Western Arctic Regional Network of Seismographs (WARNS): History, challenges and improvements in continuous broadband seismic data recordings in northwestern Canada

Andrew J. Schaeffer and Jeremy M. Gosselin*
Natural Resources Canada, Geological Survey of Canada - Pacific, Sidney, BC

Pascal Audet
University of Ottawa, Ottawa, ON

Maurice Colpron
Yukon Geological Survey, Whitehorse, YT

Scott Cairns and Barrett Elliott
Northwest Territories Geological Survey, Yellowknife, NT

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Abstract

The Western Arctic Regional Network of Seismographs (WARNS) is a collection of 20 seismic stations that addresses critical gaps in the seismic network coverage in northwestern Canada. This seismic network has a complex history of adoption and integration of past temporary seismic experiments. We summarize this history along with the challenges in operating in the Canadian North. The WARNS stations provide continuous, weak-motion broadband seismic recordings. The data from these are made accessible (in real time for many stations) via integration within the EarthScope Data Management Centre. This enables open access and facilitates improvements in regional earthquake monitoring and geoscientific discovery. Northwestern Canada is geologically and tectonically complex, which leads to elevated geohazard potential. The environment in the Canadian north is also rapidly evolving in response to climate change, which has the potential to enhance hazards. Studies that rely on data from WARNS play an important role in developing adaptation strategies for the evolving needs and hazards in Canada's north.

Plain language summary

The Western Arctic Regional Network of Seismographs (WARNS) is a system of 20 seismic stations in northwestern Canada that continuously measures ground vibrations created by local and distant earthquakes. This network is designed to address gaps in earthquake monitoring across this remote region. The network builds on earlier temporary experiments. The WARNS stations provide continuous recordings of ground motion, and much of this data is available in real time through the EarthScope Data Management Centre. This open access improves earthquake monitoring and supports numerous branches of scientific research. Northwestern Canada is a geologically complex area with significant earthquake and geological hazards. This is further complicated by climate change rapidly transforming the northern environment, potentially increasing risks. Research using WARNS data is essential for developing strategies to adapt to these evolving hazards and meet the region's future needs.

* andrew.schaeffer@nrcan-rncan.gc.ca

Introduction

Northern regions have been warming at several times the average global rate during the last 50 years (Rantanen et al., 2022). In northwestern Canada, this leads to environmental changes that impact ecosystems, accessibility and economic integration, which can increase the frequency and severity of geohazards (e.g., earthquake shaking and subsequent triggered landslides; Larsen and Huskey, 2015). The impacts of climate change disproportionately affect livelihoods and Indigenous communities of Canada's northern regions (Vogel and Bullock, 2021). Studies on geological processes in the Arctic, including routine earthquake monitoring, play an important role in developing adaptation strategies for the evolving needs and hazards in Canada's north. Geologically, northwestern Canada is a region of complex, active tectonics with abundant earthquake activity. Associated elevated hazards are acknowledged in the national seismic hazard model of Canada (Kolaj et al., 2020). Yet, many details of the ongoing tectonic processes and the associated hazards (and how those hazards may be evolving with environmental forcing) are poorly understood. The information that is input for hazard models in northwestern Canada is sparse compared to Canada's southern regions.

Among several contributing factors, the remoteness of the Canadian territories has resulted in a historically sparse network of seismograph stations that are critical for research and routine earthquake monitoring. Furthermore, it has been demonstrated that large-scale geophysical observations capable of imaging the lithospheric system play a critical role in the identification and quantification of new critical mineral resources (Hoggard et al., 2020; Lawley et al., 2022). Recognition of the complex geology, hazards, natural resource potential and evolving environment has motivated scientific discovery in northwestern Canada in recent years. This has included significant changes to the regional network of seismograph stations, which is the focus of this report. As an initiative of the Geological Survey of Canada (GSC), University of Ottawa (UO), Yukon Geological Survey (YGS) and Northwest Territories Geological Survey (NTGS), WARNS represents a set of seismograph stations that complement the established Canadian National Seismograph Network (CNSN), and significantly enhance geoscientific research and earthquake monitoring. The data from these stations are made openly accessible via integration within the EarthScope Data Management Centre to promote geoscientific discovery.

Regional tectonics and seismicity

Northwestern Canada is a region of complex geology and deformation due to past and ongoing tectonism throughout the region. It can be broadly subdivided into the Beaufort-Mackenzie basin, parts of the Canadian Shield and the North American Cordillera. The Beaufort-Mackenzie basin is a large sedimentary basin located in the Beaufort Sea, off the northern shore of mainland Canada (Fig. 1). The Canadian Shield is a stable, ancient craton that forms the geological core of North America. Precambrian rocks that form the Shield indicate a long history of tectonic stability (Nelson et al., 2013; Hyndman, 2023). The Cordillera is a geologically young and active mountain belt that extends along the western margin of North America, juxtaposed against the stable craton (Nelson et al., 2013). In northwestern Canada, it is often referred to as the Northern Canadian Cordillera (NCC; e.g., Estève et al., 2023). The complex geology of the NCC is characterized by far-travelled fragments of crustal material (terranes) of different origins that have accreted to the North American margin throughout geological time (Monger and Price, 2002; Nelson et al., 2013). Terrane accretion has resulted in a variety of rock-type assemblages throughout the NCC. Active tectonics within the NCC is evidenced by ongoing orogenesis, volcanism and seismicity (Hyndman et al., 2005; Hyndman, 2010; Russell et al., 2023). As a result, the region hosts a broad range of mineral deposits (Nelson et al., 2013).

Active tectonics in northwestern Canada are driven by the oblique collision of the Pacific plate and Yakutat microplate with the North American plate. The ongoing convergence of the thick, buoyant Yakutat microplate has resulted in flat-slab subduction (Eberhart-Phillips et al., 2006; Finzel et al., 2011; Bruhn et al., 2012) and rapid uplift and exhumation of the St. Elias Mountains (Fig. 1; Enkelmann et al., 2008). Regional tectonic plate motions are accommodated by this significant coastal uplift, as well as partitioning between convergence and several major strike-slip faults. These include the Denali, Teslin and Tintina faults, crustal-scale faults that have accumulated hundreds of kilometres of right-lateral offset over geological time (Gabrielse et al., 2006; Waldien et al., 2021).

In the Richardson and Mackenzie mountains (Fig. 1), active plate tectonics is driven by the convergence of the NCC with the stable North American plate. Convergence within these inland mountain ranges is suggested to be driven by far-field stress transfer from the collision of the Yakutat microplate (Mazzotti

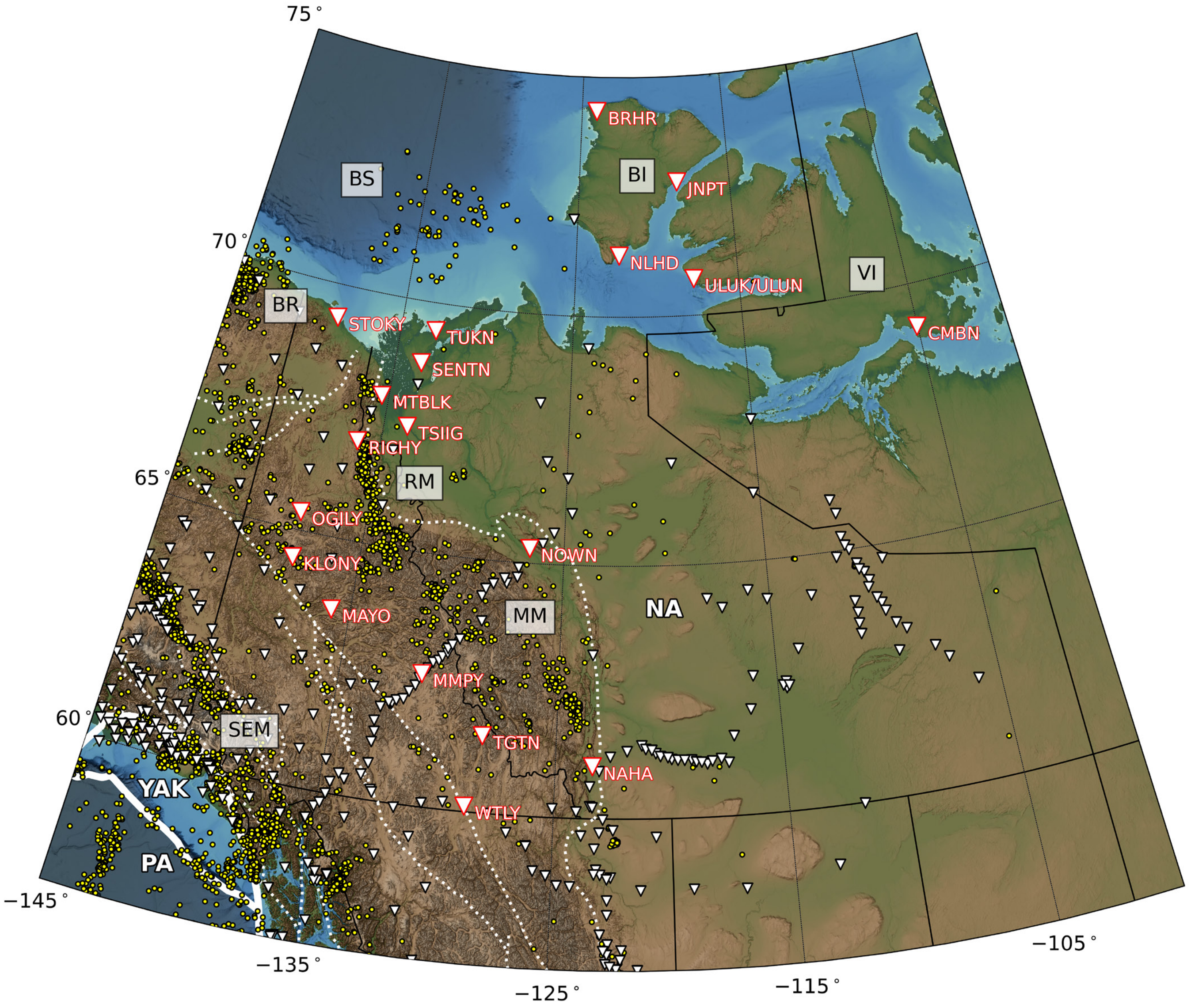

Figure 1. *Seismicity in northwestern Canada. The epicentres of earthquakes of magnitude ≥3 between 2000 and 2024 are shown as yellow circles. Seismicity in northern Canada is clustered near tectonic and topographic features, including the St. Elias Mountains (SEM), Mackenzie Mountains (MM), Richardson Mountains (RM), Brooks Range (BR) and the Beaufort Sea (BS). Seismic stations within the Western Arctic Regional Network of Seismographs (WARNS) are shown as large white triangles (outlined in red). Seismic stations with publicly available broadband seismic recordings (of any duration) are shown as small white triangles. Active tectonics are characterized by the interactions of the Pacific (PA), Yakutat (YAK) and North American (NA) tectonic plates. Tectonic plate boundaries are shown as thick white lines. The geology in this region is characterized by the juxtaposition of the North American Cordillera next to the stable North American Craton. The Cordillera is transected by several crustal-scale faults (dotted lines). Banks Island (BI) and Victoria Island (VI) are discussed in the text. Provincial and territorial boundaries are shown in black.*

