Strong Motion Monitoring in Canada and Recent Datasets From Natural Resources Canada

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ABSTRACT

Strong motion monitoring continues to evolve rapidly in Canada, with many organisations contributing data. This article summarises the current state of strong motion monitoring across Canada and recent (since 2015) strong motion datasets. As of January 2019, the Canadian National Seismograph Network (CNSN) upgrade is nearing completion, resulting in one of the most significant changes in strong motion monitoring in Canada since the first deployment of accelerometers in 1963. As a part of this upgrade, ~100 new strong motion instruments (Nanometrics Titans) were deployed at bedrock sites (co-located with weak motion broadband instruments) in high seismic hazard regions of Canada. In addition, ~40 stand-alone strong motion instruments are being deployed. Natural Resources Canada (NRCan) operated nearly 100 strong motion Internet Accelerometers (IA's) across Canada, primarily located on soil sites, and in the urban centres of high seismic risk in southwest British Columbia and southwestern Quebec/eastern Ontario. BC Hydro operates more than 90 strong motion instruments at dam sites and substations across BC. Other strong motion instruments in western Canada are owned by utilities or transportation organisations (BC Ministry of Transportation and Infrastructure has deployed nearly 100 instruments to monitor bridges and critical infrastructure). Ocean Networks Canada now has 7 strong motion instruments on the seafloor west of Vancouver Island and 14 strong motion instruments onshore Vancouver Island, and UBC and BCSIMS have deployed dozens of instruments in southwest BC. In eastern Canada, several organisations operate strong motion instruments, including: Hydro-Quebec at dams and substations; Ontario Power Generation and New Brunswick at their nuclear power stations; PWGSC at Parliament Hill; and Gaz Metropolitain at its Montreal LNG plant. Since 2014, more than 726 accelerograms have been recorded, most in the Vancouver Island region (e.g., 126 recordings of a Mw 4.7 near Victoria). While there were no nearby recordings of large earthquakes in the past 4 years (the strongest ground motions are accelerations of ~ 5% g) these datasets are useful for comparison with proposed attenuation relations, for evaluating local earthquake site response, and are valuable to engineers evaluating strong ground shaking during future earthquakes.

Keywords: seismic hazard, strong motion, seismic monitoring.

INTRODUCTION

The purpose of this paper is to provide: 1) a brief overview of the strong motion networks in Canada as of January, 2019; and 2) a summary of post-2015 Natural Resources Canada (NRCan) strong motion network datasets. For details of the history of strong motion instrument deployments in Canada see [1-8]. As in the previous summaries, there is an emphasis on free-field instruments, and the survey does not cover most structural monitoring instruments. Since the last review [8] the number of instruments deployed has increased by nearly 40%, all instruments are digital (most with real-time data availability), and a major deployment of nearly 100 strong motion (Titan) instruments at CNSN sites (bedrock) across Canada has occurred. These modern digital instruments provide high data quality even near their limit of resolution and have adjustable triggers, which means the trigger levels can be optimized based on the local site conditions. The largest networks are the strong motion network operated by NRCan (nearly 200 instruments), British Columbia Ministry of Transportation and Infrastructure (BCMoTI) with ~100 free-field and down-hole instruments and more than 50 additional structural monitoring instruments, BC Hydro, including dams and transmission facilities (91 instruments), UBC (67 instruments), Hydro-Québec (10 instruments), and Ocean Networks Canada (ONC) (34 instruments). Most of the strong motion sensors are deployed in the earthquake-prone areas of British

Columbia, Quebec, and the Yukon (Figures 1 – 5). A summary of instruments and owners is provided in Table 1, and a list of recent NRCan datasets is provided in Table 2.

STRONG MOTION NETWORKS – WESTERN CANADA

As of January, 2019, more than 418 strong motion instruments were operating across British Columbia (Figure 1). A brief description of the instruments operated by various organisations is provided below. It is noteworthy that nearly half of these instruments (e.g., those operated by BC MoTI and NRCan) are interconnected through the BC Smart Infrastructure Monitoring System – BC SIMS (http://www.bcsims.ca/) and, for the first time, 35 Titan strong motion instruments have been deployed at bedrock NRCan sites across the province as a part of the Canadian National Seismic Network (CNSN) network renewal. Many of the strong motion instruments operate through partnerships, for example BC MoTI now operates many of the NRCan IA's in BC, at several sites ONC and NRCan share facilities, communications and instrumentation, and NRCan and the BC Oil and Gas Commission (BCOGC) share 6 new sites in northeast BC.

