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2018

Canada

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2018

Permanent link: https://doi.org/10.4095/313286

This publication is available for free download through GEOSCAN (http://geoscan.nrcan.gc.ca/).

Recommended citation
Brillon, C., Cassidy, J.F., Nykolaishen, L., Allen, T.I., Bednarski, J.M., Greene, P., Bobrowsky, P.T., and Huntley, D.H., 2018. Assessment of seismic hazards in British Columbia's north coast region (2013–2018); Geological Survey of Canada, Open File 8461, 23 p. https://doi.org/10.4095/313286

Publications in this series have not been edited; they are released as submitted by the author.

Abstract

British Columbia's north coast (BCNC) has been the location of a number of development proposals over the last decade. As such, it has the potential to experience significant industrial, and consequently, economic and population growth. Negative impacts of geohazards, such as earthquakes and slope failures, and their secondary effects such as tsunamis could be detrimental to the region. Due to the historically low frequency of damaging geohazards in the BCNC, until 2013 there had been minimal research to understand them beyond the national-scale level. In 2013, Natural Resources Canada initiated a regional geohazard assessment, including marine and terrestrial-based research activities within BC's North Coast. The terrestrial-based component of the assessment specifically aimed to achieve a more detailed comprehension of active faulting, earthquake recurrence relationships, and strain accumulation patterns in the BCNC, necessary to improve seismic hazard models for use in the National Building Code of Canada. Through a multidisciplinary approach, including the deployment and monitoring of data from 7 new seismographs, it was confirmed that the regional seismicity pattern was, in general, being captured by the exisiting Canadian National Seismograph Network. However, the additional seismographs allowed for microseismicity patterns in the BCNC to be mapped in more detail. Displacements recorded on 8 new GNSS (Global Navigation Satellite System) stations show that the BCNC was, and is still (as of mid-2018) affected by the the 2012 M_W 7.8 Haida Gwaii earthquake more than 150 km to the west. Over the course of this project a seismic microzonation study was conducted in the town of Kitimat, the town at the most inland extent of the Douglas Channel. Results of this study show that the geology underlying Kitimat is complex with a number of deep channels filled with soft, glaciomarine sediments, which are prone to amplification of up to approximately four times. Although this project was formally completed in March 2018, seismic, GNSS and InSAR monitoring will continue for a number of years to allow for a more detailed understanding of seismicity and crustal strain in the region. This, in turn, will allow for improved seismic hazard models with applications to building codes, engineering design, and decision-making.

Contents

1. Introduction

With a significant number of ongoing and proposed infrastructure projects British Columbia's north coast is emerging as a region of growth and an important contributor to Canada's economy (British Columbia Major Projects Inventory, 2018). The environment and therefore the economy are vulnerable to the negative impacts of geohazards (and their secondary effects), such as earthquakes and slope failures. Within the Coast Mountains between Prince Rupert and Bella Bella, herein referred to as the BCNC (Figure 1), there has been minimal research to understand regional geohazards. Specifically, a more detailed understanding of where and how regional strain is being accumulated in the crust and the likelihood of damaging earthquakes occurring in this area is necessary to improve seismic hazard models for use in the National Building Code of Canada.

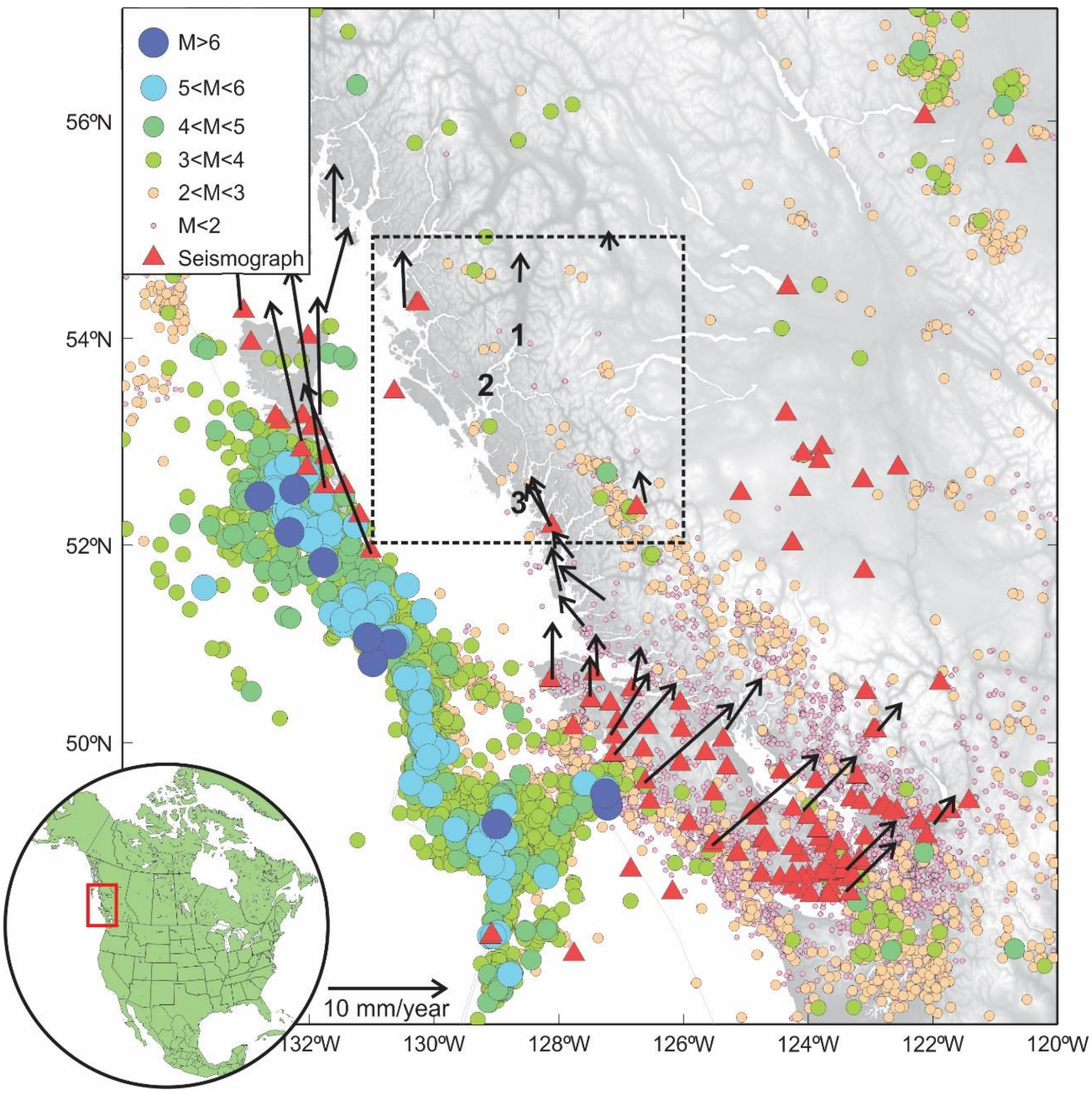

Figure 1 - Map of Canada's Pacific margin (area outlined by red in inset), showing observed horizontal deformation (black arrows, from Hippchen, 2011); seismicity (circles) and seismograph stations (red triangles) operating between 2004 and 2014. 1, 2 and 3 are locations of 1974 & 1975 Kitimat Arm failures; Hawkesbury Island submarine failures; and Kitasoo Hill (respectively). The black, dashed square outlines the BCNC study area.

