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Abstract

The development of unconventional hydrocarbon resources in the Norman Wells region of the Central Mackenzie Valley, Northwest Territories, has been explored by the energy industry. In early 2014, Conoco-Philips Canada conducted two multi-stage test operations of hydraulic fracturing (HF) in the region. In this study, we combine seismic data from the Canadian National Seismograph Network, four new stations established by the Northwest Territories Geoscience Office in collaboration with Natural Resources Canada in the Norman Wells region, and a local dense array installed by Conoco-Philips Canada to study the seismicity distribution during the pre-HF, HF and post-HF periods. We have identified and located 130 earthquakes within 100 km of the geographic centre of the local seismic network near Norman Wells for the pre-HF period (11 September 2013 – 7 February 2014). In comparison, 231 events are located during the HF period (8 February 2014 – 10 March 2014), and for the two post-HF periods, 11 March 2014 – 31 July 2014 and 27 February 2015 – 31 December 2015, we have catalogued 255 and 138 events, respectively. Source parameters and detailed phase pickings of each earthquake are given in the Appendices.

1. Introduction

Norman Wells is located in the Mackenzie plain and on the north side of the Mackenzie River in the Northwest Territories. The Mackenzie plain, also known as the Central Mackenzie Valley (CMV), was the focus of land sale and drilling in the last decade associated with the unconventional oil play of the Canol and Bluefish Formations. As a result, members of local communities have expressed concerns about the impact of using hydraulic fracturing (HF) technology on the region, including environmental issues and increasing seismic hazard due to induced seismicity.

To address critical knowledge gaps in induced seismicity related to unconventional shale gas development and to establish reliable baselines, this study was conducted to investigate the effect of HF operations on the background seismicity near Norman Wells. Earthquake activity was monitored during three intervals: before, during and after two multi-stage test operations conducted in February and March of 2014 by Conoco-Philips Canada. Continuous waveforms from 11 September 2013 to 31 July 2014 and from 27 February 2015 to 31 December 2015 were carefully analyzed to better define the spatiotemporal distribution of local seismicity.

In general, although seismicity in the Norman Wells region is moderate, the Mackenzie Mountains to the west of the study area is the most seismically active area in the mainland Northwest Territories. The high rate of seismicity can be linked to the transfer of crustal stress from the Yakutat collision zone, which reactivates shallow thrust faults within the foreland fold-and-thrust belt of the Mackenzie Mountains (Mazzotti et al., 2008). The largest recorded event in the region occurred on 23 December 1985 (M_S 6.9), and in fact, is part of a remarkable earthquake series that struck the northern Canadian Cordillera over a three-year period from 1985 to 1988 (Cassidy et al., 2010).

There are nine earthquakes, all M <4.5, found in the national earthquake database compiled by Natural Resources Canada (NRCan) within one hundred kilometers of Norman Wells between 1985 and 2016. However, by expanding the search area to a radius of 200 km from the geographical centre of Norman Wells, the total number of events increases to 104 for the same time window. This is due to many earthquakes occurring in the Mackenzie Mountains, including a large Mw 5.7 earthquake in 2006. Given that the main scope of this study is to locate local earthquakes possibly associated with the HF operations in the Norman Wells area, we only consider events within 100 km of the center of the local seismograph network and compare the seismicity rate during the pre-HF, HF and post-HF periods in 2013, 2014 and 2015. The main objective of this open-file report is to document all the phase pickings used in our location process and to provide an earthquake catalogue for the Norman Wells region in a format useful to the research community.

2. Data and Analysis

Waveform data from stations of the POLARIS network (FDSN network code: PO) is the primary source of information for this study. Prior to 2013, station NOWN, located in the Norman Wells quarry, was the only station in the area (Figure 1a). There are two other PO stations in the broader McKenzie region located in the communities of Colville Lake (CLVN) and Wrigley (WGLY). In 2013, the Northwest Territories Geoscience Office in collaboration with NRCan installed four new seismic stations on either side of the Mackenzie Valley near Norman Wells (Figures 1a) to enhance detection capability of the regional network (Cairns et al., 2014); these stations (CARC, MOON, PYRD and TULN) were installed and operationalized between 11 and 18 of September 2013. Due to a malfunctioned vertical component of the seismometer, seismic station MOON was upgraded and moved a few kilometers closer to Norman Wells under a new station code (DCYN) in mid-August 2014 (Table 1).