Natural Resources Canada

The NRCan strong motion network in western Canada (Figure 1) is comprised of 35 Titan's, and nearly 100 other accelerometers (mostly IA's) operated in partnership with the BC MoTI, ONC, and the BCOGC. The IA's are connected to the internet and locally record data continuously (in miniseed format). They continuously compute a suite of ground parameters (e.g., PGA, PGV, PGD, and Katayama Spectral Intensity) and automatically push out these key parameters when triggered. The waveform data can be retrieved at any time via the internet. For more details of the IA, see [9] or http://www.earthquakescanada.nrcan.gc.ca/stndon/CNSN-RNSC/sm/IA_Details-eng.php (last accessed, January, 2019). The goal is to acquire strong ground motion records in or near urban environments and to define strong motion attenuation relationships in western Canada. There is also a focus on acquiring ground motion records on the soft soils of the Fraser River delta, and the Georgia Basin area to better assess the role of surficial soils, and deep basin structure (e.g., [10]) in earthquake ground shaking. These IA's are deployed in schools, surface vaults, or small buildings to provide near free-field recordings.

Much of the growth of strong motion instrumentation in British Columbia is the result of modernisation of the CNSN and the addition of instruments for development of earthquake early warning systems by ONC and UBC.

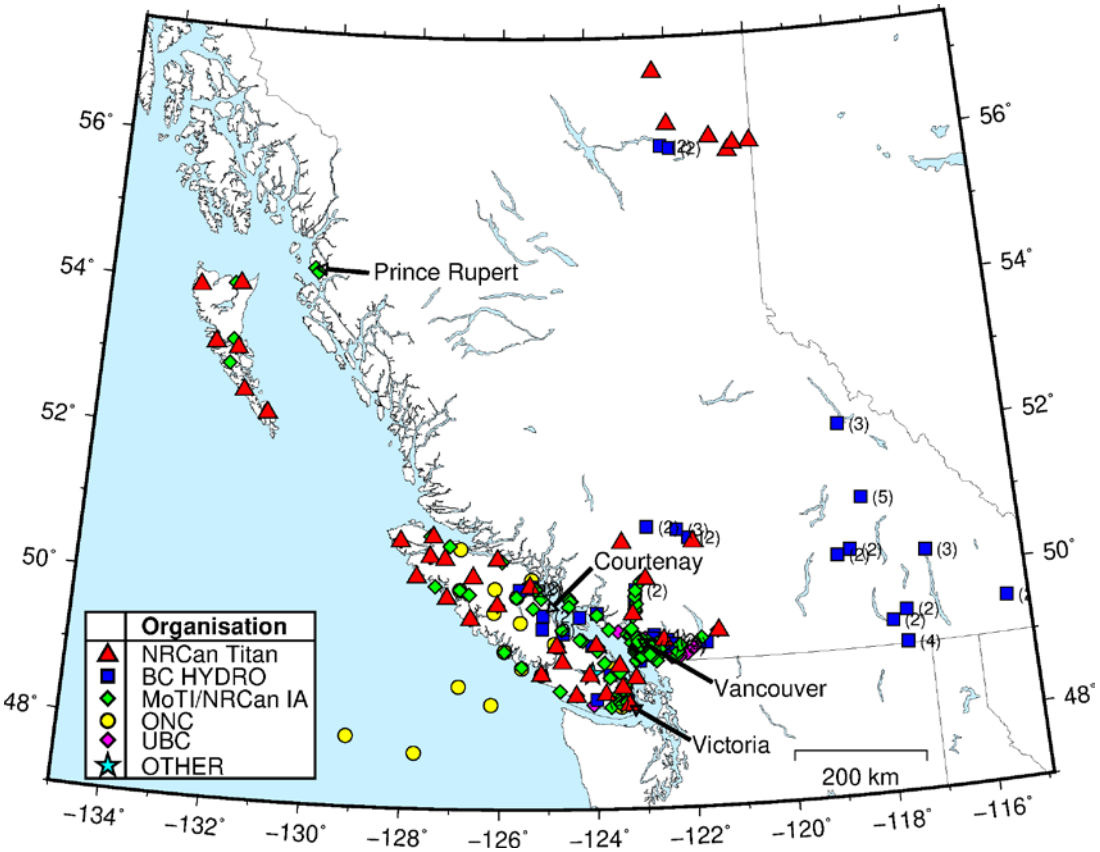

Figure 1. Strong motion seismographs in British Columbia. Numbers in parenthesis indicate the total number of instruments at that site.

