Seismic Activity in Southern Ontario: Annual Progress Report for the Period January 1 – December 31, 2020

NWMO-TR-2022-22 December 2022

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ABSTRACT

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Company: [1]Canadian Hazards Information Service;
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As part of geoscientific investigations for Ontario Power Generation (OPG) and Nuclear Waste Management Organization's (NWMO) Deep Geologic Repository (DGR) projects, the Canadian Hazards Information Service (CHIS) of Natural Resources Canada has been monitoring and reporting on microseismic activity surrounding the Bruce nuclear site near Tiverton and regional seismic activity in southern Ontario since 2007. This report summarizes seismic activity observed to the end of 2020.

Following the decision by OPG to not proceed with the proposed low and intermediate level waste DGR at the Bruce nuclear site in June 2020, the emphasis of this reporting year (2020) is maintained on the Bruce nuclear site as an interim measure. Future regional reporting in southern Ontario will be recentered around the proposed site for used nuclear fuel near Teeswater. The proximity of Teeswater site to the Bruce nuclear site means that the data and results presented in this report need not be fundamentally altered.

Seismic activity is observed using the existing Canadian National Seismic Network (CNSN) and Southern Ontario Seismic Network (SOSN) stations in the region, as well as three additional borehole seismographs located within 50 km of the Bruce nuclear site commissioned for the DGR project in August 2007. This network was designed to be capable of recording seismic events of magnitude 1 and above within 50 km of the Bruce nuclear site.

All stations transmit continuous digital data in real-time to a central acquisition hub in Ottawa. CHIS staff in Ottawa integrate the data from these stations with those of the rest of the CNSN and provide monthly reports of the seismic activity within 50 km and 150 km of the Bruce site.

In 2020, three earthquakes occurred within 150 km of the Bruce nuclear site, all less than m_N 2. A group of earthquakes 275 km southeast of the site, near Niagara Falls, included the largest in the region used for earthquake-recurrence estimation. This was a 2.9 m_N for which the depth was estimated to be 6.0 km based on regional depth phase modeling (RDPM). In all, 41 earthquakes have been catalogued within 150 km of the site since 1952.

Since 2004, 13 earthquakes have been catalogued within 50 km of the site. These events have all been very small, ranging in magnitude from 0.1 M_L to 2.5 m_N, and grouped in a single cluster under Lake Huron, approximately 34 km to the north of the site. More work is needed to relocate these events accurately with respect to one another, to find out, for example, if they resolve into a linear structure.

A new area has been proposed for estimating earthquake recurrence parameters in Southern Ontario, one which is more seismotectonically uniform. The rate of M>5 events using the new recurrence region is estimated to be once every 145 years.

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1 INTRODUCTION

In 2007, Ontario Power Generation (OPG) retained the Canadian Hazards Information Service (CHIS) of Natural Resources Canada to monitor and report on microseismic activity near the Bruce nuclear plant. Starting in 2020, the Nuclear Waste Management Organization took over the contract, as part of on-going geoscientific investigations in southern Ontario relating to a proposed Deep Geologic Repository (DGR) for used nuclear fuel. The focal point for these investigations is the Bruce nuclear site (44.327°N, 81.586°W[1]) near Tiverton, ON (see Figure 1). This report summarizes seismic activity observed during 2020.

To record the seismic activity down to magnitude 1.0, additional stations were required to supplement the then-existing stations in southern Ontario. The existing stations included those of the CNSN (Canadian National Seismic Network, network code CN) and POLARIS (Portable Observatories for Lithospheric Analysis and Research Investigating Seismicity, network code PO), established in 2002. The POLARIS network included a station near the Bruce nuclear site, BRCO. Three POLARIS-type installations were installed around BRCO by the University of Western Ontario (UWO; network code WU) in 2007, to form the Bruce nuclear site sub-network. These stations (see Section 2) consist of 3-component down-hole instruments. Additional surface instruments were operated until 2009 at the borehole sites.

In 2014, the wind-down of POLARIS operations was completed. At that time, the University of Western Ontario began operating the former-POLARIS stations in Southern Ontario as the Southern Ontario Seismic Network (SOSN). Since the beginning of 2016, the SOSN and associated stations have been operated by Nanometrics, Inc., including an obligation to refurbish digitizers and telemetry before the end of 2017. Continuous waveform data from POLARIS, SOSN and CNSN stations are publicly available.