In addition to the aforementioned stations, Conoco-Philips Canada also temporarily deployed a local array of seven seismic stations from 7 February (one day before the start of the local HF operation) to 7 August 2014 in the vicinity of the well pad to monitor HF-induced seismicity (Table 1).

In this study, we re-evaluate the pattern of background seismicity in the CMV by measuring the differential travel times between the *P* and *S* phases (i.e., *S*-*P* times) from all available local stations. The manually derived *S*-*P* times were analyzed with the software package, "Seismic Analysis" (SEISAN, Ottemöller et al., 2012) to determine the corresponding source parameters, including the origin time, epicenter, focal depth, and local magnitude. We utilize a 1-D velocity profile based on local well log data, instead of a generalized regional model, to minimize hypocentral location errors during the location process (Table 2).

In the case where waveform data are available from only one station, the single-station location (SSL) method in the SEISAN package was used to determine source parameters. The principle concept of the SSL method is to determine the source's hypocenter by tracing back the corresponding ray path. To do this, we first pick a short time window containing the *P* arrival on the vertical-component seismogram. Cross-correlation functions are then calculated between the vertical component and the two horizontal components, respectively. Using the ratio between the two cross-correlation functions we are able to estimate the back azimuth (i.e., the direction from station to the source). The incident angle can subsequently be estimated from the ratio between the cross-correlation between the radial and vertical components and the auto-correlation of the vertical component. Finally, the ray path is traced backward from the recording station toward the source based on the assumed velocity model and the hypocenter is located at the point that satisfies the observed *S*-*P* time. Readers are referred to the original paper by Roberts et al. (1989) and the SEISAN user manual (Ottemöller et al., 2012) for more technical details.

3. Parameters in the Earthquake Catalogue and Pick Files

We were able to identify and locate 130 earthquakes within 100 km of the geographical centre of the local seismic network near Norman Wells between 11 September 2013 and 7 February 2014 (Figure 2). During the HF period of 8 February – 10 March 2014, we determined source parameters for 231 seismic events (Figure 3). During the two post-HF periods, i.e., 11 March – 31 July 2014 and 27 February – 31 December 2015, an additional 255 (Figure 4) and 138 earthquakes (Figure 5) were located, respectively.

We provide the earthquake catalogue as four tables in Appendix 1: Table A1.1 from 11 September 2013 to 7 February 2014, Table A1.2 from 8 February 2014 to 10 March 2014, Table A1.3 from 11 March 2014 to 31 July 2014, and Table A1.4 from 27 February 2015 to 31 December 2015. Each line corresponds to one event showing the date, origin time, latitude, longitude, depth, root-mean-square error (RMS) and magnitude (coda magnitude, MC; local magnitude, ML). The RMS value is set to zero for an earthquake if only one station was used to determine its location.

Phase picks and location parameters of events listed in Tables A1.1–4 are included in Appendices 2, 3, 4 and 5, respectively. The following abbreviations are found in the pick files:

STAT: Seismic station code

SP: Instrument Type - Component

IPHASW: Quality Indicator - Phase ID - Weighting indicator

D: First Motion

HRMM: Hour-Minutes

SECON: Seconds

CODA: Duration (s)

AMPLIT: Amplitude (nm)

PERI: Period (s)

AZIMU: Direction of Approach (Degrees)

VELO: Phase Velocity (km/s)

SNR: Signal to Noise Ratio

AR: Azimuth Residual

TRES: Travel time Residual

W: Weight

DIS: Epicentral Distance (km)

CAZ: Azimuth at source

More information about the location parameters and abbreviations can be obtained from the SEISAN manual that is available online at: http://seisan.info.