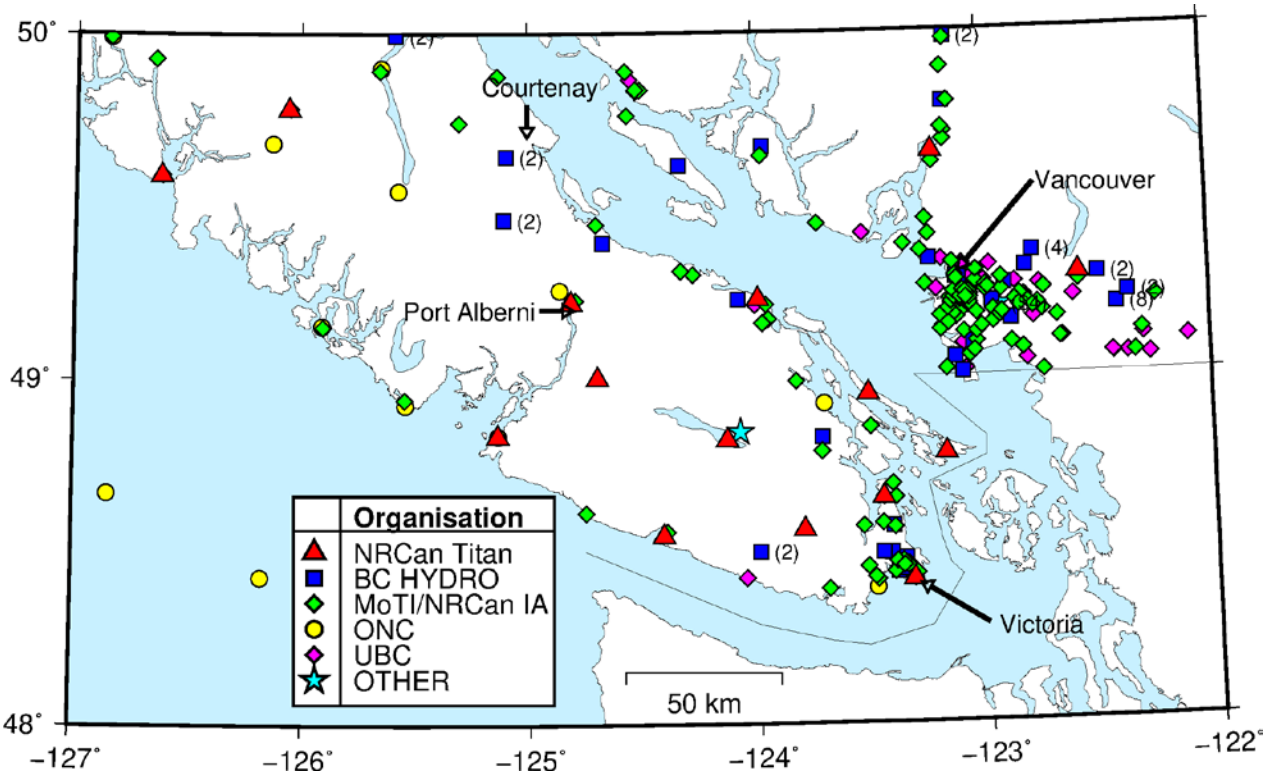

Figure 2. Strong motion seismographs in southwest British Columbia. Numbers in parenthesis indicate the total number of instruments at that site.