and Hyndman, 2002). This implies a rigid upper crust within the NCC that transfers stress over hundreds of kilometres via a thermally modulated detachment in the lower crust, which has implications for crustal structure (e.g., Estève et al., 2021; Schutt et al., 2023). Oblique collision pushes the NCC to the northeast. The northerly motion causes strike-slip deformation in the Richardson Mountains and may contribute to the seismicity in the Beaufort Sea (Hyndman et al., 2005; Hyndman, 2010). An alternative mechanism for deformation in the Mackenzie and Richardson mountains involves stress transferred westward through the stable North American craton via the opening of the North Atlantic Ocean (Enkelmann et al., 2019; McKay et al., 2021).

The NCC is characterized by high temperatures at shallow depths, which impacts natural resource potential (e.g., geothermal) and natural hazards. Evidence of high temperatures includes high geothermal heat flow measurements (e.g., Grasby et al., 2011), shallow Curie depths (e.g., Gaudreau et al., 2019), an inferred shallow lithosphere-asthenosphere boundary (LAB; e.g., Audet et al., 2019) and low seismic velocities in the mantle (e.g., Schaeffer and Lebedev, 2014; Tesauro et al., 2014). Distributions of seismicity throughout the NCC concentrated at shallow depths (often approximately 10 km or less) suggest that high temperatures in the lower crust may inhibit brittle deformation (e.g., Choi et al., 2021; Estève et al., 2022; Drooff and Freymueller, 2023; Biegel et al., 2024). In contrast to the NCC, the adjacent North American craton is cold, tectonically stable, and exhibits low levels of seismicity. Additionally, the NCC is among the most volcanically active regions of Canada (Cassidy and Mulder, 2023; Russell et al., 2023), and although no volcanoes in Canada have erupted since seismic monitoring began more than a century ago, volcanic seismicity likely also occurs throughout the NCC. Furthermore, seismic monitoring limitations may preclude the ability to detect micro-earthquake activity associated with many volcanoes in Canada (Cassidy and Mulder, 2023).

Seismicity in northwestern Canada is spatially clustered near the aforementioned tectonic features associated with major tectonic domains and their bounding faults and structures. Notably, the majority of earthquakes occur in southwestern Yukon due to the active convergence of the Yakutat microplate with the western edge of North American (Fig. 1). The geometry (obliquity) of the active tectonic boundary with respect to relative plate motion leads to predominantly reverse and dextral strike-slip earthquakes (and likely slip partitioning) in this region (Doser, 2014; Gosselin et al., 2023, 2024). The largest earthquakes in northwestern Canada also occur here. This includes events along the active plate margin (Plafker et al., 2008), as well as inboard along major faults such as the Denali fault (Eberhart-Phillips et al., 2003). Much of the interior of the NCC exhibits low levels of seismicity (Fig. 1), and limited seismicity along other major faults (e.g., Teslin and Tintina). Seismicity is also clustered along the Cordilleran deformation front (eastern edge of the NCC), including the Mackenzie and Richardson mountains (Fig. 1). Earthquakes in the Mackenzie Mountains exhibit predominantly reverse mechanisms due to active convergence of the NCC with the North American craton. This transitions to predominantly dextral strike-slip earthquakes in the Richardson Mountains due to the component of northerly motion of the NCC relative to the North American plate (Hyndman et al., 2005; Ristau et al., 2007; Leonard et al., 2008). Despite their position hundreds of kilometres from the active plate boundary, recorded seismicity includes several large magnitude (M) earthquakes (M >6) in both the Richardson (e.g., Cassidy and Bent, 1993) and Mackenzie (e.g., Wetmiller et al., 1988; Horner et al., 1990; Cassidy et al., 2005) mountains.

Moderate seismicity is also clustered in the Beaufort Sea (Fig. 1). The western part of the basin is characterized by a fold and thrust belt associated with the Cordilleran orogen, whereas the eastern part of the basin is characterized by extensional structures (Hyndman et al., 2005). As these events occur offshore but are only observed at seismograph stations on land, the constraints on seismicity in the Beaufort-Mackenzie basin are poor; improving these details will require offshore ocean-bottom seismometer deployments. Limited earthquake mechanism solutions exhibit normal and strike-slip faulting, and consistently subhorizontal tension axes (Hyndman et al., 2005). Earthquakes beneath the Beaufort Sea are interpreted to occur in the lower crust or uppermost mantle (Audet and Ma, 2018). It has been suggested that this seismicity may be related to flexural bending and tension in the upper lithosphere due to loading from the rapidly developing Mackenzie Delta (and associated sedimentary trough; Lane, 2002; Hyndman et al., 2005). Furthermore, the Beaufort Sea continental margin is considered a Cenozoic convergent boundary and may represent incipient subduction (Estève et al., 2022). Furthermore, large (M >6) earthquakes have been recorded in the region, demonstrating the potential for future large (though infrequent) earthquakes (Hasegawa et al., 1979).

Evolution of seismic infrastructure in northwestern Canada

The historically limited density of geophysical infrastructure across the Canadian Arctic was due to various factors, including accessibility, the vastness of the terrain (i.e., sparse resources), and weather that may exhibit severe seasonal fluctuations. Much of the region is inaccessible during winter months, and there are few passable roads. Combined, these factors made routine scientific operations, including instrument maintenance, more challenging. The challenges in field operations and maintenance necessitate larger budgets to work in remote, northern regions. Such research budgets were often difficult to justify, in part due to the low population density of the Canadian territories, and therefore lower inferred risk. With the present increase in proposed northern development and infrastructure projects, the recognition of the growing risks posed to northern inhabitants, in addition to the potential opening of the Northwest Passage through the Canadian Arctic Archipelago, it becomes even more critical to maintain a strong geophysical monitoring network to inform policy, impact assessments, and infrastructure design and resilience to a range of natural and induced hazards.

Despite these challenges, geophysical instrumentation has made its way into the Canadian north episodically during the last few decades. Though the expansion and improvement of the permanent CNSN has been slow, temporary experiments have resulted in a significant advancement in geophysical instrumentation, followed by a regression of the cumulative network when these temporary stations have been removed (Fig. 2). However, some stations from these deployments have been retained and converted into permanent sites. The history of the cumulative seismic network reflects this growth and cyclical nature (Fig. 2).

Despite knowledge of the occurrence of large earthquakes in northwestern Canada (which can be detected on distant global seismic stations), the first seismograph station in the Yukon was not installed until 1971, in Whitehorse (Fig. 3). This was many decades after the establishment of the seismograph network in southern Canada and adjacent Alaska, and was motivated by the desire to improve the understanding of seismicity in the Yukon and the Mackenzie Valley due to ongoing discussions of a potential pipeline project in the region. Driven by the M 7.9 Denali earthquake in central Alaska in 2002 (Eberhart-Phillips et al., 2003), the CNSN was augmented with approximately 10 new seismograph stations in 2010. These were installed in the vicinity of the eastern segment of the Denali fault (in southwestern Yukon), significantly enhancing routine earthquake monitoring capabilities (Meighan et al., 2013) and improving capacity for research in regional seismology and tectonics. Several large-scale temporary deployments occurred around this time (a few years before and after; Fig. 2).

Numerous stations across Canada were associated with the multi-institution Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity (POLARIS; Eaton et al., 2005) experiment. This large-scale investigation comprised more than 100 telemetered (i.e., real-time data transfer) broadband seismic stations, and 10 continuously recording magnetotelluric instruments. In the context of northwestern Canada, these stations (network code PO) were initially deployed over the Slave Craton in the Northwest Territories during the early 2000s (Fig. 4). Later, some stations were relocated westward toward the Mackenzie Mountains and the westernmost extent of the Canadian Shield.

Concomitant to the POLARIS experiment in northwestern Canada was the United States-led Canadian Northwest Experiment (CANOE; Gaherty and Revenaugh, 2003), which was deployed from 2003 to 2005 as a three-prong array centred on Fort Nelson, British Columbia. The instrumentation included 50 broadband seismographs from the Portable Array Seismic Studies of the Continental Lithosphere (PASSCAL) instrument pool (Aster et al., 2005), as well as an additional 10 seismographs from the University of British Columbia. The western transect extended from Fort Nelson to Whitehorse along the Alaska Highway, and the northern arm along the highway from Fort Nelson to Yellowknife (Fig. 4). The southern arm connected Fort Nelson to Edmonton, where it met with the northern termination of a similar experiment spanning from Florida to Edmonton.

The migration of the EarthScope Transportable Array (TA) from the continental United States to Alaska (Busby and Aderhold, 2020) represented another significant (though temporary) improvement in seismological instrumentation in northwestern Canada (Fig. 2). During the eight-year duration of the TA in Alaska, 38 stations were installed within Canada: 4 in Northwest Territories, 28 in the Yukon and 6 in British Columbia (Fig. 4). The earliest TA stations installed in the Canadian north during 2012 and 2013 were located in Sachs Harbour and Paulatuk, Northwest Territories, and Eagle Plains in the Yukon. The remaining TA stations in northwestern Canada were mostly installed between 2015 and 2017.