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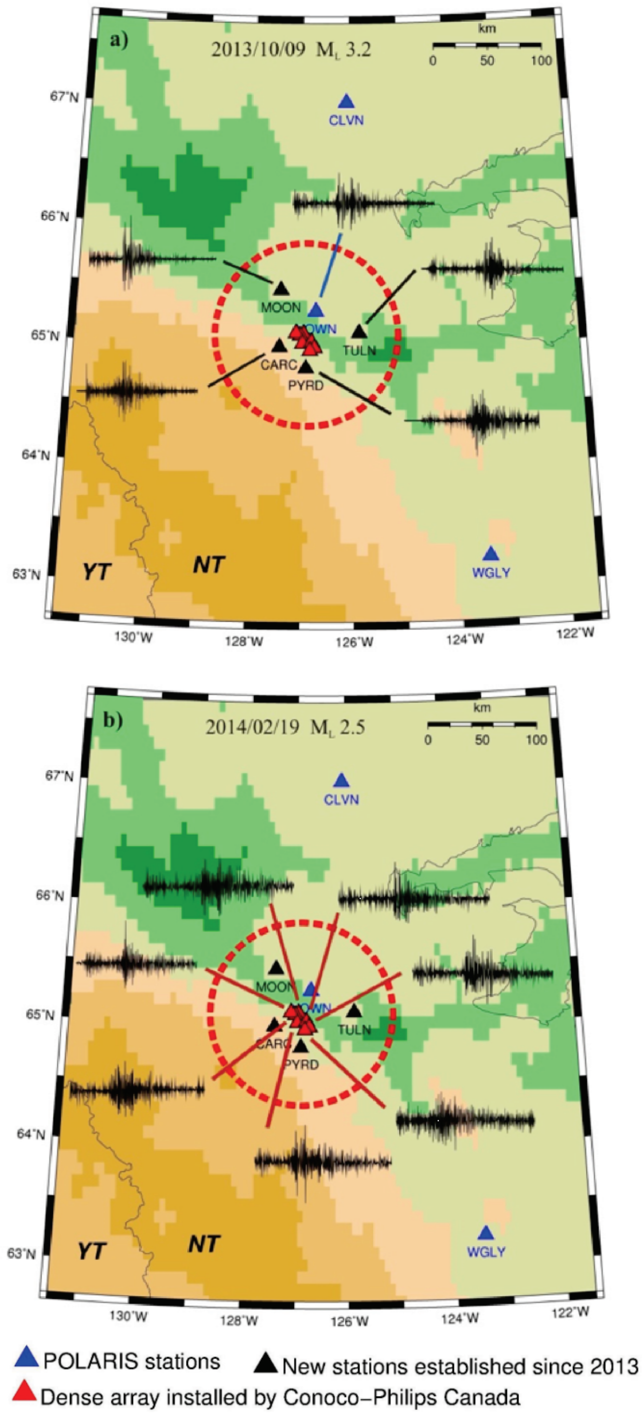

Figure 1: Distribution of the local seismic stations in the study area. (a) POLARIS station (NOWN, blue triangle) and four new stations (black triangles) deployed in 2013. Examples of recorded waveforms (~1 minute; N component of MOON and Z component of the others) at each station of a local earthquake (2013/10/09, M_L 3.2) are shown. Red triangles correspond to a local dense array setup by Conoco-Philips Canada. Dashed red circle marks the radius of 100 km from the center of the seismograph array. (b): Examples of seismograms of another local earthquake (2014/02/09, M_L 2.5). CLVN and WGLY are seismic stations located at the communities of Colville Lake and Wrigley, respectively.