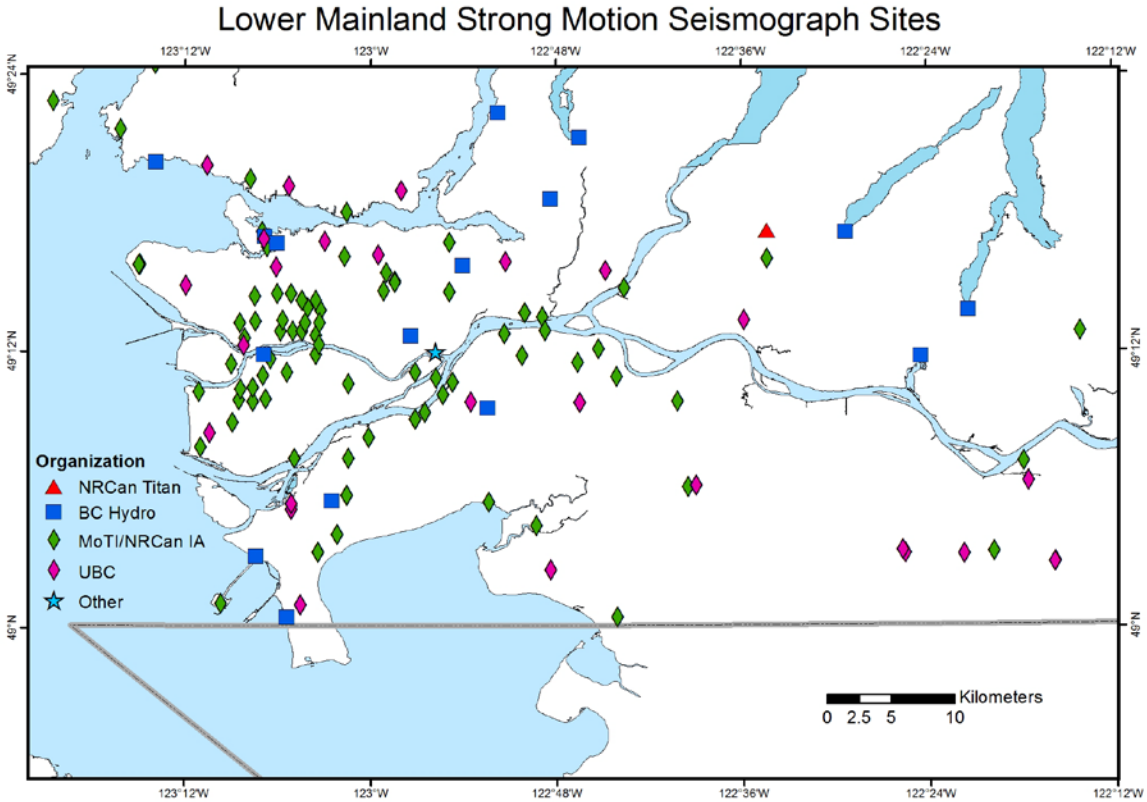

Figure 3. Strong motion seismographs in Greater Vancouver and the lower mainland

Current operation and site conditions of NRCan Titans

The Titans are currently streaming data at 100 s/s and are set for the maximum 4 g recording level. The continuous records from the Titan sensors are available by request to the NRCan's National Waveform Archive. It is intended that higher sample rate streams be implemented, with the understanding that the data will be stored in the digitizer for later request, and not streamed because of bandwidth costs. The availability of 100 s/s data is very important for developing GMMs at short periods, and it is important to extend acquisition of the data to 200 or 250 s/s in order to acquire data for future studies.

Almost all NRCan Titans are deployed on bedrock (co-located with CNSN broadband instruments). The goal is to record the pattern of shaking on rock, but a few Titans are deployed on soil to help determine the non-linear behaviour of the soil under strong shaking. The latter is very important for the thick Leda clay deposits of the St. Lawrence valley, as we know that they provide very strong linear amplification of weak shaking (up to ~50 times stronger than on rock) with basin effects, but currently we have no records of their behaviour in the non-linear domain (i.e. for the strong shaking that is important for damage).

British Columbia Hydro

The BC Hydro strong motion network in British Columbia has expanded since 2007. BC Hydro maintains 91 strong motion instruments at most hydroelectric dams and transmission facilities across the province (Figures 1-3). These instruments provide data for both the dam safety program (e.g., for post-earthquake dam performance) and the transmission program (e.g., post-earthquake analysis of transmission facility performance). A total of 67 instruments operate at 26 dam facilities (labelled "BC Hydro" in Figures 1-3), with multiple instruments often installed at a dam site in locations such as the crest, abutment or toe (in a few cases on foundation bedrock). In addition, there are 15 seismic triggers that provide notification of shakings exceeding target threshold levels. Of the 67 instruments, most are digital SYSCOM MR202 units, with 2-g full scale, and trigger thresholds of about 0.5%g, 5 are Altus-ETNA's and 6 are EpiSensors (2g). A further 24 instruments are deployed at transmission facilities (major substations and terminal stations – most are in urban settings and deployed on soil). These are all SSA-2's or ETNA's, 2-g full scale with trigger thresholds of either 0.4%g or 0.6%g.