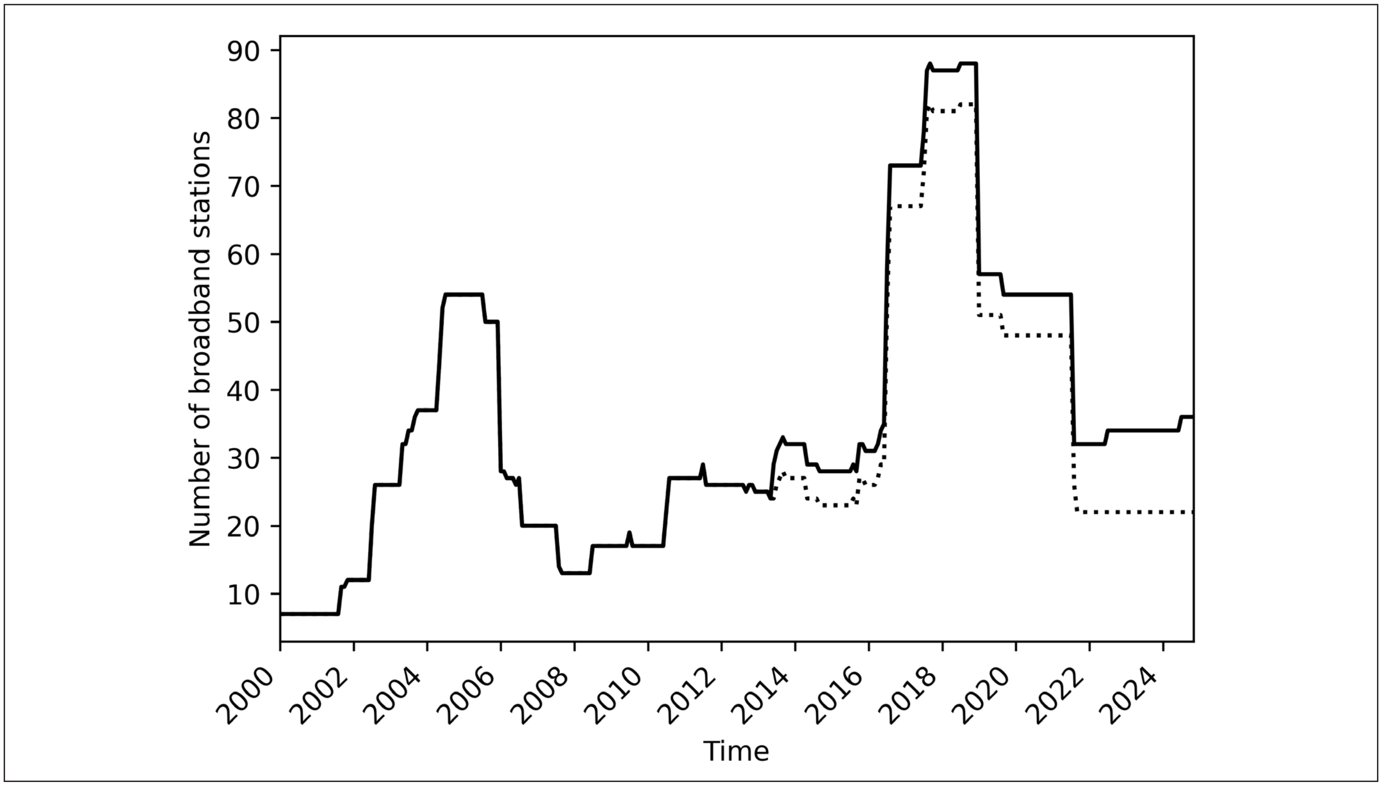

Figure 2. *Evolution of digital broadband seismic recordings in the Canadian territories, and the monthly number of broadband seismic stations with publicly available digital recordings in the Yukon, Northwest Territories and Nunavut (specifically within the range of 100°–141° longitude and 60°–80° latitude). Note the significant increase in available seismic recordings between 2002 and 2008 due to the Portable Observatories for Lithospheric Analysis and Research (POLARIS; Eaton et al., 2005) and Canadian Northwest Seismic Experiment (CANOE; Gaherty and Revenaugh, 2003) experiments. Similarly, a significant increase in available seismic recordings is observed between 2016 and 2022 due to the EarthScope Transportable Array experiment extension into western Yukon (Busby and Aderhold, 2020), as well as the Mackenzie Mountain transect experiment (Baker et al., 2020). The dashed line illustrates the number of available stations without the Western Arctic Regional Network of Seismographs (WARNS) stations. Without WARNS, the current broadband seismic network in northwestern Canada would revert to pre-2010 numbers.*

Decommissioning was planned for 2020; however, due to the global COVID-19 pandemic, the TA sites in Canada continued to operate for an additional year.

The flexible array Mackenzie Mountains EarthScope Project (MMEP; Baker et al., 2020) was a network of 40 broadband seismograph stations that also temporarily improved seismological instrumentation in northwest Canada (Fig. 2). The MMEP stations were deployed in a roughly linear array transecting much of the Northern Canadian Cordillera and extending into the Canadian Shield (Fig. 4), between 2016 and 2018, coinciding with the EarthScope TA experiment in Alaska.

The Yukon Northwest Seismograph Network (YNSN, network code NY) consisted of an array of seven seismic stations straddling the Mackenzie Mountains of central Yukon and the westernmost Northwest Territories. Originally deployed in 2013, the YNSN was a Canadian Foundation for Innovation (CFI) and Natural Sciences and Engineering Research Council of Canada (NSERC)-funded initiative of the University of Ottawa motivated by the EarthScope TA experiment. Data from all seven stations were telemetered in real time to the GSC Pacific Data Centre (GSC-PDC) via satellite-based communications. Currently, three of the YNSN stations have been decommissioned with the termination of the experiment (FLDN, WGLY and FARO), whereas four remain operational (MAYO, MMPY, TGTN and WTLY) due to adoption by the GSC and inclusion in WARNS (Figs. 4 and 5).

In 2015, the Banks Island Seismograph Network (BISN) was established as a joint endeavour between the formerly known Northwest Territories Geosciences Office (NTGO) and the University of Ottawa. The

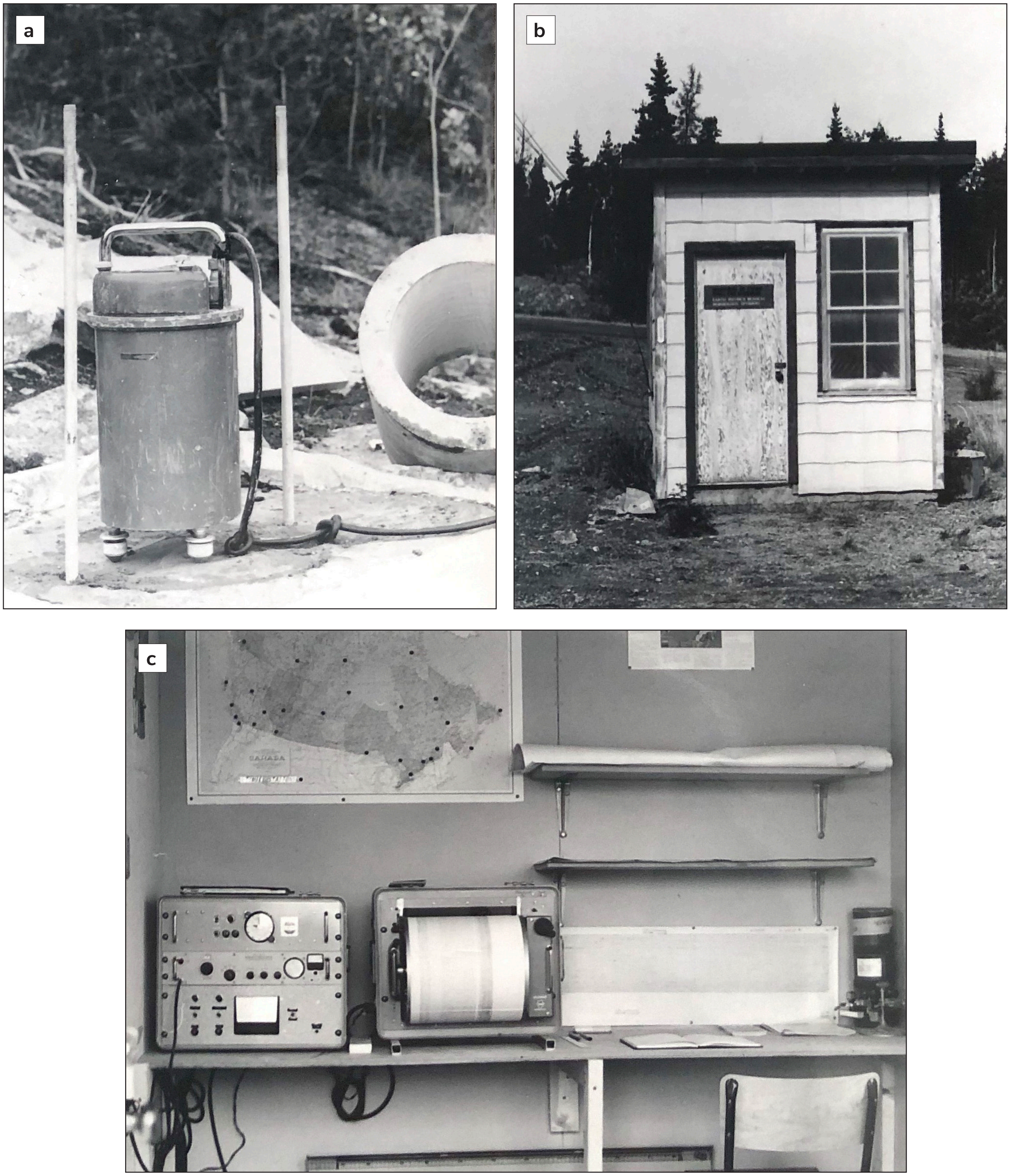

Figure 3. *The first seismograph station in the Yukon was originally installed in 1971 in Whitehorse.* ***(a)*** *The station consisted of a Willmore seismometer (sensor) installed on a cement pad.* ***(b)*** *The recording equipment for the station was housed in a nearby structure.* ***(c)*** *The sensor was connected to a Teledyne EA310 amplifier and helicorder inside the structure (Garry Rogers, pers. comm., November 2024).*