One motivation for this study was triggered by the findings from Conway et al., 2012, in which analysis of multibeam and bathymetry data revealed two large Holocene submarine slides off the west shore of Hawkesbury Island (Figure 1). These 30 m^3 blocks of fjord wall are now identified as submarine sackungen (Conway and Barrie, 2018). In addition, two tsunamigenic landslides occurred in Kitimat Arm on October 17, 1974 and April 27, 1975 (Figure 1; Murty, 1979; Murty and Brown, 1979). While the 1974 Kitimat Arm slide was related to construction, less is known about the cause of the 1975 Kitimat Arm and Hawkesbury Island failures. The north coast geohazards research project set out to explore, amongst many other things, possible relationships between observed ground failures and earthquake-induced ground shaking. Specifically, is the seismicity being underrepresented in the region, is there microseismicity (earthquakes less than magnitude (M) 2.0) that is not being recorded or located, is there an alignment of seismicity that could indicate motion along a known or unknown fault, which in the event of failure could trigger tsunamegenic ground failures?

Following a baseline assessment (Brillon, 2016), field programs were conducted and instrumentation was installed in the BCNC with the aim of improving the regional geohazard knowledge. Included in the field programs were a number of marine and airborne surveys discussed in Conway and Barrie, 2015; Huntley et al., 2018; Shaw and Lintern, 2016; Shaw et al., 2017 and Maynard et al., 2017. To address shortcomings of the regional seismic hazard, seven seismometers and eight GNSS (Global Navigation Satellite System) stations were installed to monitor seismicity and long term deformation in the BCNC. In addition, LiDAR and paleotsunami surveys were conducted, and InSAR studies are underway to augment the GNSS and seismic data. In addition, a number of surveys were conducted to better understand local ground motion amplification within Kitimat, BC, the community at the head of the Kitimat Arm of the Douglas Channel.

2. Enhanced Seismic and GNSS Monitoring

In 2014, NRCan installed five temporary earthquake-monitoring sites in the BCNC, each including a seismometer and GNSS pier (Table 1; Figure 2). It was anticipated that the densified seismic network would aid in identifying, locating and decreasing location errors of earthquakes in the BCNC, as well as eventually decreasing the completion magnitude (M_c) below the pre-2014 level of M 2.1. In late 2015, a seismometer was installed on soft soil in Kitimat to compare ground shaking at station KITB, installed on bedrock in Kitimat, as part of a ground-motion amplification study (discussed in a subsequent section). In 2017 a seismometer was installed on Gribbell Island near a fault extending along the west coast of Hawkesbury and Gribbell Islands (Conway and Barrie, 2015), to ensure that any microseismicity potentially related to the fault could be recorded. In addition, between 2014 and 2015, real-time GNSS stations were upgraded on Bonilla Island and in Bella Coola, Smithers*, and Bella Bella* (*GEOBC sites), which were all sites of previous GNSS surveys (Hippchen, 2011 and references therein).

The targets for the monitoring sites were chosen to optimize network coverage, allowing for microseismicity ($M<2$) to be located, as well as measure crustal strain rates which could help assess the potential of $M>7$ crustal earthquakes occurring in the BCNC. All sites, except for those in Kitimat and on Bonilla Island, are remote mountaintop locations where main power is supplied by solar panels and communications are through the local cellular network, or VSAT (very-small-aperture terminal). Due to the remote location of most of the stations, anthropogenic noise levels are within Petersen high and low noise levels (Petersen, 1993; Figure A1). The high elevations of the stations resulted in numerous weather-related instrumentation failures. Wind, lightning, snow and cloud cover all contributed to disabling power and/or communications for periods of time, thus hindering data return (network return is 88%; Figure A2) and data analysis capabilities.

Planning is in progress to upgrade communication instrumentation (which will decrease station downtime) with the intention of continuing to operate the monitoring stations for up to 10 or more years. This will allow for a GNSS time-series adequate for determining crustal movements and a more compete earthquake catalogue.

Table 1 - Details of earthquake monitoring stations in BCNC (* are GeoBC stations. ^ are CNSN stations). See Figure 2.

Station Code	Latitude	Longitude	Location	Seismometer	GNSS	Installation or Upgrade Date
BBB	52.19	-128.11	Bella Bella	X^		1986-12-05
BCTE	54.51	-128.63	Terrace		X*	1996-06-21
RUBB	54.33	-130.25	Prince Rupert	X^		2001-07-18
BCPR	54.28	-130.43	Prince Rupert		X*	2004-11-04
KITB	54.08	-128.64	Kitimat	X		2014-03-20
BNAB	53.49	-130.64	Bonilla Island	X^	X	2014-03-25
BNKB	53.33	-129.90	Banks Island	X	X	2014-08-20
BUTB	53.06	-128.46	near Butedale	X	X	2014-08-21
HWKB	53.60	-129.15	Hawkesbury Island	X	X	2014-08-21
GRNB	53.85	-129.96	near Grenville Channel	X	X	2014-08-24
BLCL	52.39	-126.59	Bella Coola		X	2015-03-19
BCDI	52.16	-128.11	Bella Bella		X*	2015-03-27
KTMT	54.09	-128.60	Kitimat		X	2015-09-25
SMTH	54.82	-127.19	Smithers		X*	2015-12-08
MBLB	54.04	-128.63	Kitimat	X		2015-12-09
GRIB	53.34	-129.14	Gribbell Island	X		2017-08-29

2.1 Seismicity

The installation of additional monitoring stations in the BCNC increased the ability to detect microseismicity to approximately M 0.7 near the centre of the network. For the first 3 years after the installation, almost 400 earthquakes (Figure 2) and upwards of 100 industry-related blasts were located within the BCNC. The majority of the blasts were near Huckleberry mine. The earthquakes range between M 0.5 and M 3.7, with depths between 1 km and 20 km. While the M_C has not noticeably decreased (Figure A3), the number of M<2 earthquakes located in the BCNC over a 3-year period beginning September 2014 is the same as the number of earthquakes located in the 10 years prior to this project. Similarly, location errors decreased 75% and 50% in the N/S and E/W directions (respectively) and magnitude calculations are more robust as they are derived from more stations. Since a large number of events are near the southern extent of the network, near Bella Coola, the majority of depths remain difficult to determine and are generally fixed by a seismic analyst. Despite the increased number of small earthquakes located in the BCNC since 2014, there are no new significant clusters of earthquakes or alignments of seismicity that obviously indicate motion on a fault.

