. To highlight our results, we focused on a smaller area just west of Nimbus Mountain, along a section of the steep, gullied valley-wall of Hoult Creek. Surficial geology and terrain stability mapping, InSAR monitoring, and debris flow susceptibility mapping using Flow-R all indicate high instability in the steep channels. This must be considered when building linear infrastructure such as pipelines,bridges and roads.

Correlations with climate data (temperature and precipitation) and InSAR monitoring results were made in the same area west of Nimbus Mountain showing cumulative negative and positive surface displacement (InSAR data) in the upper reaches of a debris flow channel and of the lower slope, respectively. The links with climate were somewhat tenuous since a 19 month period is a short period of time and the climate station is located at a distance of 50 km . Nevertheless, InSAR monitoring proves as a valuable and cost-effective tool for monitoring remote mountainous areas.

5. ACKNOWLEDGEMENTS

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