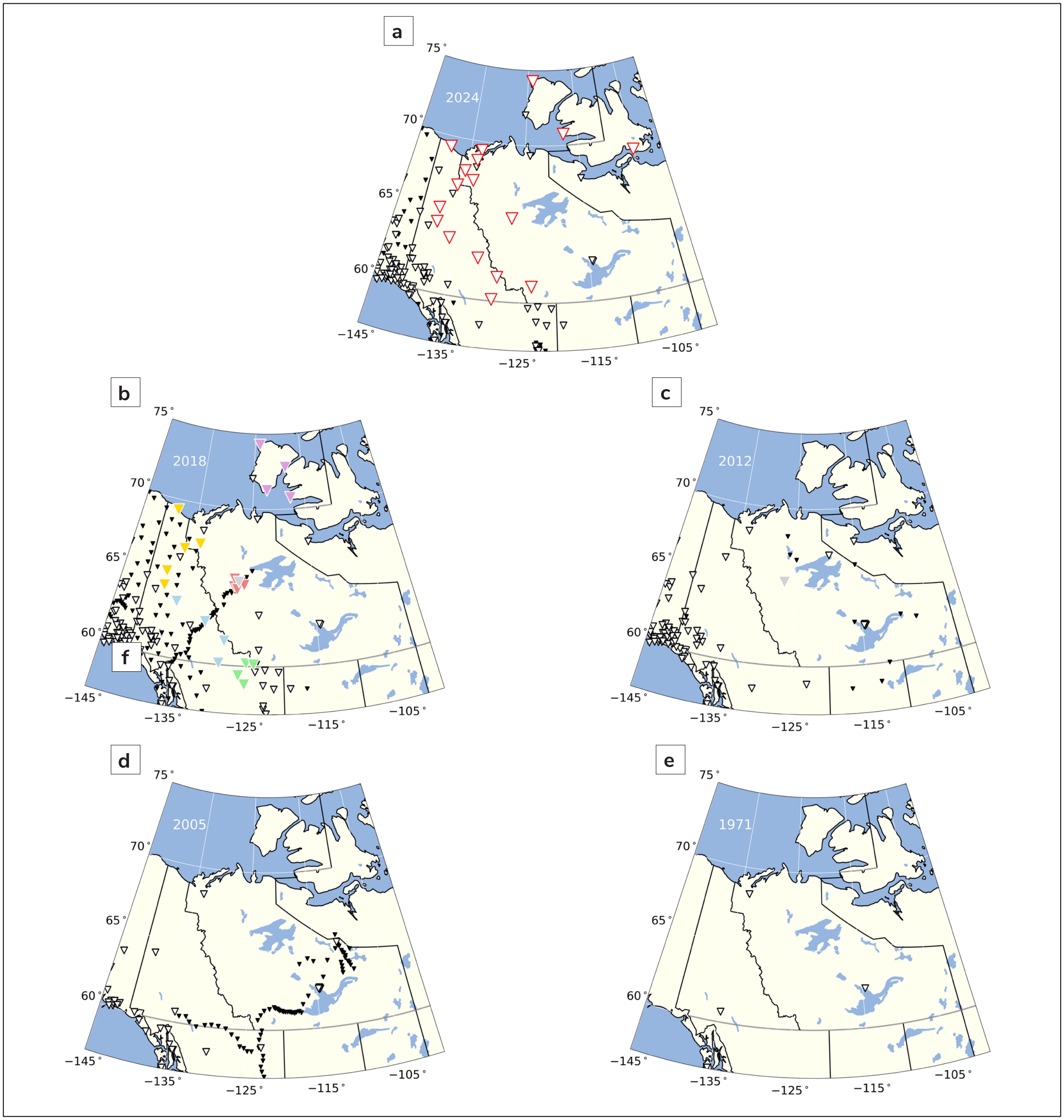

Figure 4. *Seismic network evolution in northwestern Canada. Stations that are part of the Western Arctic Regional Network of Seismographs (WARNS) are depicted by the red-outlined triangles. The locations of broadband seismic stations that were actively recording during the specific years of 2024, 2018, 2012, 2005 and 1971 are depicted in* ***(a)–(e)****. Stations affiliated to WARNS (details discussed in the text) are highlighted in (b) and (c) and are coloured according to experiment (same as Figure 5). Other permanent and temporary broadband seismic stations are represented by large (white) and small (black) triangles, respectively. The first seismic station in the Yukon was installed in Whitehorse in 1971. The POLARIS (Eaton et al., 2005) and CANOE (Gaherty and Revenaugh, 2003) experiments are illustrated in (d). The EarthScope TA (Busby and Aderhold, 2020) and MMEP (Baker et al., 2020) experiments are illustrated in (b). Provincial and territorial boundaries are denoted with solid black lines.*

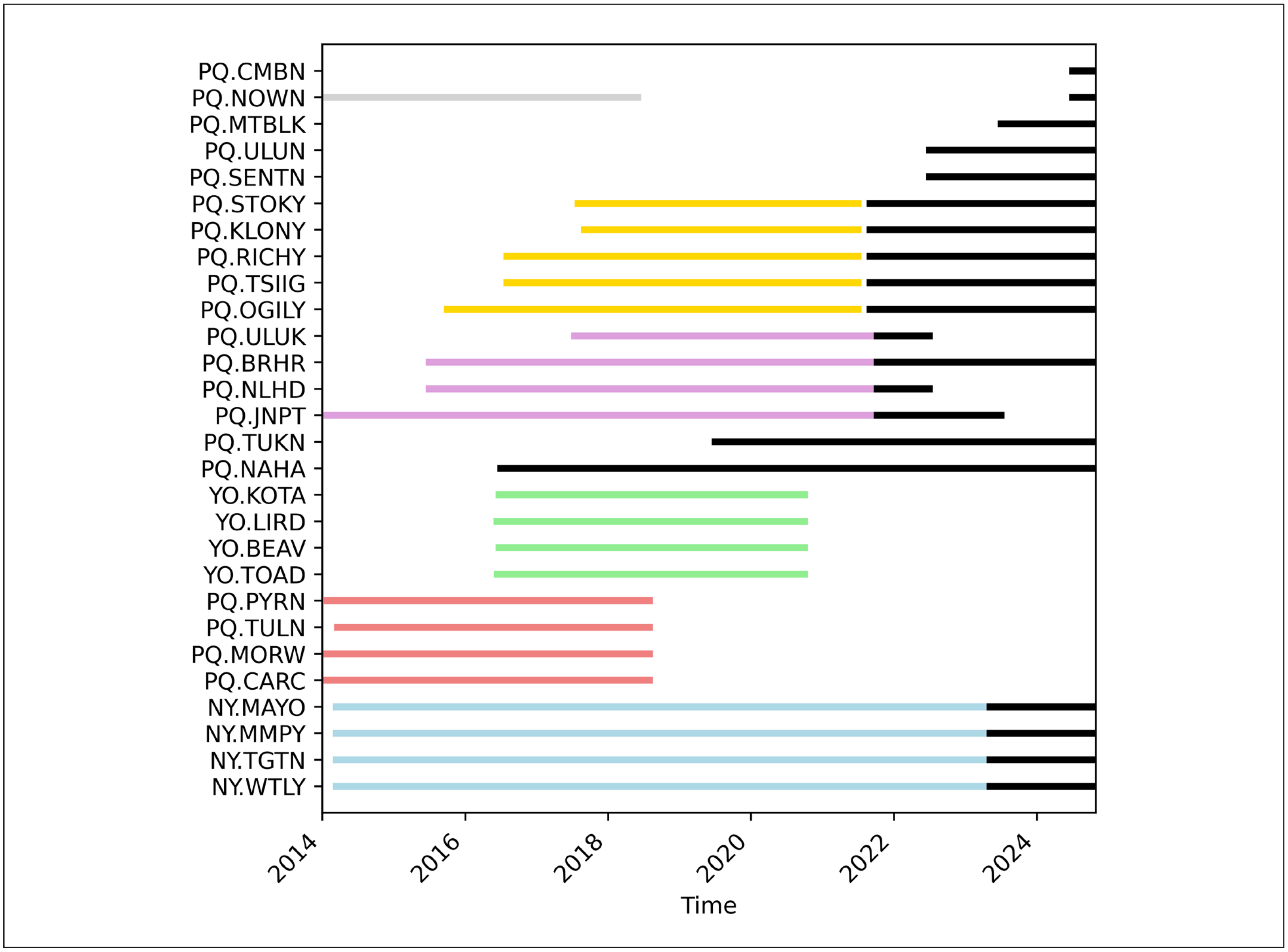

Figure 5. *Deployment history of stations in the Western Arctic Regional Network of Seismographs (WARNS). The history of WARNS station deployment is depicted in black. Select station deployment history for other networks and experiments are also illustrated, including the EarthScope Transportable Array (TA; yellow), the University of Ottawa Yukon Northwest Seismograph Network (YNSN; blue), the Normal Wells Seismic Monitoring array (NWSM; pink), the Yukon Observatory array (YO; green), the Banks Island Seismograph Network array (BISN; purple), and the Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity (POLARIS; grey). Some sites and equipment were subsequently adopted by WARNS upon completion of the respective temporary experiments. Details are discussed in the text.*

objective of this experiment was to examine the nature of the lithosphere beneath Banks Island and the nearby continental shelf slope in the Beaufort Sea (Fig. 1). Two temporary stations had previously existed in the southwest Canadian Arctic Archipelago on Banks and Victoria islands (Fig. 1). The site at Johnson's Point on Banks Island (JNPT) was situated along the Prince of Wales Strait and hosted an exploration camp. It consisted of a significant beach landing strip that was once capable of handling a C-130 Hercules Aircraft. The equipment for JNPT had previously been located near the Hamlet of Ulukhaktok (ULU) on Victoria Island, at the western point of the Diamond Jenness Peninsula. The decision to relocate the equipment across the strait was made as station ULU had been damaged by wildlife several years in a row. Station JNPT was ultimately retained in BISN, which was eventually acquired by WARNS (Fig. 5). Both BISN and WARNS were assembled and operating, and a minimal budget was spent on the purchase of new seismic equipment (i.e., most sites were assembled and operating using preexisting available equipment).

Farther to the south near the Town of Norman Wells, NT, the NTGO and GSC deployed the Norman Wells Seismic Monitoring (NWSM) array. This consisted of a cluster of four stations (MORW, CARC, PYRD and TULN) around a central station (NOWN) in Norman Wells, where oil and gas development has been ongoing for many decades. In response to the possible expansion of facilities, directional drilling and potential hydraulic fracturing, NWSM was deployed to generate a baseline of local seismicity and facilitate ongoing monitoring. This experiment operated from 2014 to 2018. The central station NOWN operated from 2012 to 2018 (Figs. 4 and 5) and was revived in 2024 for WARNS due to its critical position for earthquake monitoring in the Mackenzie Mountains.