The CNSN is able to locate all earthquakes of magnitude 3.0 and above in the more populated regions of southern Canada (see Section 4 for a discussion of earthquake magnitude estimation). Since 2002, the POLARIS network has pushed the completeness threshold down to approximately magnitude 2.0 for southern Ontario. Waveform data from other network operators with stations near the Bruce nuclear network complement data from the CNSN and SOSN. Seismograph stations from which data was acquired in real time 2019–2020 are mapped in Figure 1.

The installation of the Bruce sub-network aimed to lower the location threshold to magnitude 1.0 within 50 km of the Bruce nuclear site. The station spacing was intended to be small enough to detect and locate very small earthquakes within the immediate region, and large enough to span any regional faults, should they occur and prove to be seismogenic. For the latter, an area of about 150 km radius from the site was selected. This approach conforms to the International Atomic Energy Agency's requirements for evaluation of seismic hazards for nuclear facilities (IAEA, 2010). Since this local study area has very low seismicity, and has not yet yielded enough earthquakes to permit detailed recurrence parameter estimation, a larger regional study area is also considered (see Section 5). The local and regional study areas are mapped in Figure 1.

The organization of this report is as follows. Section 2 summarizes station operations in the study area for 2020. Section 3 summarizes current and historical seismicity in the local and regional study areas. Section 4 describes the procedures employed in characterising earthquakes. Section 5 estimates earthquake occurrence rates in the regional study area. Finally, the conclusions are summarized in Section 6.

[1] Reports for years prior to 2016 used 44.316 °N, 81.616 °W, 2.6 km WSW of this location, and slightly offshore.