None of the BC Hydro and Transmission instruments currently provide data in real-time. There are plans to upgrade this monitoring network over the next several years.

British Columbia Ministry of Transportation and Critical Infrastructure (BC MoTI)

The BC Ministry of Transporatation and Infrastructure (BC MoTI) has expanded and densified its strong motion monitoring network (labelled "MoTI" in Figures 1-3) in recent years and is in the process of improving visualisation software and web access to information (including shakemaps). The purpose of this expansion is to contribute to situational awareness at the time of an earthquake (providing shakemaps and ground shaking parameters for BC MoTI and emergency responders), and, much like ShakeCast (e.g., [11]), to prioritise infrastructure inspections and aftershock response, and to provide data in real-time that may be useful for other applications such as earthquake early warning.

In addition to monitoring key bridges and transporatation infrastructure, strong motion instruments have been deployed at some schools and BC Housing facilities, and are being added at remote "DriveBC" sites with power and internet. As of January, 2019, nearly 100 strong motion seismographs are operating (in free-field conditions) and many more instruments are operating on key structures (e.g., the new Port Mann Bridge has a total of 350 channels, and the Second Narrows Bridge has 122 channels). The majority of the free-field strong motion sensors are IA's. In addition, BC MoTI has deployed five new downhole strong motion arrays on the Fraser River delta just south of Vancouver (two arrays on the South Fraser Perimeter Road project, and three downhole arrays near the Port Mann Bridge). These data are combined with those of other organisations and are available via the British Columbia Smart Infrastructure Monitoring (BCSIMS) project [12]. Future plans including instruments at additional DriveBC sites, partnering with the City of Vancouver for bridge monitoring, and perhaps adding GPS data to generate displacement maps.

Ocean Networks Canada (ONC)

As of January 2019, Ocean Networks Canada operates a total of 34 strong motion instruments in southwest BC, including 7 seafloor strong motion instruments (2 Guralp accelerometers and 5 Titans) at 5 sites offshore Vancouver Island, and 27 Titans onshore (mostly on Vancouver Island). A number of the ONC instruments are co-located with NRCan instruments (broadband seismic and GNSS) in order to share resources and communications where possible. In total, ONC expects to operate (or contribute to) a total of 38 sites for use with earthquake early warning systems (e.g., see [13])**.**

University of British Columbia (UBC)

The University of British Columbia (Department of Civil Engineering – Earthquake Engineering) is a leading contributor to the BCSIMS project [12]. In addition, UBC has deployed P-wave detectors at ~30 schools across southwestern BC as part of

an earthquake early warning system. Currently 67 instruments (not linked with BCSIMS at this time) are deployed at 33 sites (Figures 2 and 3), most located in greater Vancouver.

Other

FortisBC Gas operates two strong motion instruments at the Tillbury Island LNG plant, just south of Vancouver, Tata Communications Canada (formerly known as Teleglobe Canada) operates an instrument at Cowichan Lake on Vancouver Island, and the BC Oil and Gas Commission (BCOGC), in partnership with NRCan, operates 6 strong motion instruments (Titan PH sensors) in the Dawson Creek and Fort St. John areas of northeast BC (Figure 1).

STRONG MOTION NETWORKS – EASTERN CANADA

As of January, 2019, approximately 70 strong motion instruments are operational at 68 sites in eastern Canada (Table 1). The substantive change since the last review [8] has been the network refurbishment referred to above. Unlike western Canada, where nearly all seismograph stations will have Titan sensors, in eastern Canada fewer will have strong motion instruments added. Those to receive Titan sensors are those located where broadband seismometers have the highest probability of clipping during a 20-year period, i.e. the ones in the higher seismic hazard regions. A second aspect of the refurbishment underway in 2018-2019 is the replacement of most of NRCan's ETNA and IA eastern network with streaming Titan sensors. A third aspect is the deployment (in the coming year or two) of additional of Titans in previously non-instrumented areas between Hamilton and Quebec City, with the goal of achieving a ~70 km spacing in order to speed up rapid earthquake notifications and provide rapid, high-quality records of strong shaking and extra records for some nearby weaker earthquakes (because of the low-noise floor of the Titan sensors).