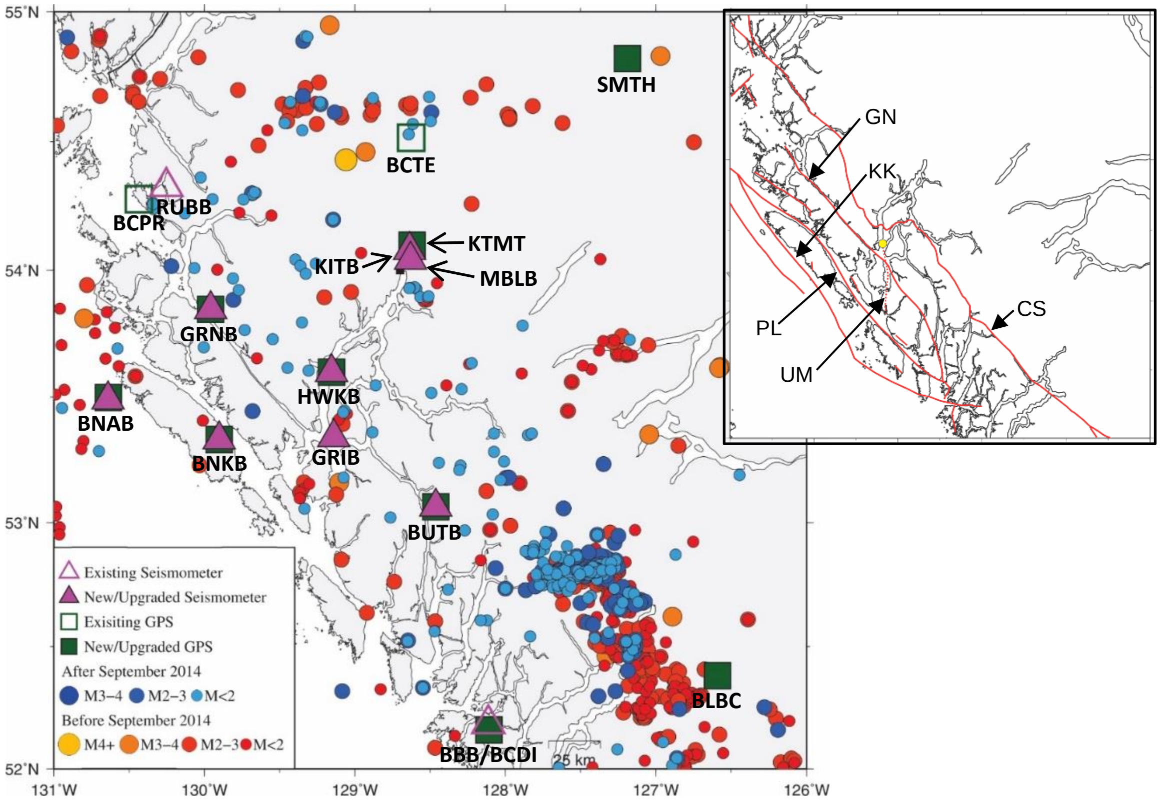

Figure 2 - Historic seismicity located in BCNC prior to (1973-2014, hot colours) and after (2014-2017, cool colours) the installation of BCNC monitoring stations. Inset (after Wheeler et al., 1996; Chardon et al., 1999; Crawford et al., 2005) shows mapped faults as red lines (GN – Grenville Channel Shear Zone, KK – Kitkatla Shear Zone, CS – Coast Mountain Shear Zone, PL – Principe-Laredo Shear Zone), previously unmapped fault (UM – Unmapped fault) as dashed, red line and location of submarine sackungen as yellow circle.

Similar to historic seismicity patterns, the majority of earthquakes located in the BCNC are near to, and likely related to, the Anahim Volcanic Belt (Cassidy et al., 2011). Although the number of earthquakes in this area appears high relative to the rest of the BCNC, the high M_C as well as network and catalog inconsistencies, do not currently allow for a robust analysis of the seismicity in this area.

It is known that landslides in the BCNC are common (e.g., Geertsma et al., 2006; Jakob et al., 2006). Due to the geography and climate of the region, numerous ground failures occur annually. During the fall and winter of 2017-2018 a record number of landslides were observed in the BCNC (S. Hutchings, 2017, personal communication). Although the exact causes of these landslides are not determined, two significant rainfalls on September 10 and October 23, 24 bringing 75 - 90 mm of rain to the BCNC each of those days (Environment Canada, 2018) likely contributed the reported historical number of landslides. During the autumn of 2017, a number of signals were observed on BCNC seismographs that have characteristics similar to known, recorded landslides (Kao et al., 2012). These have no clear P-wave and S-wave arrivals, predominant frequencies between 0.5 to 5 Hz, and are tens of seconds in duration. Of the documented landslides in the BCNC, at least two can be spatially correlated with seismic events derived from these signals, suggesting that the signals could be ground motions related to the observed landslides. Unfortunately, exact dates and times of the landslides are not known, which does not allow for confirmation of this link. With more detailed investigation, automatic detection, location and forecasting of rain-triggered landslides in some areas of the BCNC could be possible. The accuracy of this will depend on landslide characteristics and proximity to seismic stations. Information regarding recent landslides or landslide hazards would be useful for stakeholders whose infrastructure and safety may be at risk from landslides, and landslide-triggered tsunamis.

Given the relatively short length of time these monitoring stations have been installed, the observations made thus far represent only an initial step towards completely understanding seismic hazards of this region. We have learnt that the BCNC has smaller earthquakes which until 2014 had likely not been detected, and therefore were not included in the Canadian earthquake catalogue. At this time, the magnitude, frequency and location of these small earthquakes do not introduce a significant change to the seismic hazard in the BCNC. Moreover, with additional time and the occurrence of significant earthquakes in active tectonic regions, such as Haida Gwaii, updates to source zones, seismic attenuation relationships and regional stress models used in the Canadian seismic hazard model will be feasible.

2.2 GNSS

With a network of 11 GNSS stations operating in the BCNC (Table 1; Figure 2), in the long term it will be possible to determine the regional strain rate. Currently, the ability to determine strain rates is impacted by the short monitoring period as well as post-seismic motions from the October 28, 2012 Haida Gwaii M_W 7.8 earthquake (Cassidy et al, 2014). In addition, seasonal and inter-annual surface loading are contributing to the observed signal. Since the 2012 Haida Gwaii earthquake significant post-seismic motions have been observed at GNSS sites on Haida Gwaii. Displacements measured on the GNSS stations in the BCNC are consistent with those observed on Haida Gwaii, indicating a broad area to a distance of at least 300 km remains affected by the earthquake more than five years later (Figure 3; Nykolaishen et al., 2015, 2016).

Currently, the amount of displacement observed in the BCNC is not sufficient to warrant a change to the regional seismic hazard. However, as the majority of these stations were installed late 2014 to early 2015, results are based on a relatively short time-series. With the extension of the lifetime of the stations, calculation of strain rates will be possible. This will allow for a better understanding of the strain being accumulated in the BCNC, give insight to the earthquake cycle, and ultimately allow for incorporation of strain rates in seismic hazard maps for use in building codes.