The Yukon Observatory (network code YO), developed and operated by the YGS, was an array of four seismic stations that were operational from 2016 to 2020 (Fig. 5). Similar to the NWSM array, the YO was deployed in response to industrial interest in the Liard basin for oil and gas (Fig. 4). The observatory was to establish baseline seismicity then monitor ongoing activity. However, legislation placed a restriction on oil and gas extraction in the Liard basin unless approved by the local First Nations. As a result, the YO was decommissioned in 2020. The equipment from the observatory was redeployed at new sites within WARNS.

The creation of WARNS is largely based on the coincident termination of YNSN, BISN and the EarthScope TA in Canada in 2021. Efforts by the GSC (including funding) and YGS (equipment and in-kind) contributed to the adoption and continued operation of many seismic stations in northwestern Canada. This GSC-YGS collaboration adopted five of the EarthScope TA stations in the Yukon and the Northwest Territories and continues to operate them to this day (Fig. 5). These include sites D28M, F31M, G30M, I29M and J29N, which have been renamed under WARNS (STOKY, TSIIG, RICHY, OGILY and KLONY, respectively). The CNSN also adopted five stations from the EarthScope TA experiment: A36M, C36M, F28M, EPYK and P32M. With the assistance of the YGS and Northwest Territories Geological Survey (NTGS) in facilitating data transfer, these stations are now renamed under CNSN (SACHN, PAULN, CROWY, EAGLY and ATLI, respectively). WARNS and its predecessors have expanded and improved the seismic array through the conversion of offline sites into sites with real-time data transfer. In 2019, a new BISN station was deployed in the Hamlet of Tuktoyaktuk, on the coast of the Arctic Ocean at the end of the Inuvik-Tuktoyaktuk Highway. Through colocation with the Canadian Hydrographic Service (CHS) tide gauge station, and a Canadian Geodetic Service (CGS) geodetic monument, the new TUKN station streams real-time data to the GSC-PDC. Furthermore, the station ULUK, in the Hamlet of Ulukhaktok on Victoria Island (Fig. 1) was colocated with CHS and CGS infrastructure in 2022, enabling real-time data streaming. Additionally, WARNS has also expanded independently through new station deployments, for example, MTBLK and SENTN (Fig. 5).

WARNS

Motivation for continued operation

Seismological infrastructure in northwestern Canada reached a peak in density and uniformity of coverage in 2018–2019 (Fig. 2). Since then, the number of stations has decreased by a factor of apprximately 2–3. Most of the attrition was due to the termination of United States-led experiments (28 of 38 EarthScope TA stations and all 40 MMEP stations were removed). These experiments provided unprecedented potential to unravel new insights into the structure and evolution of the NCC and surrounding regions. However, 10 of these stations were adopted by the GSC and CNSN with territorial partners. As illustrated in Figure 2, it is evident that without the operation of WARNS, the decline in instrumentation post-EarthScope would have decreased station numbers by a factor of approximately four. Ignoring the several large (but temporary) experiments, Figure 2 also illustrates the slow expansion of the cumulative seismograph network in northwestern Canada over time.

The temporary influx of stations, and the data they provide, has led to improved resolving power to address important geoscientific questions. This work has also led to new questions regarding the structure and tectonic evolution of northwestern Canada, as well as associated implications for natural resources and hazards. In particular, enigmatic bands of seismicity are observed beyond the extent of the MMEP array and within the Richardson Mountains in the Yukon and the Northwest Territories. These may be related to deep offshore seismicity in the Beaufort Sea region. The WARNS network is poised to continue contributing to unravelling fundamental, outstanding tectonic questions and improving routine earthquake monitoring in a region of rapidly changing environmental conditions.

The northern territories of Canada are susceptible to more extreme impacts of climate change, which can significantly disrupt day-to-day life for northerners and potentially erase whole communities. For example, much of the northern territories of Canada are underlain by permafrost that is expected to degrade and thaw in the coming years (Smith and Burgess, 2004). Changes in local site conditions due to the changing environment have the potential to enhance geohazards (including earthquake shaking and associated hazards). The ongoing operation and expansion of WARNS complements the CNSN and other temporary, national and international seismic stations. Together, these afford the capacity to discover the complex and interacting geohazards across the Canadian Arctic. In addition, with increasing accessibility to the Canadian Arctic due to melting sea ice, new development and transit opportunities are being sought, which may lead to an increased susceptibility to geohazards. Continuing the geophysical observations provided by WARNS is important for developing adaptation strategies for northerners and informing future industrial and socio-economic developments.

Challenges

Canada is a vast country, particularly in the northern territories. Beyond 200 km of the Canada-United States border, the distances between population centres are significant. The harsh northern climate further exacerbates the challenges of conducting geoscientific research in remote settings. However, the most significant barrier to conducting research or any type of fieldwork in the north is cost. All individual challenges ultimately result in increased costs compared to performing the same operation at southern latitudes. While year-round highways service many communities in the north, numerous communities remain accessible only by air or via winter roads. Furthermore, many of the areas that need to be accessed to install or maintain seismic stations that fill spatial gaps do not have roads or any nearby communities. In these cases, sites are only accessible by chartered aircraft (fixed wing or helicopter), snowmobile (during winter months) or boat. In addition, while a local community may provide a relatively accessible base for staging field operations, all equipment must still be shipped thousands of kilometres to these northern destinations. Transportation logistics are also generally more challenging due to insufficient transportation options. Adapting to challenging weather, wildfires, landslides and other phenomena may not always be possible. Northern residents are very familiar with these challenges and have lived through many of these phenomena. This presents a stark contrast for those accustomed to the often seamless, logistical benefits of working in southern Canada.

Beyond challenges in terms of cost and logistics, there are many unique challenges encountered specific to operating seismological infrastructure in the Canadian North. The main components of a seismograph station include the power supply, the sensor and digitizer, and communications (for real-time stations). A high-quality installation is typically located away from most sources of local activity capable of generating ground vibrations (e.g., pumps, generators, roads). Access to alternating current (AC) grid power allows for the simplest installations. In more remote settings, direct current (DC) power can be provided by solar panels (or small wind turbines) with supplemental battery banks (for when environmental conditions do not allow for electricity generation). Cellular services or line-based telecommunications are possible near communities to enable real-time seismic data transfer. In more remote settings, satellite telemetry is often required. The trade-offs between site quality, benefits and logistics are more apparent in Canada's north. Locating a station within a community simplifies logistics, power and communication. However, this comes at the cost of signal quality (i.e., higher background noise) and potentially poor site location within a regional context (i.e., not addressing spatial gaps in network coverage). Achieving better signal quality (or site selection) often increases logistical demands, and site accessibility, power and communication requirements.

The use of DC power is further complicated in polar regions. In the summer months, the solar input is significant and can be maximized to charge and maintain battery banks with carefully constructed and oriented solar arrays. However, during the winter months, there is little to no solar input and maintaining a battery bank is challenging. The cold temperatures compound the challenges for power systems. Even though the scientific instruments are typically rated to operate at these temperature extremes, the battery banks are highly temperature sensitive. The available amperage of a standard chemistry lead-acid or gel-cell style battery decreases significantly with decreasing temperature, requiring a larger battery bank to store power during winter months. The power systems used by the WARNS stations adopt a best-practice approach based on similar past experiments. An in-depth analysis of the range and complexity of cold-weather, off-grid power systems is beyond the scope of this report.

The WARNS stations are operated by a small group using a modest budget. Consequently, damage to instrumentation poses a significant operational challenge. As illustrated in Figure 6 (a–c, e), damage can