In 2019, NRCan operated an eastern regional network of 54 instruments (many in the vicinity of the seismically-active Charlevoix region) to gather near-field strong motion data and to help define strong ground motion attenuation relations for eastern Canada. The current NRCan strong motion network (see Figure 4) comprises 43 Titans (34 of which are co-located with weak motion seismographs and 9 of which are "stand-alone"). There are also seven IA's (four deployed in Montreal and three in Ottawa) and 4 ETNAs scheduled for replacement by Titans in 2019. In a joint deployment with Carleton University, NRCan instrumented several deep-soil basins near Ottawa together with a nearby rock reference site for periods of a few years, but these deployments have ended.

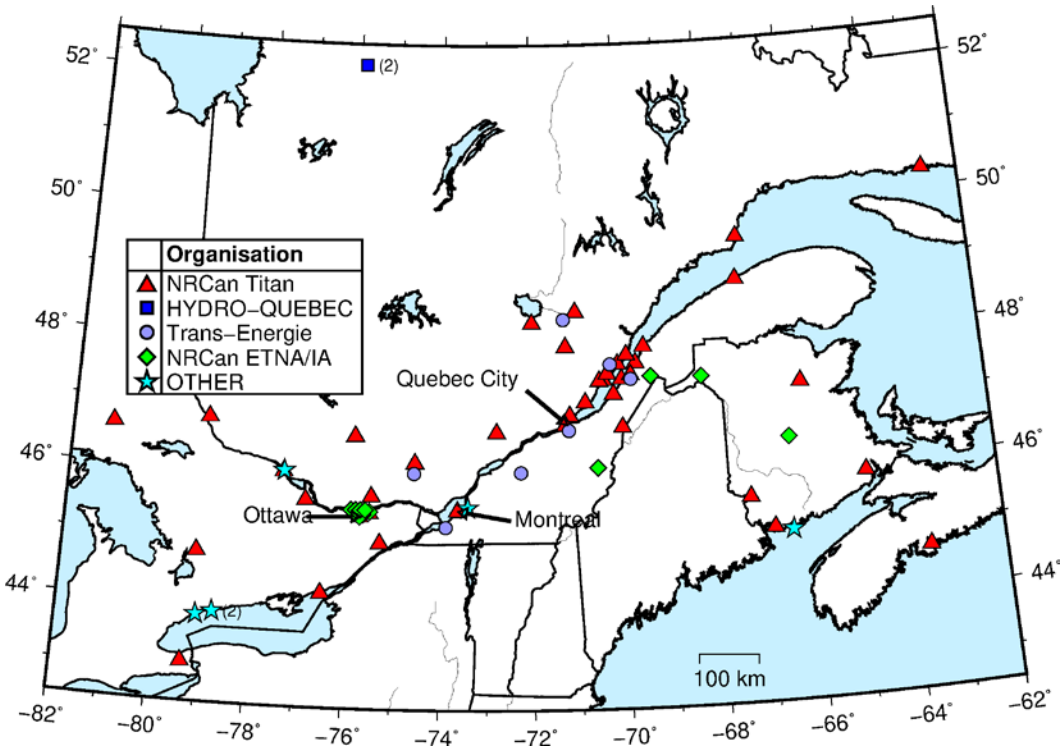

Figure 4. Strong motion seismographs in eastern Canada.

Strong motion instruments are also operated by Hydro-Québec Production and Trans-Energie units of Hydro-Québec. Their instruments are installed at key hydroelectric dams and transformer sub-stations (Figure 4) as a part of their overall permanent seismic monitoring program. Most of the 10 instruments are Kinemetrics SSA-1's (1 or 2g) or 2g ETNA's. Ontario Power

Generation and New Brunswick Power operate triggered strong motion instruments in and (for free-field motions) near their nuclear power plants in Ontario and New Brunswick, respectively, and Gaz Metropolitian Inc. has a free field digital accelerograph installed at their LNG plant in Montreal.