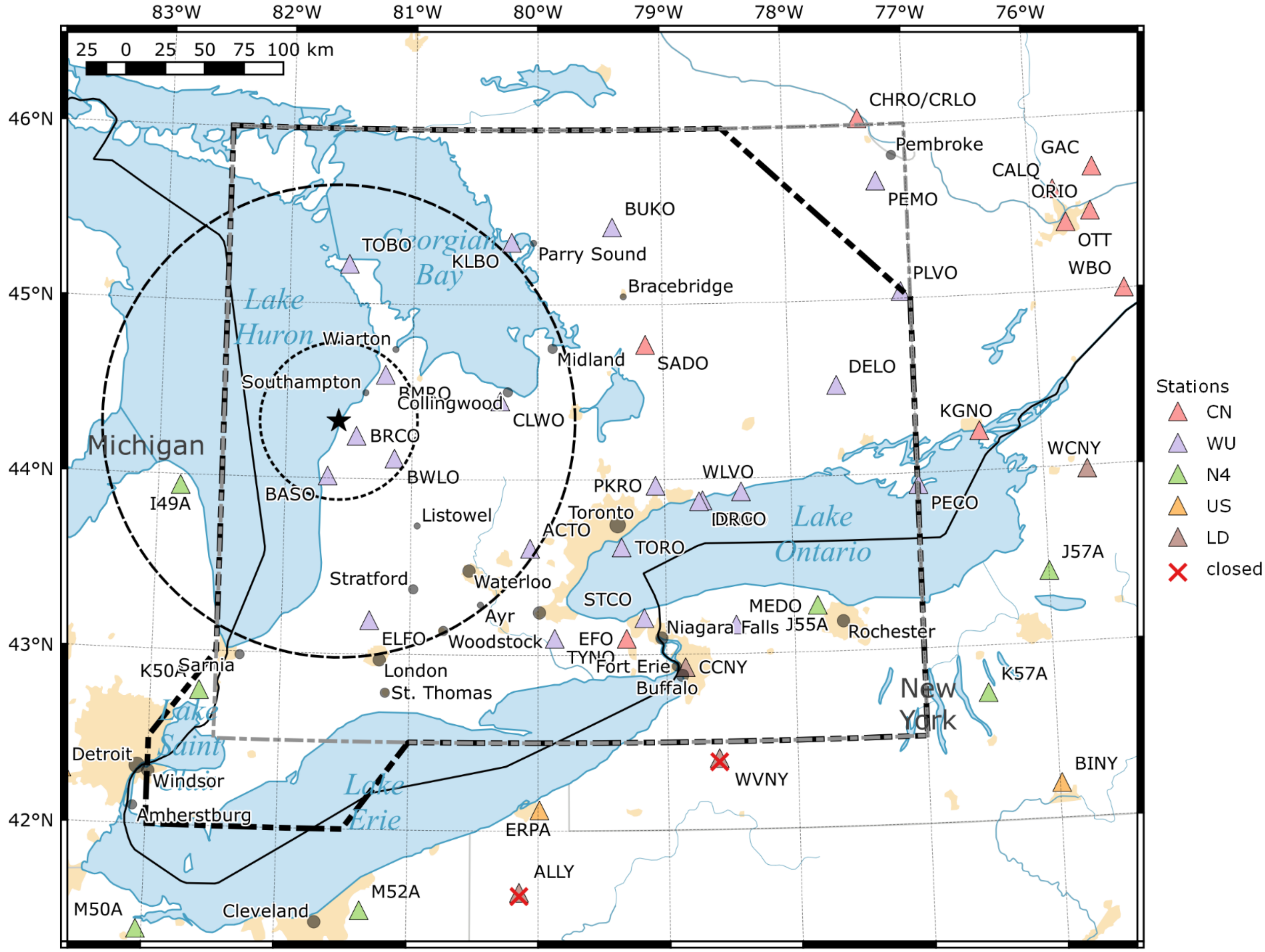

Figure 1: Seismograph stations in southern Ontario, 2019–2020. The Bruce nuclear site is indicated with a black star, and dashed circles are approximately 50 and 150 km radii around this site. The grey rectangular (dash-dotted) and black polygonal (dash-dot-dotted) outlines are two areas used for recurrence calculations (see Section 5.2). Triangles are operational stations, coloured by network code. Stations that closed during 2020 are marked with an X. Urban areas (Schneider, Friedl, McIver, & Woodcock, 2003) are marked in pale yellow.

2 STATION OPERATIONS

The Bruce nuclear sub-network was installed by the University of Western Ontario (UWO) in 2007, with sensors at depth in boreholes, as well as sensors at ground surface as part of UWO research. The stations were sited approximately 40 km from the Bruce nuclear site at Walkerton (WU.BWLO[2]), Ashfield (WU.BASO), and Maryville Lakes (WU.BMRO) in such a way as to complement the existing site near Tiverton (WU.BRCO). The seismometers installed were all three-component broadband sensors. The surface sensors were removed in April 2009, but this did not affect the detection threshold, because the remaining borehole sites tended to be quieter than the surface sites.

Table 1 gives the installation dates and the operational periods (uptimes) of the Bruce nuclear site sub-network for the last two years. The stations around the Bruce nuclear site, initially installed by UWO, are now part of the SOSN, which is operated by Nanometrics, Inc. on behalf of OPG.

Refurbishment efforts undertaken in 2017 (Nanometrics, Inc., 2018) have resulted in high and consistent levels of data availability.

The data availability for the Bruce nuclear sub-network in 2020 is shown graphically in Figure 2. Throughout the year there were few significant outages, except for a minor one on 2020-02-26 that affected all four stations in the near-Bruce region, but was not SOSN-wide, and on 2020-08-06 and 2020-08-12 that affected WU.BMRO. Since the shutdown of the direct SeedLink connection from Nanometrics to CHIS on 2018-09-17, there have been occasional SOSN-wide outages. These show up as light grey vertical stripes in Figure 2. In 2020 these outages were typically less than a minute in duration.

In addition to the Bruce nuclear site stations, many stations of the CNSN (e.g. CN.EFO, CN.SADO) and SOSN (e.g. WU.ACTO, WU.BANO, WU.BUKO, WU.CLWO, WU.ELFO, WU.KLBO, WU.PLIO, WU.TOBO, WU.TYNO) are important to monitor the study area. Two SOSN stations closed in 2017: WU.BANO (Bancroft, ON: 2017-09-26) and WU.PLIO (Pelee Island, ON: 2017-09-27); these were chiefly important for regional monitoring. The maps in Section 3.1 show stations that are important to monitoring seismicity near the Bruce nuclear site, and in southern Ontario, in 2020.

[2]In some instances in this report, the network code and a period "." have been prepended to the station code for clarity.