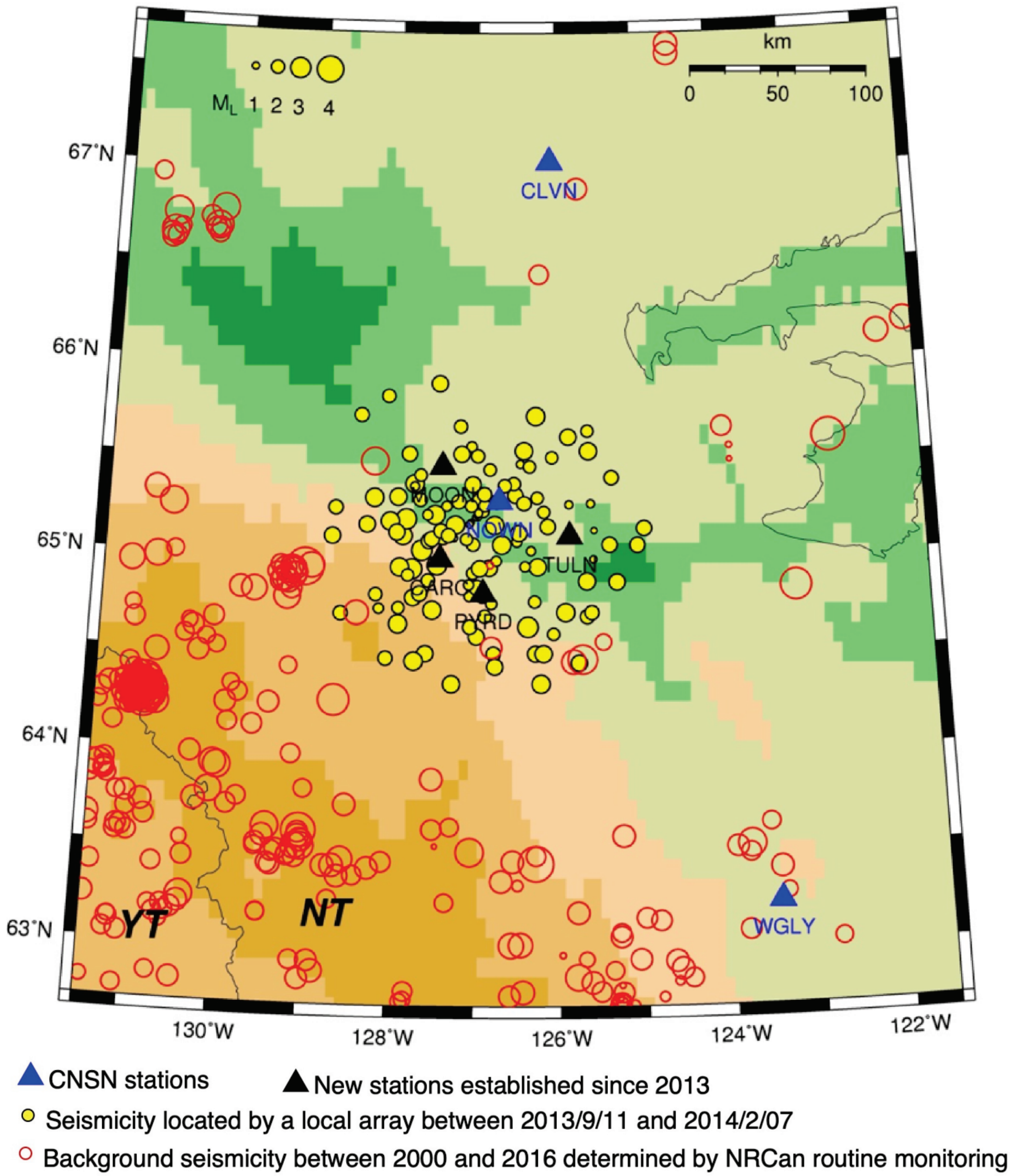

Figure 2: Earthquake distribution between 11 September 2013 and 07 February 2014 (the pre-HF period) as determined by the local seismograph array. The size of circle corresponds to the magnitude of the event. Colors crudely indicate topography. YT: Yukon Territory, NT: Northwest Territories.