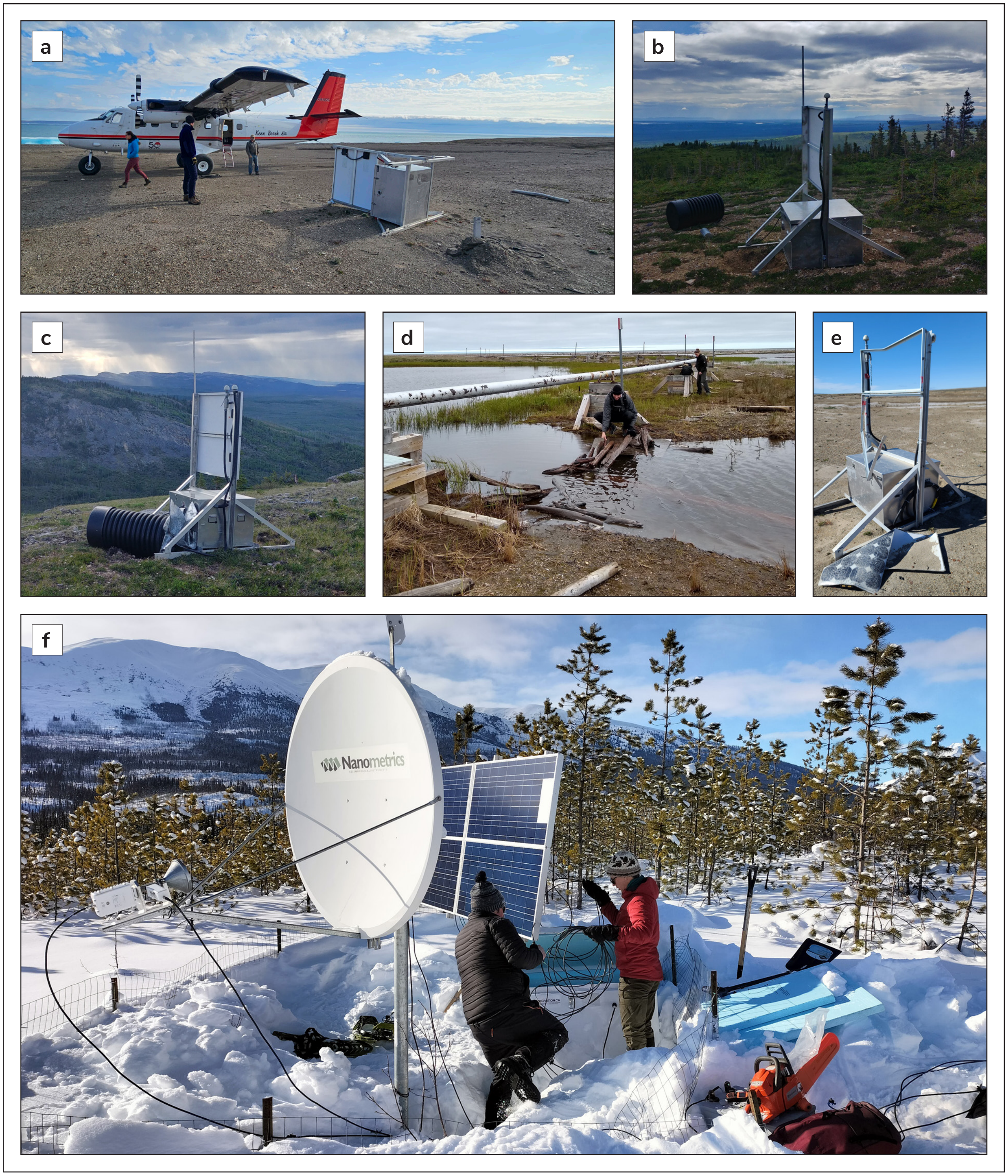

Figure 6. *Common challenges encountered operating geophysical instrumentation in the Canadian north.* ***(a)*** *Site access requires a chartered aircraft capable of off-strip landing. Also pictured is common damage to instrumentation, where polar bears have knocked over the 400 lb. battery and electronics kiosk with mounted solar panels.* ***(b, c)*** *Examples of helicopter-access-only locations where wildlife, likely grizzly bears, have exhumed the seismometer vault (and sensor).* ***(d)*** *Unexpected hazards or washouts are not uncommon when visiting remote sites.* ***(e)*** *The winds in some regions can reach hurricane-force speeds, and cause equipment to fail. Pictured here are two solar panels where high winds blew the panel interiors out of their frames.* ***(f)*** *Snow accumulation can present challenges in mountainous regions of the Northwest Territories and the Yukon. In this example, near Nahanni National Park during March, snow removal was required for site access and to expose the solar panels.*

be caused by various sources that are often unanticipated and/or challenging to prepare for. Due to accessibility and budgetary constraints, sites are generally visited yearly. Efficient and effective station servicing is critical as charter availability (including seasonal or weather limitations) may preclude the ability to visit a site for multiple years. There are several offline stations within WARNS (i.e., non-cellular and non-telemetered). For these stations, data must be harvested during site visits. Since the station's condition is unknown before arrival, a complete set of replacement equipment is typically transported to the site in case significant repairs are required. This includes replacement instrumentation (sensor and digitizer), solar panels, wiring and new batteries.

In the history of WARNS (and its predecessors), significant station damage is typically caused by wildlife. This predominantly involves damage by polar bears (e.g., Fig. 6a) and grizzly bears (e.g., Fig. 6b, c). In these cases, the entire power system and/or electronics enclosure may be overturned. The vault that houses the sensitive and costly seismometer may also be exhumed. While bears generally cause the most catastrophic damage to seismic stations, many smaller animals are also capable of disrupting station operations and causing costly damage. This can include rodents and other small mammals that chew through exposed cables (including costly seismometer cables) and strapping. As a result, where possible, cabling is typically installed in armoured conduit; however, given enough time, harsh conditions can also degrade or damage these materials. Fencing and other enclosures around a seismic station can be effective in some regions. However, anecdotally, enclosures have not made a noticeable difference to station preservation in tundra conditions typical of the Arctic. Here, the flat landscape and lack of vegetation means station infrastructure is visible from great distances and may be an attractant to curious wildlife.

In terms of weather, additional challenges beyond temperature and visibility include high winds in exposed regions. The seismic station equipment installed across this harsh landscape is routinely exposed to hurricane-force winds very close to the ground surface. This has resulted in solar panels getting cracked by high wind pressure and/or being blown out of their frames (e.g., Fig. 6e). In some cases, high winds have resulted in satellite communication dishes that have been rotated on their mounts or have had their solid steel mounting plates sheared off and the dish blown a great distance away.

There is also a perpetual element of new and unknown challenges that arise while operating seismic stations in remote regions of northern Canada. In one instance, high water and wind-driven waves washed out the access trail between the beach-side landing strip and the seismic station located some distance away on the tundra (Fig. 6d). Adaptability and improvisation are often necessary for success. In this case, a bridge over the washed-out trail (now under a metre of water) was constructed using driftwood scavenged from the nearby beach. This unforeseen damage and necessary repair resulted in using up more of the precious time available from the chartered flight schedule. This solution kept critical equipment and people dry. In all subsequent visits to this particular location, a ladder was brought to serve as a temporary bridge over this slowly widening water feature. In addition to adapting to unforeseen challenges, weather will dictate seismic station maintenance and operations in the Arctic. It is not uncommon to have a weather system disrupt small aircraft flights for many days, as pilots must adhere to the visual flight rules, which requires the weather to be clear enough for safe operation. Field teams are often waiting to access a site or more problematically, the team may be stuck at a remote site waiting to be able to leave.

In recent years, the western Canadian Arctic has experienced many wildfires that have had significant negative impacts on communities and their residents. These events have also caused downstream impacts on all activities within the region, including the operation of WARNS and other geoscience research. This has included evacuation orders for communities, air quality below national standards for safety, and rescheduling other aircraft that are not being used in firefighting activities or medical evacuations. Wildfires also cause highway closures that prevent the flow of goods and people, and limit the ability for large-scale road-based evacuation. Wildfires present an evolving hazard of seismic station operations in northwestern Canada and, indeed, the rest of Canada.

WARNS broadband seismic stations and their data in northwest Canada

The stations making up WARNS are diverse in their origin and, therefore, in their design and layout (Fig. 7). However, all sites share the same basic components. A seismometer is central to each station, and is the sensor that is placed in or on the ground that measures the Earth's vibrations. All seismometers at WARNS' sites are weak-motion broadband instruments. The seismometers are connected to a digitizer, a device that

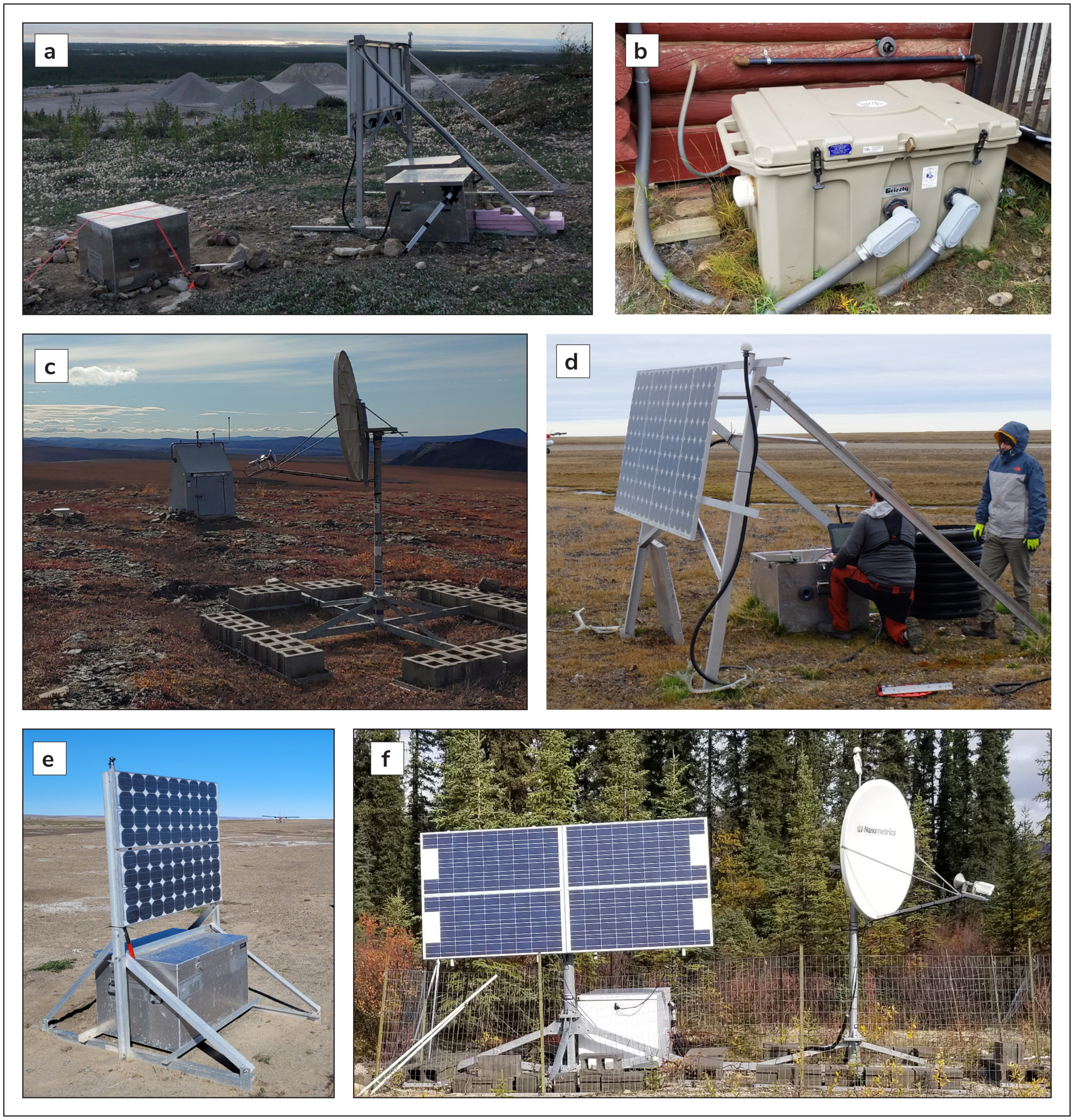

Figure 7. *Examples of WARNS seismic stations.* ***(a)*** *The NOWN station is located in a quarry east of the Town of Norman Wells. It is a solar-powered site equipped with cellular communications for real-time data streaming.* ***(b)*** *The TSIIG station is located within the Hamlet of Tsiigehtchic and is an adopted EarthScope TA station on the grounds of the local visitor's centre. It is AC mains-powered and has a dedicated DSL line for real-time data communications.* ***(c)*** *The RICHY station is located along the Dempster Highway at Wright's Pass (near the border of the Yukon and the Northwest Territories). This station was adopted from the EarthScope TA and still uses the solar power and communications enclosure from the previous experiment. Upon its adoption to WARNS, satellite telemetry was added to the station. Challenges with high winds have resulted in this location being converted to an offline site, and data is harvested annually.* ***(d)*** *The BRHR station is located at the northwest corner of Banks Island (see Figure 1). It is the northernmost WARNS station and was adopted from the BISN experiment. This is an offline solar-powered station. Data are harvested annually or as access permits.* ***(e)*** *The JNPT station was adopted from the BISN experiment and is located on the eastern coast of Banks Island (see Figure 1). This solar-powered station operates offline.* ***(f)*** *The MMPY station is located along the North Canol Road in the Yukon, southwest of Macmillan Pass. The station was adopted from the YNSN experiment and is solar-powered with a large array of panels and real-time data telemetry via satellite connection.*

converts the ground motion measured in analog volts into digital counts. The digitizer also handles assigning a time stamp to each data packet. Timing precision is achieved via a global positioning system (GPS) antenna connected to the digitizer to acquire satellite-based absolute time information. In modern equipment, the digitizer is often connected directly to the Internet and can accommodate real-time data streaming in addition to buffering and archiving the data on a local disk. Finally, the power system provides power to the digitizer, sensor and communications equipment. For WARNS, the power systems vary between sites and are either DC solar setups (with large battery banks) or AC grid power with a single backup battery. In this section, we briefly outline the equipment used at WARNS sites.