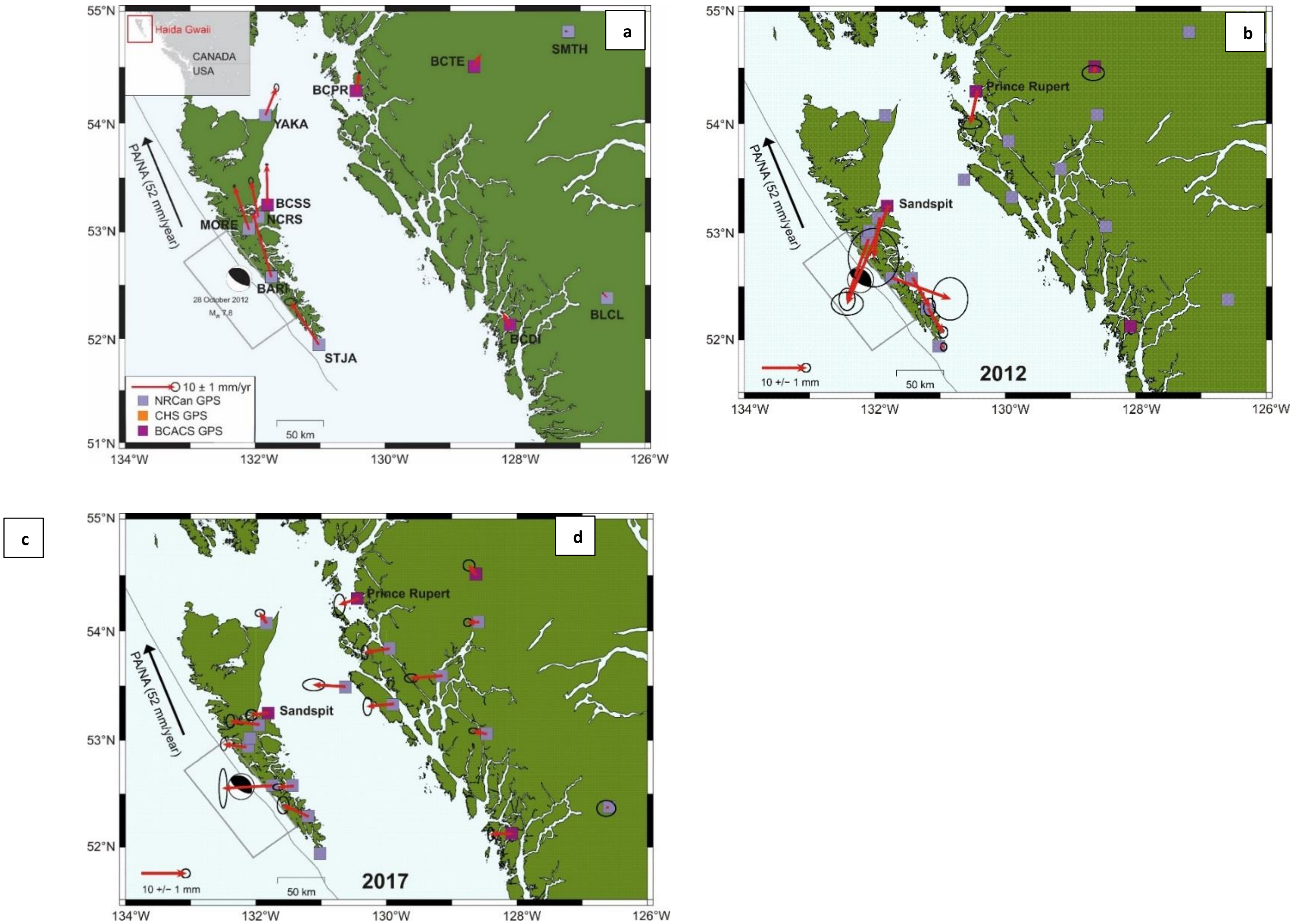

Figure 3 - Net deformation measured at GNSS sites (a) prior to, (b) during the M_w 7.8 Haida Gwaii earthquake and (c) during 2017. (d) Deformation in the north-south direction since 2006 at GNSS site in Sandspit, BC (BCSS). From Nykolaishen et al., 2015, 2016.

3. LiDAR Studies

Light Detection and Ranging (LiDAR) is a remote sensing technology that uses non-invasive lasers to create a 3D image of an area. Aerial LiDAR surveys can highlight geographical features such as landslides and faults that would otherwise be difficult to map in heavily forested areas and rough terrain. LiDAR surveys were completed along the SW coast of Hawkesbury Island, the NW coast of Gribbell Island, Kitasoo Hill, and along Sandspit Fault on Moresby Island. These surveys are being used for landslide (Maynard et al., 2017), geotechnical, and paleoseismic studies.

3.1 Kitasoo Hill

Kitasoo Hill is a small volcanic cone belonging to the Milbanke Sound cones on southern Swindle Island (Wood, 1992), situated along the northwest-trending Principe-Laredo Fault (Figures 2 & 4). The fault traverses the southwest corner of Swindle Island and, together with Price Island, appears to be displaced laterally to the right about 6 km, relative to the northern part of Swindle Island. In 2016, sub-bottom surveys along Laredo Strait found evidence of disturbed bottom sediments, possibly from a landslide (C. Stacey, 2016, personal communication). LiDAR (Figure 4) and subsequent fieldwork were completed in the Kitasoo Hill area to establish the age relationship between the volcanic eruptions of the Kitasoo volcanic cone and adjoining glacial and postglacial sediments. A specific goal of this research was to determine the genesis of the prominent terrace abutting the cone and to assess the feature's importance with respect to neotectonics along the Principe-Laredo Shear Zone, i.e. was this disturbance related to recent movement along the fault zone and is this related to the recent volcanic activity?

Preliminary analysis of the LiDAR collected shows no evidence for movement along the Principe Laredo Fault in the last 10 000 years. Fieldwork showed that the terrace is entirely composed of brecciated pyroclastic flows overlying indurated glacial till. No organic material suitable for radiocarbon dating was found but oriented samples from the terrace are normally magnetized and indicate that the entire thickness of the terrace feature was deposited in a relatively short period of time. Further analysis to determine the stratigraphic relationships of the glacial, volcanic and littoral sediments is ongoing.