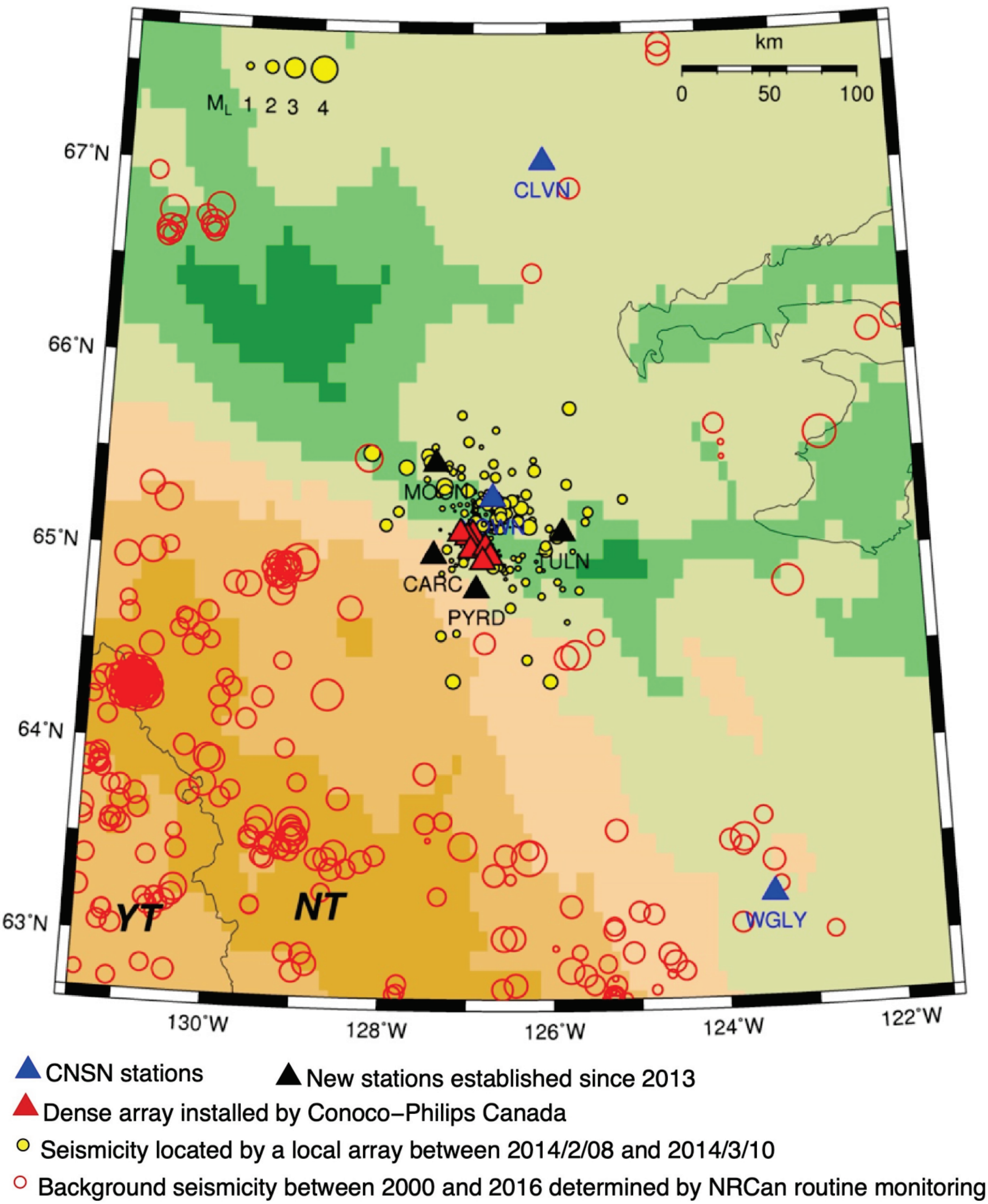

Figure 3: Earthquake locations from 08 February 2014 to 10 March 2014 (the HF operation period) using data recorded by the local array. Layout and format are the same as that in Figure 2.