STRONG MOTION NETWORKS – NORTHERN CANADA

For the first time strong motion instruments have been installed in northern Canada (north of 55º latitude). They include 19 Titans - 13 at refurbished seismograph stations (5 in the Yukon, 1 in northwest BC, 1 in the NWT, and 6 in NU) and 6 in northeast BC (BCOGC in partnership with NRCan) – see Figure 5. We note that in January 2017 a magnitude 5.9 earthquake occurred 93 km from Resolute (RES) clipped the old seismograph, but not the replacement seismograph that was running in parallel; a Titan was installed in September 2018.

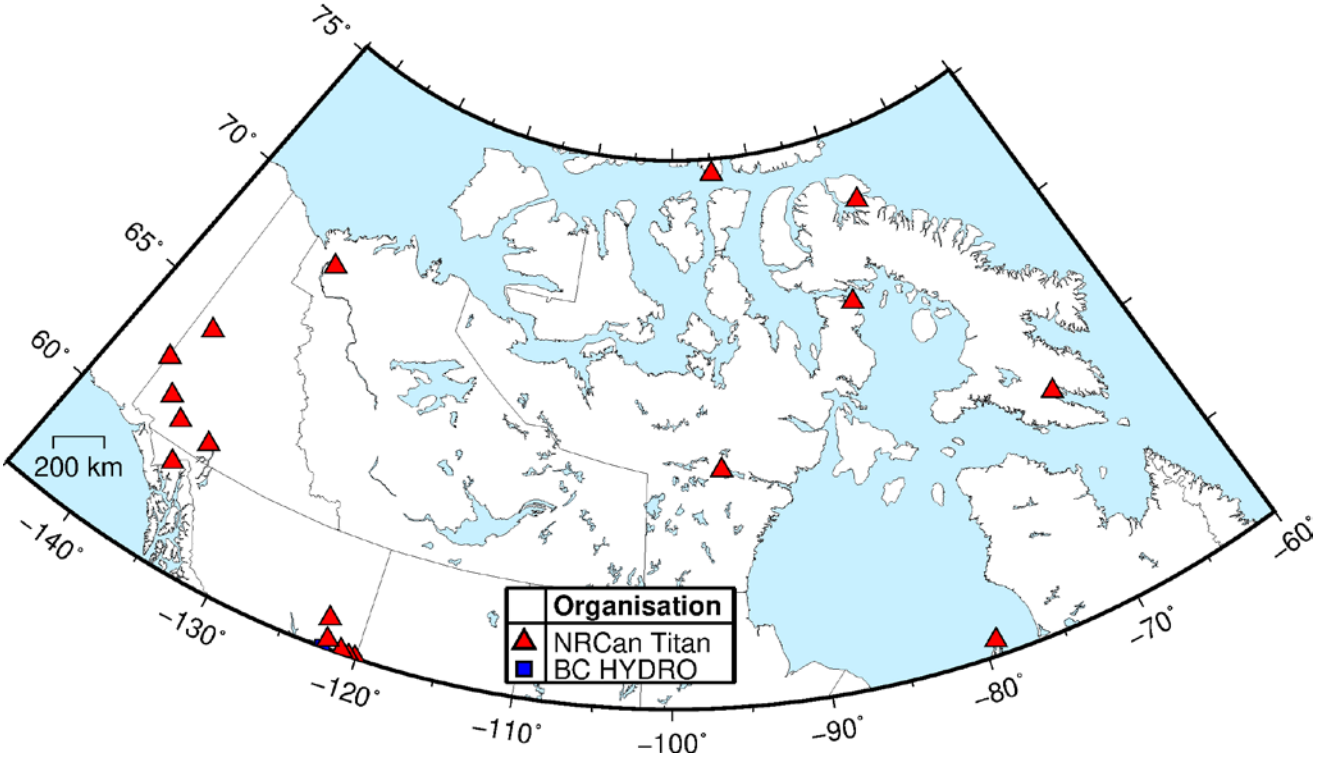

Figure 5. Strong motion seismographs in northern Canada (north of 55º). All NRCan instruments are Titans.

Table 1. Strong motion instruments deployed in Canada (as of Jan. 2019).