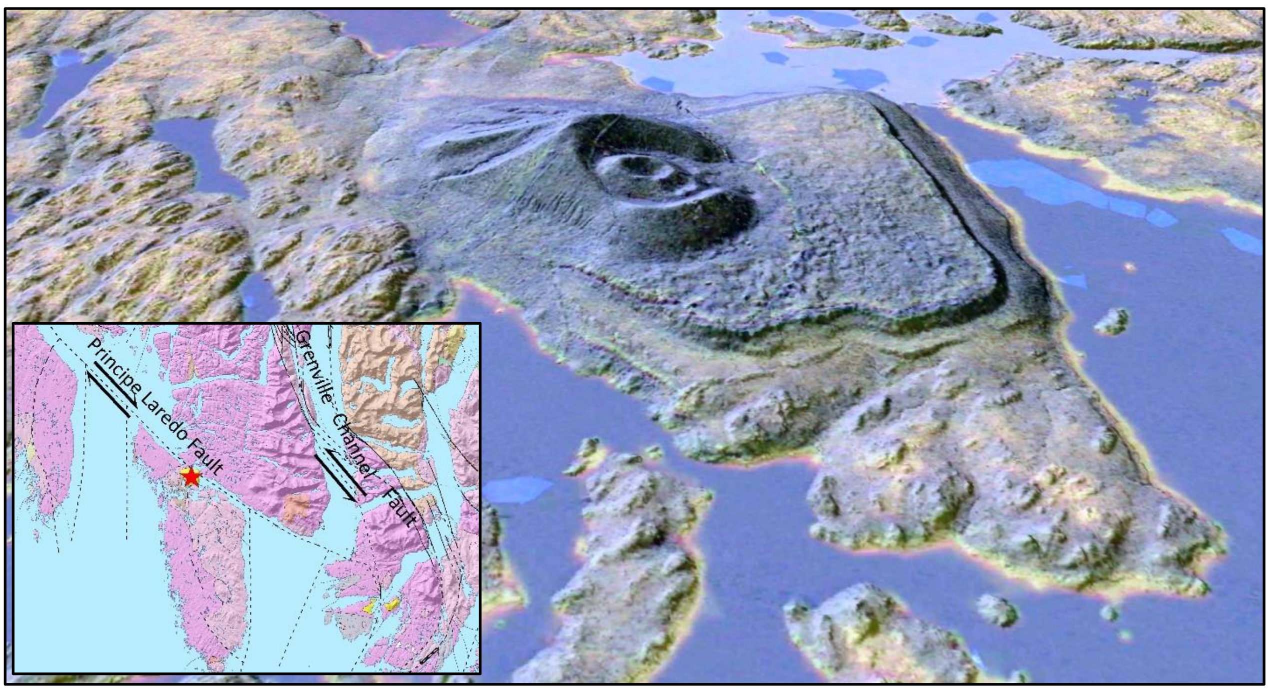

Figure 4 - Kitasoo Hill LiDAR. Red star is location of Kitasoo Hill (J. Bednarski). For regional setting, see Figure 1.

3.2 Sandspit Fault

A main contributor to the hazard in the BCNC is large earthquakes originating near Haida Gwaii (Figure 1). Not only do the Queen Charlotte Fault and Haida Gwaii thrust fault pose a hazard, but crustal earthquakes on Haida Gwaii and in Hecate Strait could also cause significant shaking throughout the region. LiDAR-derived digital surface models from Haida Gwaii are being interpreted in the context of postglacial geomorphology and earthquake activity. The focus of this mapping is the identification and measurement of offset linear features in the landscape to determine whether surface faults have been active in the Holocene. The preliminary target for this study is the Sandspit Fault (Figure 5) running NW-SE from the eastern edge of Moresby Island up into the interior of Graham Island. Across the majority of the mapped fault trace there are limited geomorphic observations that indicate Holocene motion on the fault (P. Schoettle-Greene, 2018, personal communication). Mapping of abundant linear glacial landforms such as flutes and drumlins on Haida Gwaii and their relationship with the topographic steps is ongoing and will be used to constrain the relative timescales over which this topography has developed. The final geomorphic map will provide new constraints on the potential for shallow crustal earthquakes on Haida Gwaii.

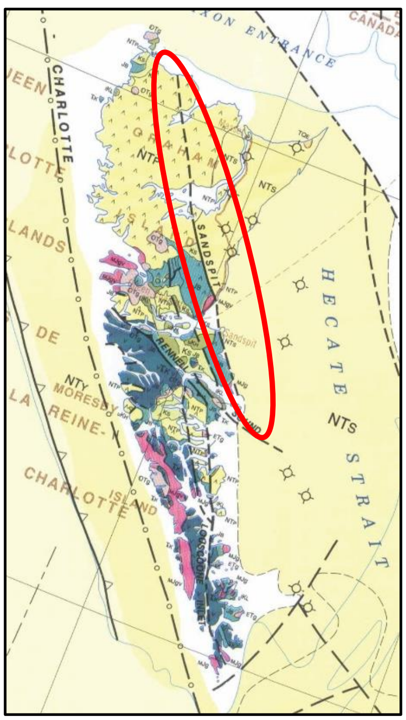

Figure 5 - Mapped faults on Haida Gwaii, including Sandspit Fault (circled in red). From Wheeler & McFeely, 1991.

4. InSAR Studies

Following the reveal of the two large deglacial submarine failures offshore SW Hawkesbury Island in 2012 (Figure 1, 2; Conway et al., 2012), the relationship between these failures and lineaments observed along SW Hawkesbury and NW Gribbell Islands came into question. Numerous approaches were taken to understand the possible relationship between these lineaments (also known as sackungen features) and the submarine failures, now identified as submarine sackungen (Conway and Barrie, 2015; Conway and Barrie, 2018). To monitor movement associated with the sackungen five corner reflectors were installed for an Interferometric Synthetic Aperture Radar (InSAR) study, using satellite imagery from Canada's Radarsat-2 (CSA, 2018). Due to the remoteness of this area, there are no coherent targets, which required the installation of corner reflectors (Figure 6). Radarsat-2 captures images of this region 3 or 4 times per month. By comparing the phase difference of signals reflected from the corner reflectors during subsequent satellite passes, changes of the landscape to the millimetre scale may be revealed (Journault et al., 2018). Trees, water and atmospheric effects can introduce random backscatter on SAR images. Given this, 2-3 years of images may be required to filter these effects and achieve reliable InSAR results.