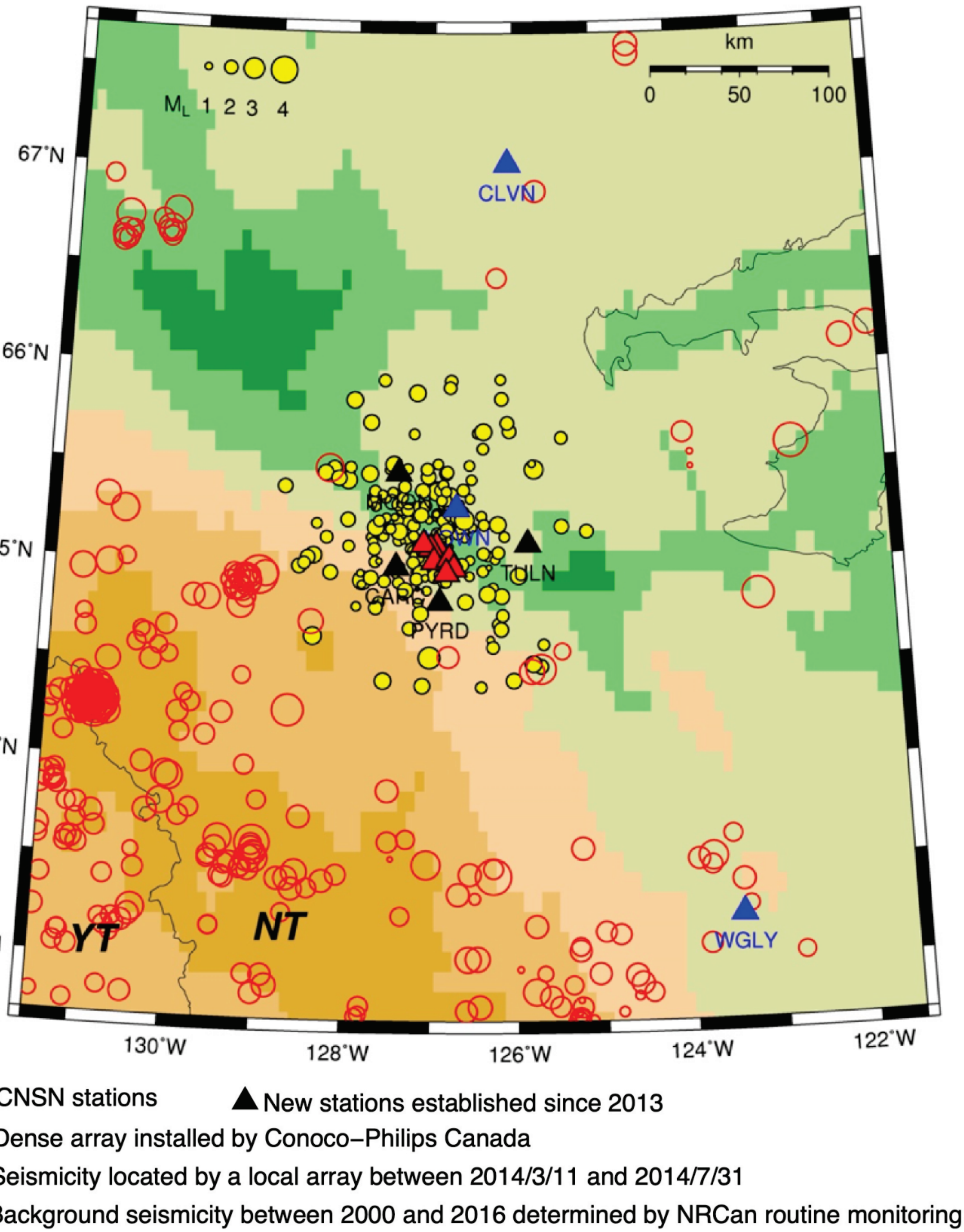

Figure 4: Earthquake locations from 11 March 2014 to 31 July 2014 (the first post-HF period) using data recorded by the local array. Layout and format are the same as that in Figure 2.