Owner	#Sites	#Instruments
NRCan West Titan	35	35
BC Hydro/Transmission	50	91
BC MoTI / NRCan IA's	163	182
UBC	33	67
ONC	32	34
Other West*	2	3
NRCan East Titan	43	43
NRCan East ETNA/IA	11	11
Hydro-Québec	9	10
Other East*	5	6
NRCan North Titan	19	19
Total – All of Canada	**402**	**501**

*these numbers may not be complete as we have not surveyed all potential owners.

RECENT NRCAN ACCELEROGRAMS

Since the last review of strong motion networks in Canada by [8], 726 seismic waveforms from NRCan strong motion instruments have been collected. Table 2 lists the 15 events that range in magnitude from 1.7- 6.8, and the number of recordings. This accounting is approximately equivalent to that in previous reviews (i.e. triggered recordings of events of interest) and does not include many recordings from the Titans that merely replicated the broadband seismometer observations. Note that CNSN network renewal provides an increasing number of Titan strong motion records beginning in 2017. All of the events listed in Table 2 are "weak shaking" recordings, with the strongest shaking being 4.4%g. The 2015 M4.7 Sidney, BC earthquake produced the largest dataset (126 records) and strongest shaking (4.4%g) that was useful to evaluate local site effects in southwest British Columbia [14].

Table 2. Recent (March 2015-January 2019) NRCan data sets from strong motion seismographs in Canada.

Earthquake	Date	Location (Lat, Lon)	Magnitude	Number of Records (IA/Titan)
Offshore Vancouver Island, BC	2015/03/06	48.40N, 123.50W	Mw 4.4	6 (6/0)
Haida Gwaii, BC	2015/04/24	51.43N, 131.06W	M_W 6.3	24 (24/0)
Sidney, BC	2015/12/30	48.62N, 123.29W	M_w 4.7	126 (126/0)
Sechelt, BC	2016/04/04	49.71N, 123.59W	M_L 3.1	21 (21/0)
San Juan Island, WA	2016/04/05	48.41N, 122.87W	M_L 3.1	9 (9/0)
Nootka Island, BC	2017/06/19	49.75N, 126.68W	M_W 4.1	48 (12/36)
Ucluelet, BC	2017/09/05	49.00N, 125.49W	M_L 3.6	39 (6/33)
Vancouver Island, BC	2017/11/28	48.45N, 123.63W	M_L 2.1	42 (6/36)
Sidney, BC	2018/02/04	48.63N, 123.13W	M_L 2.8	45 (0/45)
San Juan, WA	2018/06/08	48.82N, 123.23W	M_L 2.8	93 (51/42)
Victoria, BC	2018/06/21	48.34N, 123.43W	M_L 1.7	39 (9/30)
Sequim, WA	2018/09/09	48.29N, 123.06W	M_L 3.3	66 (24/42)
Offshore Vancouver Island, BC	2018/10/22	48.93N, 129.83W	M_W 6.6	81 (9/72)
Offshore Vancouver Island, BC	2018/10/22	48.98N, 129.85W	M_W 6.8	87 (15/42)

CONCLUSIONS

Strong motion monitoring continues to evolve rapidly across Canada, with additional organisations now contributing data, and increasing and varied applications for these data. As of January, 2019, more than 500 (near free-field) strong motion instruments are deployed across the country. One significant advancement is the renewal of the CNSN, specifically the deployment of new Titan strong motion instruments at nearly 100 bedrock sites across Canada. These data will be used to better understand ground motions and improve situational awareness following major earthquakes (e.g., more accurate shakemaps), and will contribute to the development of earthquake early warning systems in some areas. Significant datasets from the NRCan strong motion network since 2015 include recordings of the 2015 M 4.7 Sidney earthquake (shaking just under 5%g) These datasets have been used to help evaluate earthquake site response on the Fraser River Delta [14]. Fully characterising the sub-surface properties at strong motion sites across Canada would further advance ground-motion model evaluation and development.

ACKNOWLEDGMENTS

We thank our many colleagues at BC MoTI, ONC, UBC, BC Hydro, Hydro Quebec, Fortis Gas, and Trans-Energie for providing information on their strong motion networks. We thank Henry Seywerd and Tim Cote for providing detailed information on the NRCan strong motion network, and Andrew Schaeffer and Robert Kung for their help generating maps. We are grateful to Tim Cote for his helpful comments and suggestions that improved this manuscript. This is LMS contribution number 20180305.

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