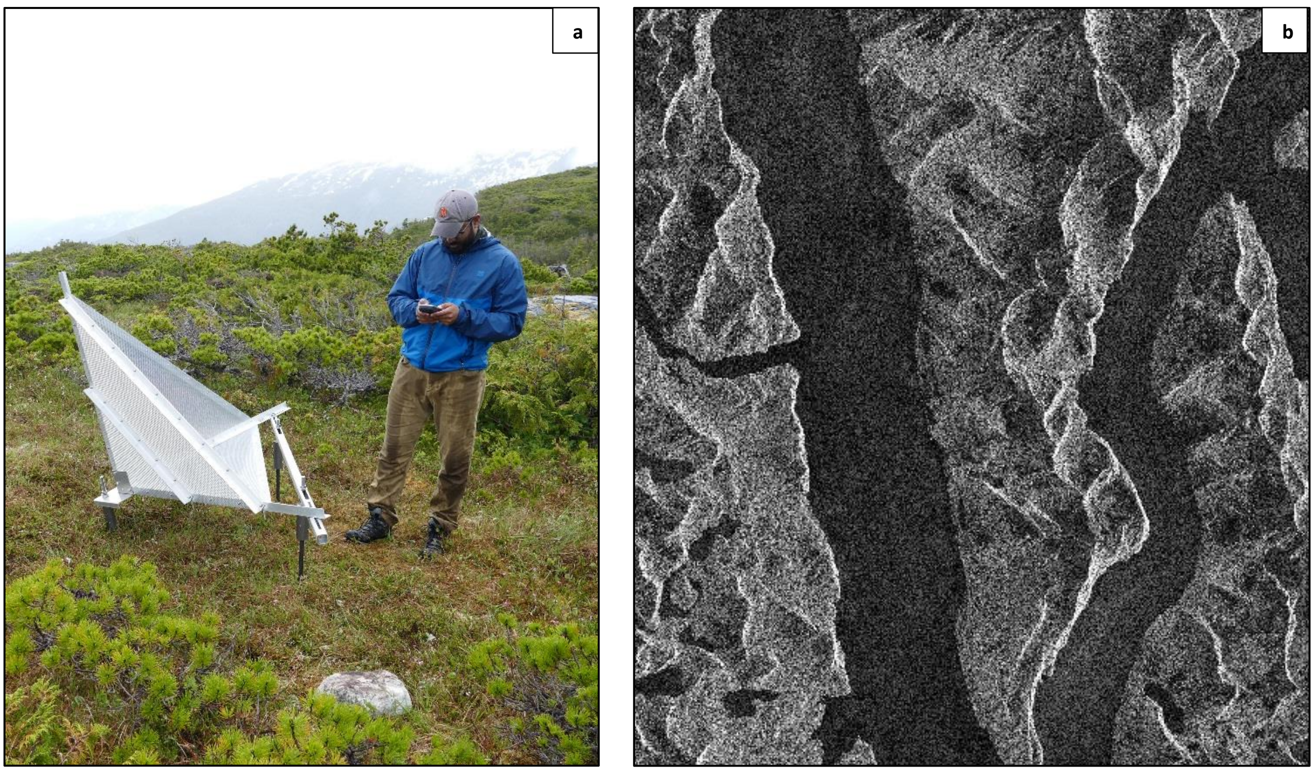

Figure 6 - (a) Corner reflector installed on southern Hawkesbury Island (b) SAR **i**mage of southern Hawkesbury Island from Radarsat-2**.**

5. Paleotsunami Studies

Numerous sites along the Cascadia subduction zone have preserved clastic deposits attributed to great earthquake-triggered tsunamis (Huntley et al., 2018). However, prior to this study a significant paleotsunami data gap existed in the BCNC. The high-energy conditions of coves, bays, lagoons, channels, inlets and fjords of the BCNC rarely support sufficient soft-sediment accumulations capable of preserving a geological record of activity during the Holocene. Moreover, those rare deposits that contain measurable amounts of unconsolidated sediment are usually no more than a few centuries old and typically reflect short-term fluvial accretion on fans and deltas; remobilization of older deposits by landslides; monotonous gravel beach accumulations from tidal wave action; or reworking of marine and fluvial sediments during storm surges. Tsunami deposits that were found in the BCNC as a part of this project represent earthquake or landslide-generated tsunamis (see Huntley et al., 2018). Efforts are now underway to distinguish the source mechanism of such deposits and confine the age of the events.

6. Kitimat Site Response Studies

Earthquake-induced ground shaking can be amplified in areas with significant impedance contrasts, i.e. thick layers of low-velocity sediments overlying stiff bedrock. In such a setting, the impedance contrast causes a shortening of shear-wave wavelengths and an increase in shear-wave amplitudes (Shearer and Orcutt, 1987; Hunter and Crow, 2012). Where there are very large impedance contrasts, amplification can be increased when shear waves become trapped in the low-velocity soil zone and 'ring' at the fundamental frequency (f_0) and subsequent harmonics until the energy eventually dissipates. In areas with irregular topography (i.e. valleys and hills), interference between reflected seismic waves can introduce further amplification effects (Hunter et al, 2010, Hunter and Crow, 2012 and references within). Local site amplification (i.e. basin effects) is not included in seismic hazard values provided by Earthquakes Canada.

To refine the seismic hazard model for Kitimat to include possible amplification of ground motions due to local geology, a number of geophysical surveys were completed in the Kitimat Valley to gather information about the thickness, structure and shear-wave velocity of unconsolidated sediments overlying bedrock (all needed to model local ground motions). Results of these surveys can be used to guide future decision-making processes of engineers and community planners. Details of collection, processing and interpretation of microtremor, seismic reflection, and borehole logging surveys, as well as externally sourced data are included in Pugin et al., 2018 (and references within). Results of dispersion array inversion for determining shear-wave velocity, National Building Code of Canada site classification, and amplification factors at specific sites in Kitimat are presented in Gosselin, 2016 and Gosselin et al., 2017.

In 2015 a seismometer (station MBLB; Table 1; Figure 2) was installed in an area of Kitimat with an average f_0 (from microtremor surveys), indicating a layer of relatively (within Kitimat) average thickness of soft soils. Ground-motion data from earthquakes recorded at MBLB are compared to that at KITB, a seismometer installed on bedrock. Whereas more traditional HVSR are calculated from local earthquakes with a higher frequency content, in the absence of local earthquakes greater than M 2, data from more distant, larger earthquakes can been used (Ferretti et al., 2007). While these distant earthquakes do not have the same frequency content, the expected fundamental frequency and amplification do agree with those from ambient noise surveys (Brillon et al., 2015; Crow et al., 2015) and dispersion arrays (Gosselin, 2016; Gosselin et al., 2017). As a result, it can be concluded that on average, ground motions in Kitimat can be expected to be amplified by approximately 4 times at a fundamental frequency near 1 Hz (Figure 7b). An improved understanding of local earthquake site response and basin amplification in this area will contribute to better building practices for future community planning and infrastructure development in Kitimat and communities located in similar environments (i.e. valleys with thick glaciomarine sediments).

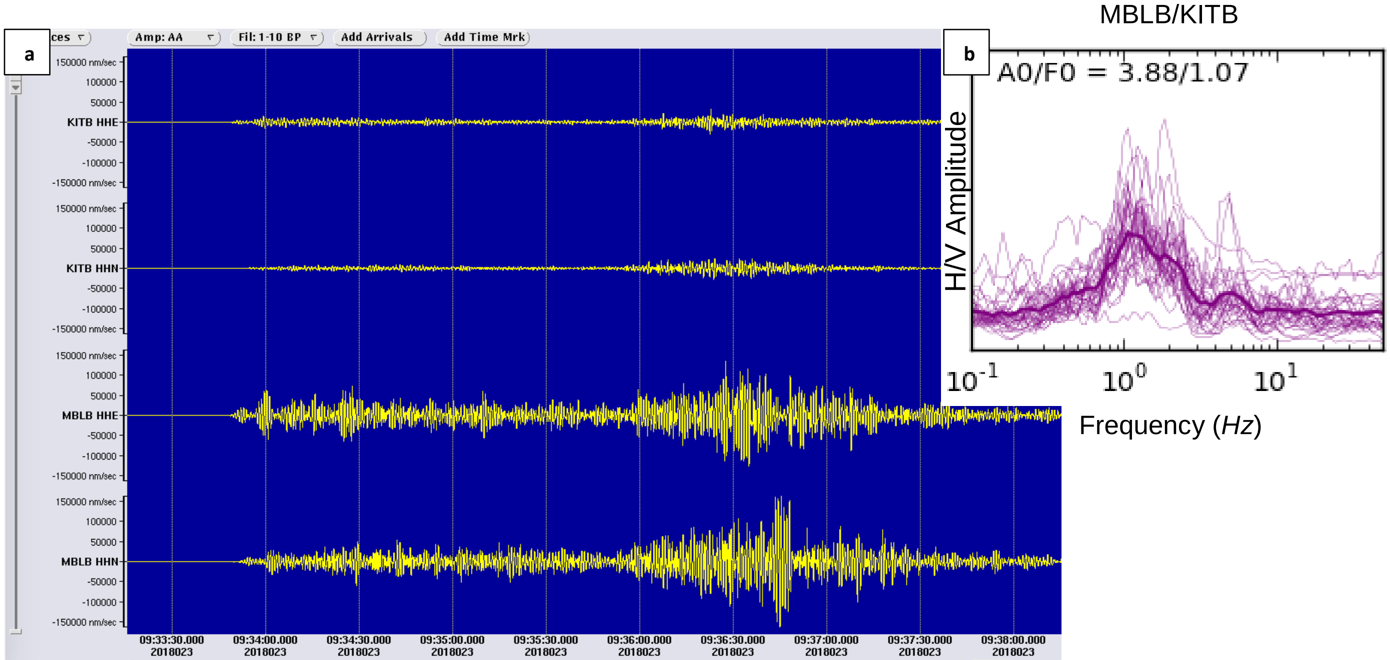

Figure 7 – (a) Seismograms recorded at KITB (hard rock) and MBLB (softer soils) during the January 23 M_W 7.8 Alaska earthquake. (b) Ratio of vertical to horizontal spectra between KITB and MBLB, showing amplification at a resonant frequency of 1 Hz of almost 4.