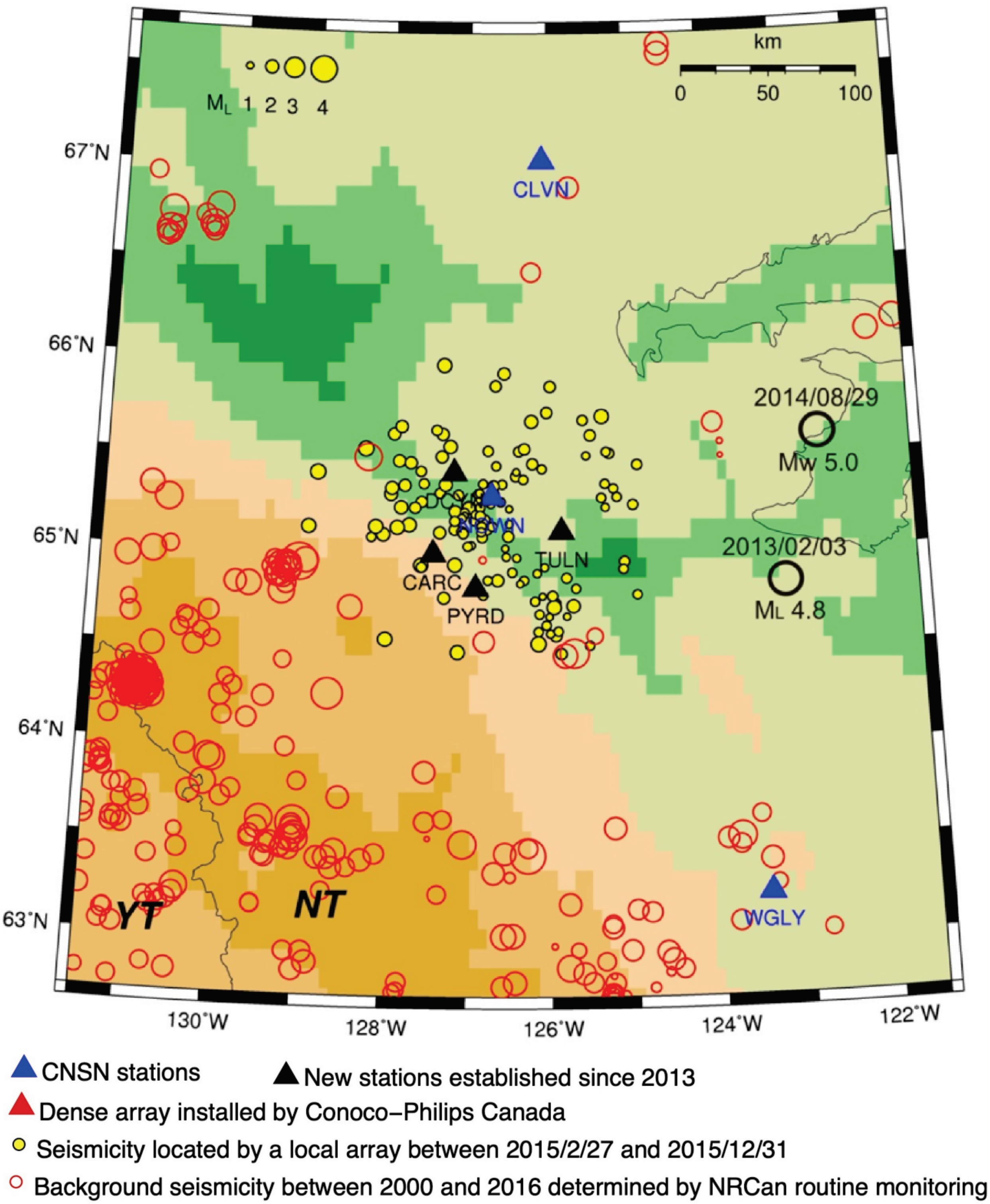

Figure 5: Earthquake locations from 27 February 2015 to 31 December 2015 (the second post-HF period) using data recorded by the local array. The only two earthquakes with M ≥ 4.0 since the start of 2013 in the entire region are highlighted and specified with dates and magnitudes. Layout and format are the same as that in Figure 2.

Table 1. Seismograph stations in our study area.

Network.Station	Latitude (degree)	Longitude (degree)	Elevation (km)	Start Date	End Date
PO.NOWN	65.29427	-126.71448	0.186	2012-08-16	2018-06-09
PO.CLVN	67.03900	-126.07790	0.263	2010-07-18	2012-11-22
NY.WGLY	63.22815	-123.45841	N/A	2013-07-01	-
CARC	64.99700	-127.43587	0.621	2013-09-11	2015-12-31
MOON	65.47310	-127.41200	0.392	2013-09-16	2015-12-31
PYRD	64.82117	126.90720	0.655	2013-09-13	2015-12-31
TULN	65.11472	-125.85529	0.639	2013-09-18	2015-12-31
DCYN	65.41950	-127.17800	N/A	2014-08-07	2015-12-31
CP01	65.1095	-126.9495	0.204	2014-Feb-07	2014-08-07
CP02	65.0956	-127.0204	0.250	2014-Feb-07	2014-08-07
CP03	65.1149	-127.1017	0.262	2014-Feb-07	2014-08 -07
CP04	65.0270	-126.9767	0.290	2014-Feb-07	2014-08 -07
CP05	65.0423	-126.7935	0.296	2014-Feb-07	2014-08-07
CP06	64.9923	-126.7401	0.274	2014-Feb-07	2014-08-07
CP07	64.9676	-126.8327	0.279	2014-Feb-07	2014-08-07

Table 2. One-dimensional velocity model used in the earthquake location process.

Layer	Thickness (km)	V_p (km/s)	V_S (km/s)
1	1.0	3.50	2.02
2	3.0	5.80	3.35
3	3.0	5.90	3.41
4	3.0	6.00	3.47
5	3.0	6.60	3.81
6	26.0	7.80	4.51