The following sensors are used across the range of WARNS stations: Guralp CMG-3ESP, Guralp CMG-40T, Nanometrics Trillium 120P/PA, Nanometrics Trillium 120PH (and SlimV2), Nanometrics Trillium Horizon 120 and Nanometrics Trillium Compact 120. The sensor selection for a given station depends on the local site conditions. Several of the sensors listed above are capable of direct-burial installations (i.e., the entire sensor is buried in soil/sediment). However, these direct-burial instruments are impractical when rock is at surface. In these circumstances, a vault-style instrument would be employed (e.g., CMG-3ESP, CMG-40T, or Trillium 120P/PA). Notably, the vault-style instruments have been used in the tundra, even when rock is not at surface. In these instances, a pit is excavated (approximately 1 m deep), and a large-diameter culvert is placed vertically within the pit to create a protective housing for the sensor. In some cases, sand is used to level the base of the pit, and a large flat rock or patio stone is used as a platform for the sensor. The range of digitizers paired with these sensors include Nanometrics Trident, Nanometrics Taurus, Nanometrics Centaur and Nanometrics Pegasus. In most cases, the seismic equipment used for WARNS stations was reused from past temporary seismic experiments (e.g., POLARIS) or loaned from interested academic collaborators.

Some stations in WARNS operate without data streaming (i.e., offline). The Taurus, Centaur and Pegasus digitizers are used for these stations because they can accommodate large flash storage volumes to maintain a local data archive. Depending on the size of the flash media and the noise conditions of the site, approximately two to three years' worth of continuous seismic recordings can be collected without concern of data loss. In practice, a station would never intentionally be left operating offline for this length of time due to the numerous challenges in collecting reliable data (discussed above). Typically, an offline station is visited once per year to harvest data and facilitate a local disk change, as well as perform upkeep and maintenance on the site equipment. However, there are circumstances when a station is not accessible during a scheduled visit (e.g., due to inclement weather preventing departure from the base of operations or landing at the remote site). In these cases, site visits are postponed until the next available flight window, or even to the following year. At present, there are five stations operating offline within WARNS: BRHR (Fig. 7d), MTBLK, SENTN, RICHY (Fig. 7c) and STOKY. The now-decommissioned JNPT station (Fig. 7e) illustrates an alternative compact station design used for WARNS.

The power systems used at WARNS stations are relatively simple and include DC solar and AC mains power. Stations located within communities use AC mains power as it substantially reduces station complexity, including maintenance requirements. A deep-cycle Absorbent Glass Mat (AGM) battery with a charger/maintainer is also connected to serve as a temporary backup DC power source in case grid power is lost. In remote northern communities that produce electricity from diesel generators, short power surges or brownouts occur frequently. The battery backup helps to ensure continuity in station operation. These simple backup power sources can keep a station operating for five to seven days without grid power. The typical power system for remote WARNS stations is solar power. This includes a battery bank on the order of 1000 amp-hours composed of AGM or Gel-cell lead-acid batteries. The battery bank is connected to a solar array ranging from 200 to 400 W using a solar controller. The battery bank is insulated to reduce temperature fluctuations, and in some circumstances, a small electric heater is added inside the battery/station enclosure.

Real-time data streaming for WARNS is accomplished in several ways. The simplest communications consist of a cellular modem colocated at the station, providing a direct data connection for the digitizer. The data are then streamed in real time from the remote site location to the GSC-PDC. In several locations, cellular communications are facilitated through collaboration with other Government of Canada departments operating other scientific equipment. Currently, three WARNS stations stream over cellular connections: TUKN, ULUN and NOWN (Fig. 7a). Colocation of stations with other agencies' research equipment also provides additional technical personnel and local contacts to assist with site maintenance when required. The WARNS stations also use digital subscriber line (DSL) services, where a dedicated account and DSL modem provide internet. The site digitizer is connected to the modem and streams the data in real time back to the GSC-PDC. To date, the WARNS territorial geological survey partners (YGS and NTGS) have provided these communication services, whereby one station is currently operating in this configuration (Fig. 7b; TSIIG). In some cases, WARNS stations are colocated with other government, research or private facilities, and arrangements have been made for the seismic instruments to be connected to existing Internet services at these sites. Currently, there are four stations operating in this configuration (OGILY, KLONY, NAHA and CMBN). Furthermore, WARNS also uses satellite-based telemetry to stream data, known as very small aperture terminals (VSATs), which are configurations of small satellite dishes capable of transmitting data while drawing relatively low power. For these stations, an additional component, Nanometrics Cygnus, is required to act as the satellite modem connecting the local digitizer (either a Trident or Centaur) to the local network back at the GSC-PDC. Currently, four of the WARNS stations stream their data using satellite connections: MMPY (Fig. 7f), TGTN, MAYO and WTLY, and an additional two are planned to be brought online in the coming years.

The near future holds interesting possibilities for the simplification of real-time communications at remote sites. Although satellite-based communications require less power, the dish can be susceptible to damage from wind or wildlife. Additionally, the agreements for these services are costly. With the upcoming implementation of direct-to-cell satellite services, remote seismic stations can be switched online using standard cellular modems equipped with SIM cards capable of connecting to satellite-LTE networks. This will be beneficial in terms of simplifying and reducing the footprint size of the site. Furthermore, there is a cost benefit with the increase in overall data transfer bandwidth.

As indicated above, all online WARNS stations stream their data in real time to the GSC-PDC and have typical latencies of two to five seconds. These data are then immediately streamed to the EarthScope Data Management Centre (previously IRIS DMC), making these raw data freely available (i.e., open access). For the offline stations, the data are processed into a common format and manually uploaded to the EarthScope DMC after returning from site visits. The stations under the banner of WARNS belong to the network code PQ, which is the research network for the Public Safety Geoscience Program of the Pacific division of the GSC (Geological Survey of Canada, 2013).

The data quality for sites across WARNS varies between locations and is dependent upon the installation type, sensor, as well as local noise conditions (e.g., within a community or located near the coast). In general, the data quality of WARNS stations is good and equivalent to other long-term broadband stations. Figures 8 and 9 illustrate probabilistic power spectral densities (PPSD) for stations TUKN and WTLY, respectively. The grey lines denote the bounds of the new, high and low-noise models (Peterson, 1993). These represent a globally averaged range of expected background ambient seismic noise across different frequencies. The PPSD for each station illustrates the long-term average site conditions in the context of the global range. The lower the PPSD level (near the lower bound of the noise model), the quieter the site is. Presumably, this leads to a higher-quality station where low-amplitude signals can be detected among the background noise. Conversely, the higher the PPSD level, the noisier the site, that is, the PPSD is not only influenced by nearby sources of Earth vibrations. The site construction, shelter and local subsurface geology (e.g., soft sedimentary material) can also influence the baseline performance of a seismic station.

Figure 8 illustrates the PPSD and spectrogram for station TUKN, located within the Hamlet of Tuktoyaktuk, Northwest Territories, on the coast of the Arctic Ocean. This site consists of a Trillium 120PH (direct-burial sensor) installed within a sand pit on a small (several metres high) bluff overlooking the bay. The site has reasonable lower noise conditions at periods of 1 to 50 s.

We observe greater variance in (and generally higher) noise levels at longer and shorter periods. High-frequency noise is likely attributed to the station location, which is within the community, near a road and within 5 m of the beach. The noise levels at longer periods are more difficult to explain. Seasonally, global ambient seismic noise at periods >1 s is attributed to ocean storm activity, and stations in the northern hemisphere experience higher noise levels during winter months (Li et al., 2022). We note the opposite seasonal trend in Figure 8, where noise levels are often lower by 40 to 60 dB during winter months. As much of the western Canadian Arctic is underlain by permafrost, the observed seasonality in the PPSD for station TUKN may be due to fluctuations in air temperature that lead to changes in soil rigidity (i.e., seasonal thawing of the