7. Seismic Hazard

As previously discussed, to date there has been no change to the estimated seismic hazard in the BCNC, as a result of this study. The seismic hazard in the BCNC, according to the 2015 Canadian Seismic Hazard Map (Halchuk et al., 2015) is highest on the west coast, decreasing towards the east and north (Table 2). This has changed since 2013; due to the inclusion of the oblique motion of the Pacific plate under the North American plate offshore Haida Gwaii as a distinct seismic source (Allen et al., 2015). The highest seismic hazard for all areas of the BCNC is from low-to-moderate period shaking less than 0.5 s, which would have the most impact on structures up to approximately five stories (Arnold, 2007). Although shaking of these levels would be felt in the BCNC, it would likely not be strong enough to cause structural damage.

Table 2 - 2015 National Building Code interpolated seismic hazard values for select locations in the BCNC (2%/50 year probability; site class C). Spectral (Sa(T), where T is in seconds), peak ground acceleration (PGA) is given in units of g (9.81 m/s^2). Peak ground velocity (PGV) given in m/s. Note that these hazard values are not based on a specific earthquake, and do not take into consideration local site conditions, which may alter the ground motion response.

		Period (s)	**0.2**	**0.5**	**1.0**	**2.0**	**PGA**	**PGV**
Location	Latitude	Longitude	2%/50y	2%/50y	2%/50y	2%/50y	2%/50y	2%/50y
Terrace (BCTE)	54.52	-128.60	0.146	0.145	0.120	0.085	0.072	0.200
Prince Rupert (RUBB)	54.33	-130.25	0.239	0.262	0.204	0.133	0.144	0.308
Kitimat (KITB)	54.00	-128.70	0.165	0.173	0.141	0.099	0.082	0.230
BUTB	53.06	-128.46	0.187	0.202	0.164	0.113	0.092	0.259
HWKB	53.62	-129.13	0.205	0.222	0.177	0.118	0.099	0.274
GRNB	53.85	-129.96	0.265	0.287	0.220	0.142	0.125	0.326
BNKB	53.33	-129.90	0.328	0.341	0.253	0.158	0.152	0.362

8. Summary

As a result of this project, the BCNC now has 10 seismograph and 11 GNSS stations to better record regional seismicity and crustal deformation. Although the accuracy of the earthquake locations significantly increased, the seismicity located in the BCNC since 2014 has not revealed any currently active structures. Given the relatively short time series of the GNSS network in the BCNC, updated strain rates for the area are not available, however, observed crustal deformation appears to remain affected by the 2012 M_W 7.8 Haida Gwaii earthquake (Nykolaishen et al., 2015, 2016). Operation of all seismic and GNSS stations in the BCNC will continue for up to another 10 years. With this additional time, a more definitive distribution of seismicity and an update of regional strain rates in the BCNC will be possible, allowing for a more detailed seismic hazard assessment.

The increased monitoring and research in the BCNC has the ability to improve the tsunami and landslide hazard models of the region, as those hazards can both be earthquake-triggered events. In the event of non-earthquake-triggered landslides (the majority), or mass-movement triggered tsunamis (i.e. landslide-triggered), they may be recorded on seismographs (this study), or subsea pressure-monitoring instruments (Lintern et al., 2018). In addition, the increased seismograph coverage will allow for improved monitoring of the Anahim Volcanic Belt.

To complement the monitoring of current seismicity and strain rates, corner reflectors have been installed on Hawkesbury Island which are bring monitored by InSAR satellite methods to identify any small movement associated with the land-based sackungen above the submarine sackungen (Figure 1). Preliminary InSAR results are expected late 2018.

Other methods of identifying the occurrences of large earthquakes include seeking evidence of secondary effects of ancient earthquakes such as tsunamis, landslides, and fault offsets. Detailed analysis of LiDAR collected along the apparent fault trace on Hawkesbury and Gribbell Islands, and on Kitasoo Hill and Moresby Island to identify evidence of ancient large earthquakes in the region is underway. Paleotsunami surveys have been conducted throughout the BCNC (Huntley et al., 2018) to identify where tsunamis have occurred in the BCNC. Thus far, evidence collected identifies a number of tsunami deposits in the BCNC. Further work will aid in identifying the origin (earthquake or landslide generated) and approximate age of these deposits.

Numerous surveys have been completed to better understand amplification of ground motions in Kitimat. Comparisons of ground motions on hard and soft rock sites reveal that earthquake shaking can be amplified at a fundamental frequency near 1 Hz, by up to 4 times in some areas of Kitimat. Results of the seismic reflection and HVSR surveys will be used to model potential amplification throughout Kitimat, and ultimately would be used in community planning and engineering design.

Combining information gained from the many aspects of the marine portion of this project (Lintern et al., 2018), with those from the terrestrial studies discussed in this paper allows for a better understanding of the geohazards in British Columbia's north coast. Many of the methods that were used to identify and assess the geohazards achieve the greatest and most reliable results when used repeatedly, or over long periods of time. Many instruments that were deployed during the 5 years of this project will stay in place for a number of additional years, which will allow for further research and a more complete geohazard assessment.

9. Acknowledgments

The work presented in this paper would not have been possible without CHIS (Canadian Hazard Information Service) who installed the monitoring stations, as well as Dan Perera and Danial Mariampillai who maintained these stations during the course of the project. Site response studies were conducted thanks to the efforts of many people (Jim Hunter, Michelle Cote, Jeremy Gosselin, Kevin Brewer, Heather Crow, Andre Pugin, and Tim Cartwright). Palaeotsunami sites were accessed with support from the crew of the Canadian Coastguard research vessels John P Tully and Vector. Many thanks to the GeoBC and Canadian Hydrographic Service for GNSS data and use of their sites. LiDAR surveys were acquired through collaborations with Brian Menounos at the University of Northern British Columbia, and Taan Forest. We would also like to acknowledge the Gitga'at, Lax Kw'alaams, Kitsumkalum, Metlakatla, Heiltsuk, Kitasoo, Gitxaala, Kitselas and Haisla First Nations, the community of Kitimat, and private landowners in Kitimat who have provided continued support for this work.

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Appendix

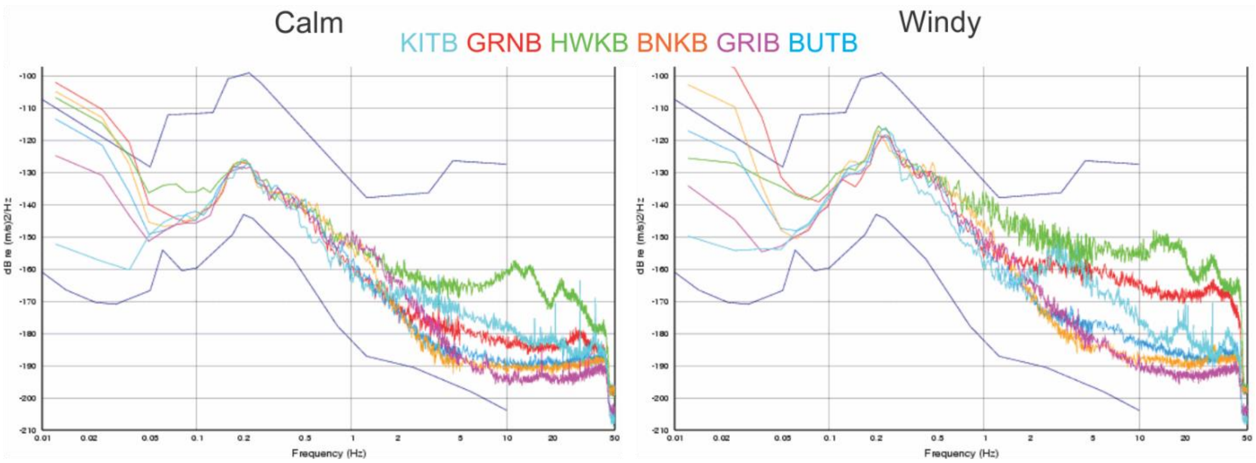

Figure A1 - Power Spectral Density plots for vertical channels of BCNC seismometers (representative colours shown by colour of the station name) for a relatively calm (October 3, 2017) and windy (October 18, 2017) day compared to Petersen high and low noise levels (dark blue; Petersen, 1993).

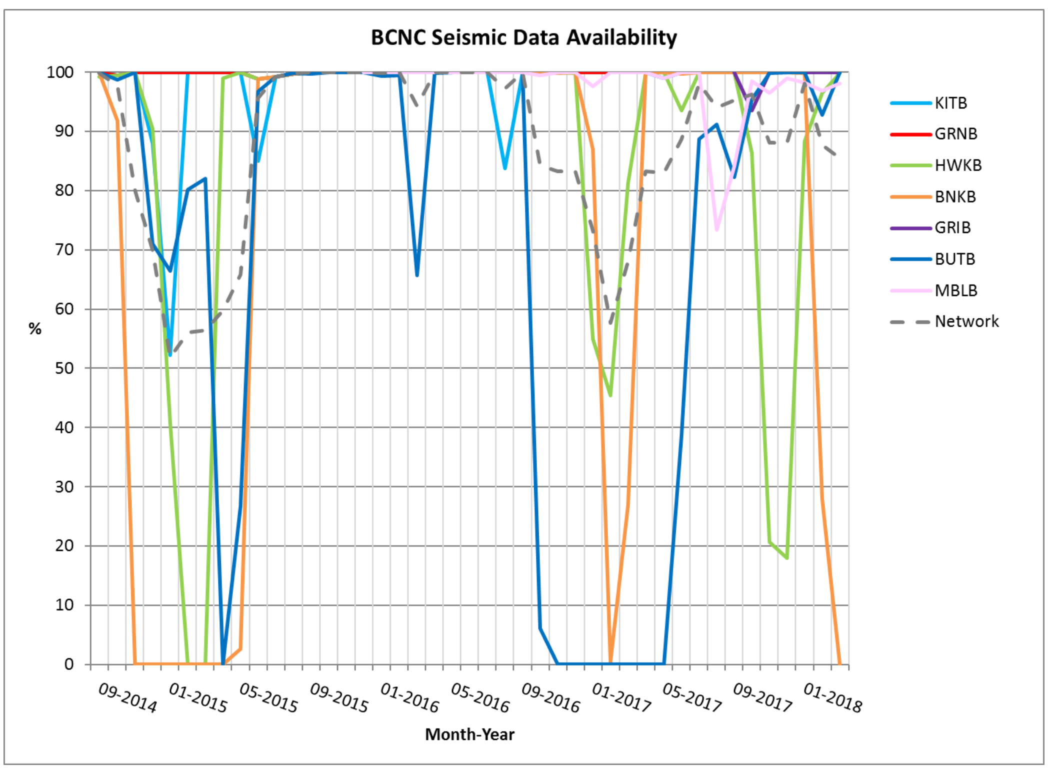

Figure A2 – BCNC seismic data availability (September 2014 through March 2018).

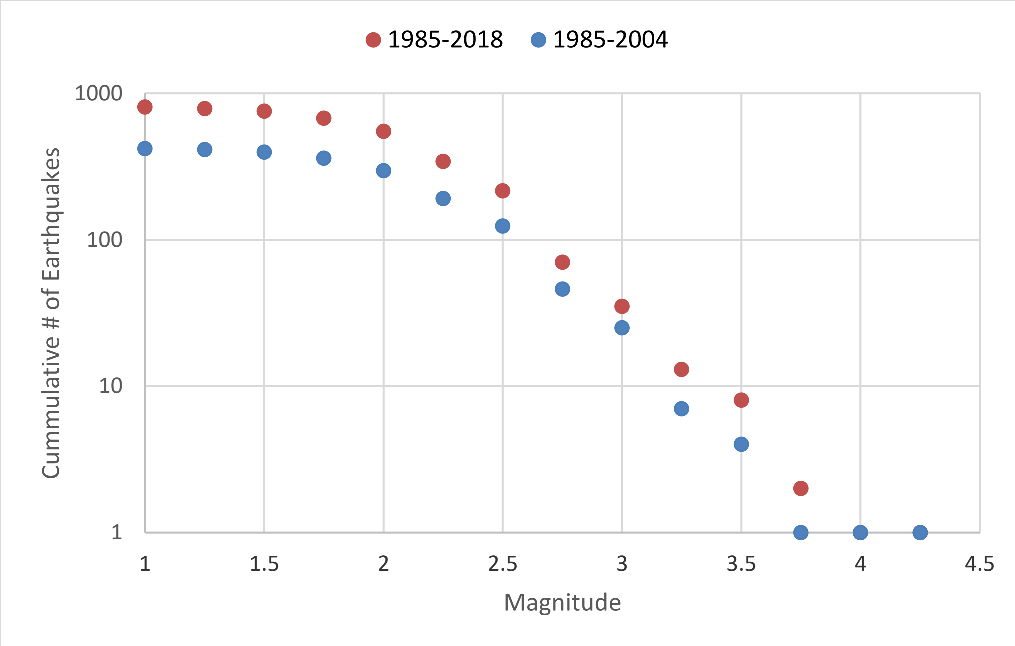

Figure A3 - Gutenberg Richter relationship, showing very little change to apparent M_c and b-value (Gutenberg & Richter, 1954) before (blue) and after (red) installation of BCNC seismograph stations.