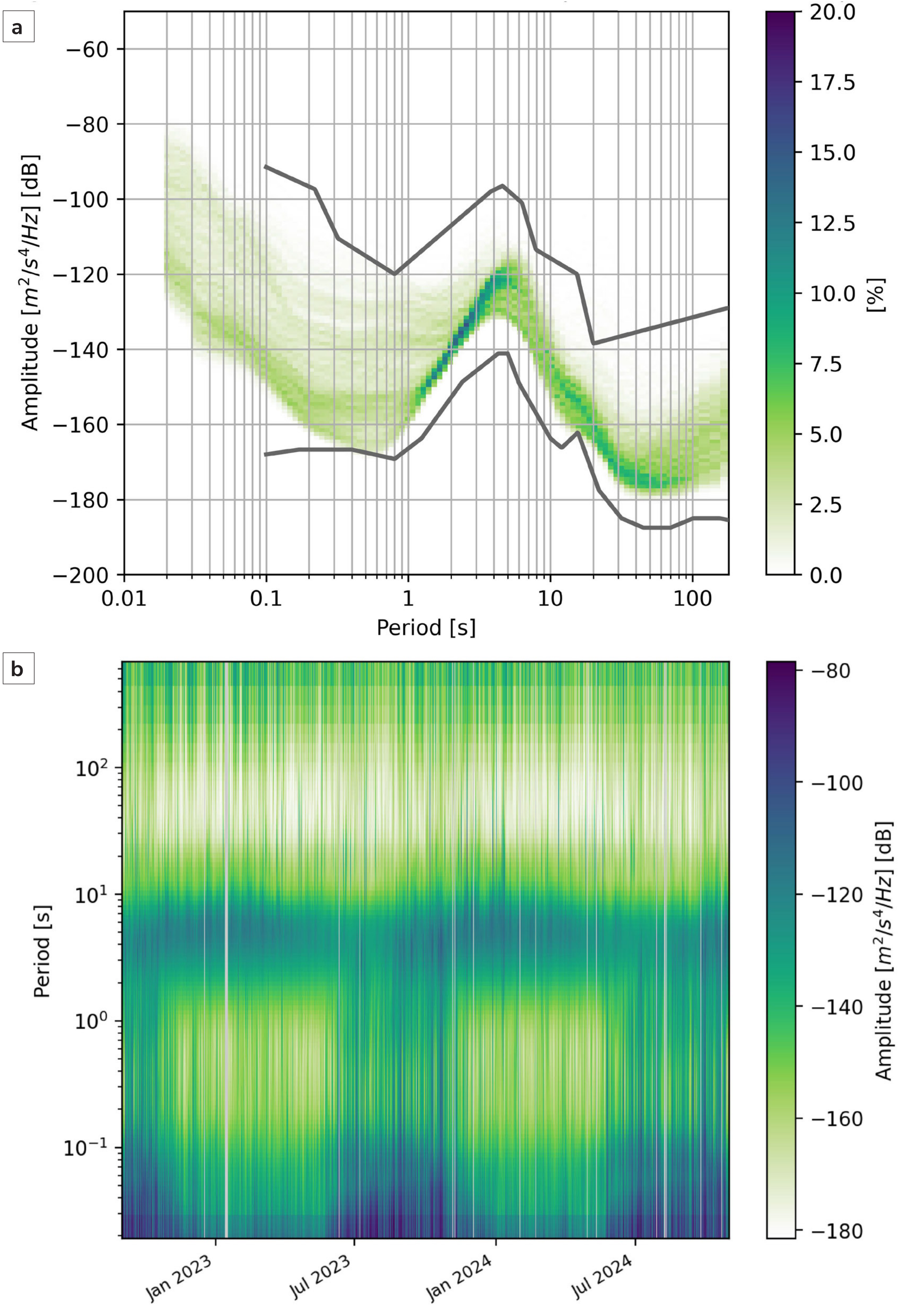

Figure 8. *Probabilistic power spectral density* ***(a)*** *and spectrogram* ***(b)*** *of ambient seismic noise for station TUKN. Upper and lower grey lines in (a) represent the new high and low-noise models, respectively (Peterson, 1993).*

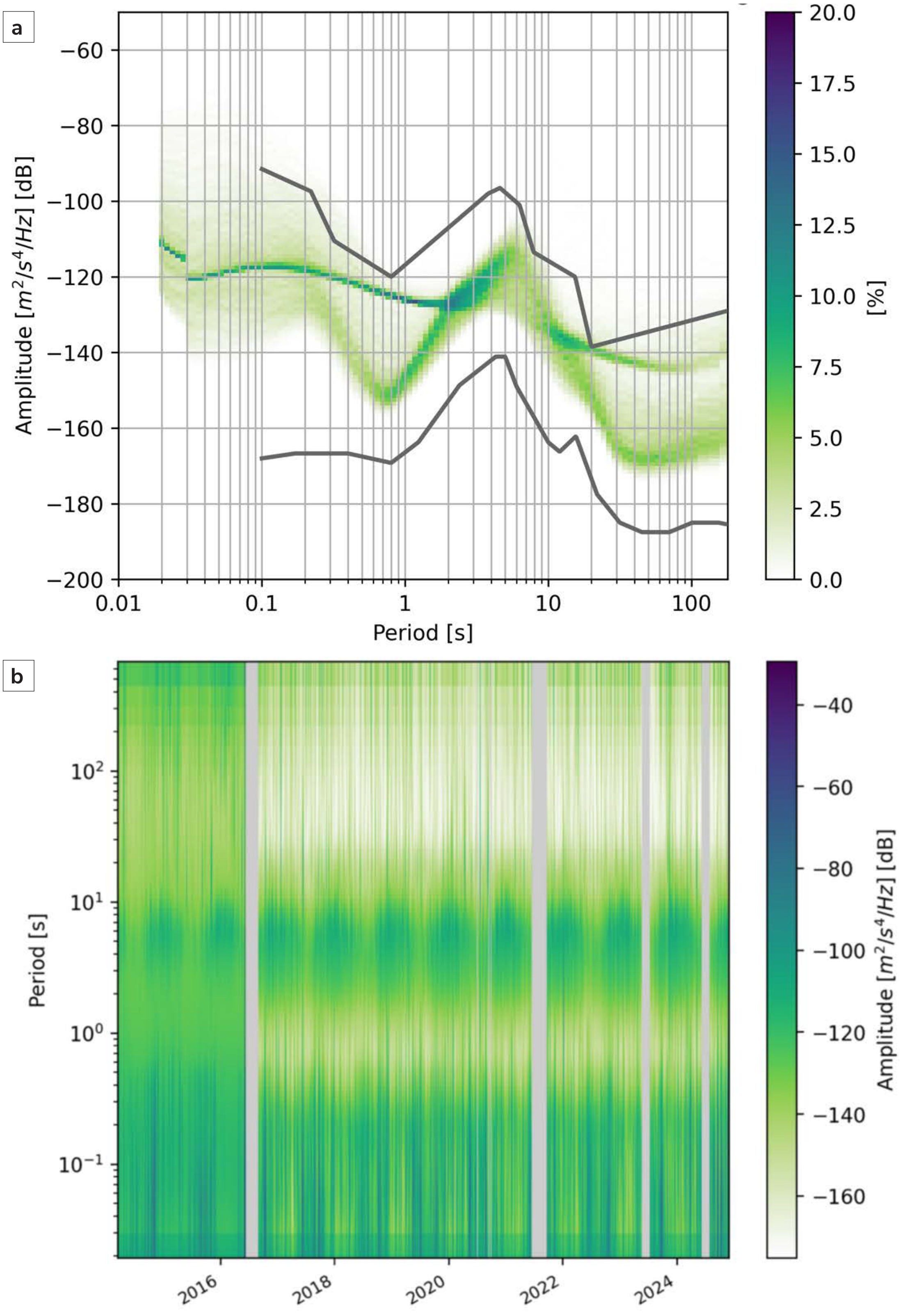

Figure 9. *Probabilistic power spectral density* ***(a)*** *and spectrogram* ***(b)*** *of ambient seismic noise for station WTLY. Upper and lower grey lines in (a) represent the new high and low-noise models, respectively (Peterson, 1993).*

active layer), resulting in dramatically different site conditions (geophysically) throughout the year.

Figure 9 illustrates the PPSD and spectrogram for station WTLY, located near the community of Watson Lake, Yukon, at the outer limits of the local airport. Though the airport does not experience regular traffic, it does serve as a base of operations for wildfire services for southern Yukon and northern British Columbia. The sensor at WTLY is a Trillium 120PH (direct-burial sensor) installed within the unconsolidated sediments located approximately 20 m away from the edge of a lake. The PPSD for WTLY exhibits similar patterns as TUKN, with higher noise levels at high frequencies (short periods). Figure 9 also illustrates variations in data quality due to technical challenges and installation. A secondary band is observed in the PPSD plot at systematically higher levels across all periods, which coincides with the early deployment period shown in the spectrogram plot before late 2016. Recorded background noise levels decreased significantly after the sensor was repaired and reinstalled.

Concluding remarks

Though vast and remote, the Canadian north is gaining an increased awareness due to improved accessibility, development interests and the impacts of climate change. The continued study of geohazards in the Canadian north is important for addressing the needs and security of northerners. The collaborative efforts between Canadian academic groups, territorial governments and the federal government have led to the development and successful operation of seismic networks in northwestern Canada, including WARNS. This initiative would not exist today without the support and contributions from a broad and diverse group during the last decade (see Acknowledgments). The WARNS program will continue to provide important open-source seismological data (mostly in real time) that enables improved earthquake monitoring and geoscientific discovery in northern Canada. As the will and the means permit, WARNS will continue to expand in the coming years to help address unresolved (and evolving) tectono-climactic questions, and will help Canada adapt to future environmental conditions.

Acknowledgments

We respectfully acknowledge that many of the seismic stations of WARNS are installed on the Traditional Territories of Indigenous Peoples of Canada. Summer 2025 will mark 10 years since the initial deployment of BISN stations. This report provides an opportunity to acknowledge and thank the many individuals who have contributed to the development and maintenance of the various seismic networks deployed in northwestern Canada that is discussed in this work, and which led to the inception of WARNS. Contributions include fieldwork assistance, logistics support, in-kind support and provision of equipment. Our thanks and acknowledgements are extended to: David Snyder (retired), Roger MacLeod, Riddhi Dave, Peter Morse, Jiri Raska, Lisa Nykolaishen and Mingzhou Li (NRCan); Justin Emberley (formerly YGS); Hendrick Falck (NTGS); Clement Estève (University of Vienna); Justin Strauss and Marisa Palucis (Dartmouth College); Yajing Liu (McGill University); Fiona Darbyshire (Université du Québec à Montréal); Michael Bostock (University of British Columbia); Quinn Worthington and Joel Cubley (Yukon University); Rick Moore and Marian Jusko (Nanometrics Inc.); Stephen Mosher (formerly University of Ottawa); Edwin Nissen (University of Victoria); Stephane Poitras (formerly NTGS); Michael Schmidt (CANImage). We also thank Dr. Jan Dettmer for his critical review of this manuscript.

Data and code availability

The seismological datasets discussed in this article are freely available, either upon request from the authors, or from the EarthScope Data Management Centre. The facilities of EarthScope Consortium were used to access waveforms, related metadata and/or derived products used in this study. These services are funded through the National Science Foundation's Seismological Facility for the Advancement of Geoscience (SAGE) Award under Cooperative Agreement EAR-1724509.

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