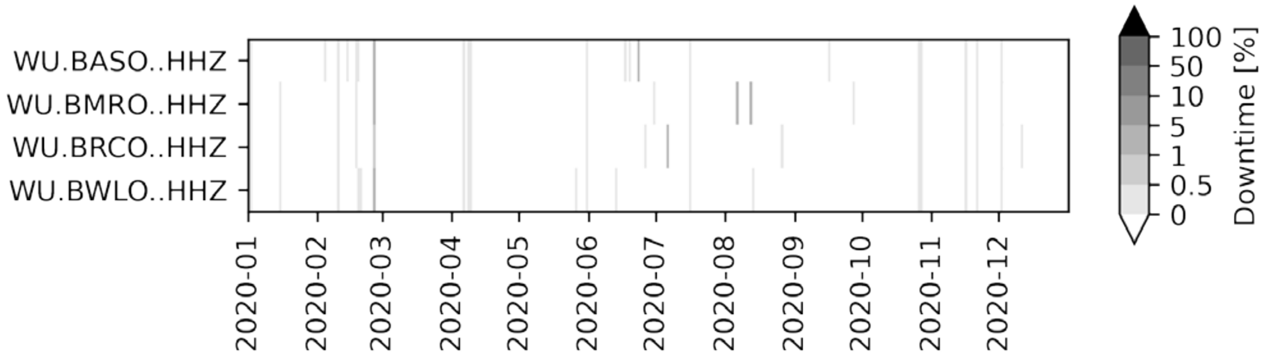

Figure 2: Daily downtime for Bruce nuclear site stations, 2020. Downtime is the complement of availability, as defined in the notes to Table 1.

Since 2013, selected former stations of the USArray transportable array (see http://www.usarray.org/) have been operating as the Central and Eastern U.S. Network (CEUSN, network code N4: http://ceusn.ucsd.edu/). Two stations that are frequently used when locating events near the Bruce site are N4.I49A (Point Hope, MI) and N4.K50A (Casco, MI). Several CEUSN stations were closed in 2018, including two on the south shore of Lake Ontario, important for monitoring the regional study area (N4.J54A closed 2018-08-28 and N4.J56A closed 2018-09-01).

The Lamont-Doherty Cooperative Seismographic Network (LCSN, network code LD) operates seismograph stations south of the border which are important for monitoring seismicity in the study area used for earthquake recurrence estimation and particularly under Lake Ontario and Lake Erie. These include LD.ALLY (Allegheny College, Meadville, PA), LD.CCNY (Canisius College, Buffalo, NY), LD.CFNY (Clifton-Fine, NY), LD.WCNY (West Carthage, NY) and LD.WVNY (West Valley, NY). It was announced in 2019 that the USGS would end funding to the LCSN, and LD.WVNY ceased transmission that same year. By the end of 2020, only LD.CCNY and LD.WCNY were still in operation.

Realtime acquisition of three nearby stations of the United States National Seismic Network (USNSN, network code US) was initiated in September-October of 2019: US.AAM (Ann Arbor, MI), US.ACSO (Alum Creek State Park, OH) and US.GLMI (Grayling, MI). Note that these stations

Table 1: Operating statistics of Bruce nuclear site stations, 2019–2020

sta	name	latitude [°N]	longitude [°E]	surface elev.[a] [m]	depth [m]	sensor elev.[a] [m]	on date (digital)	availability [c]	
								2019	2020
WU.BASO	Ashfield	44.0133	81.6648	210	25	185	2007-08-01	99.99%	99.98%
WU.BMRO	Maryville Lake	44.5952	81.2174	217	39	178	2007-08-02	99.99%	99.97%
WU.BRCO	Tiverton	44.2437	81.4423	273	0	273	2002-02-06[b]	99.97%	99.99%
WU.BWLO	Walkerton	44.1174	81.1382	255	27	228	2007-08-01	99.99%	99.99%

Note:

[a] Elevations are with respect to sea level.

[b] The first Bruce station was initially installed in 1996; date given is when the station was upgraded to provide continuous digital data.

[c] Availability statistics are for vertical channels of seismometers, as seen in the waveform archive. This is considered representative of all channels available to analysts during routine processing.

are just to the west and the south of the area mapped in Figure 1. It is hoped that this will help make seismic monitoring in southern Ontario more robust to future outages.

Where appropriate, phases from USNSN, CEUSN and LCSN stations were added for events that had already been identified near the Bruce nuclear site. However, those stations were not searched to identify new events. The U.S. stations are likely to improve the earthquake location accuracy significantly under Lakes Huron, Erie and Ontario, as they provide azimuthal coverage to the west and to the south.

3 SEISMICITY

3.1 EARTHQUAKES LOCATED IN 2020

In 2020, there were three earthquakes within 150 km of the Bruce nuclear site (see Figure 3), all less than m_N 2.0. Two of the events are clustered together northeast of the Bruce site and locate offshore in Georgian Bay, while the third event located in the northern tip of the Bruce Peninsula.

Figure 4 shows a broader region of southern Ontario and puts the 2020 seismicity around the Bruce site into a regional context. It includes both the rectangular and polygonal outline of the areas used to estimate regional earthquake-recurrence rates in Section 5.2. In 2020, 20 events were catalogued in the rectangular recurrence area.

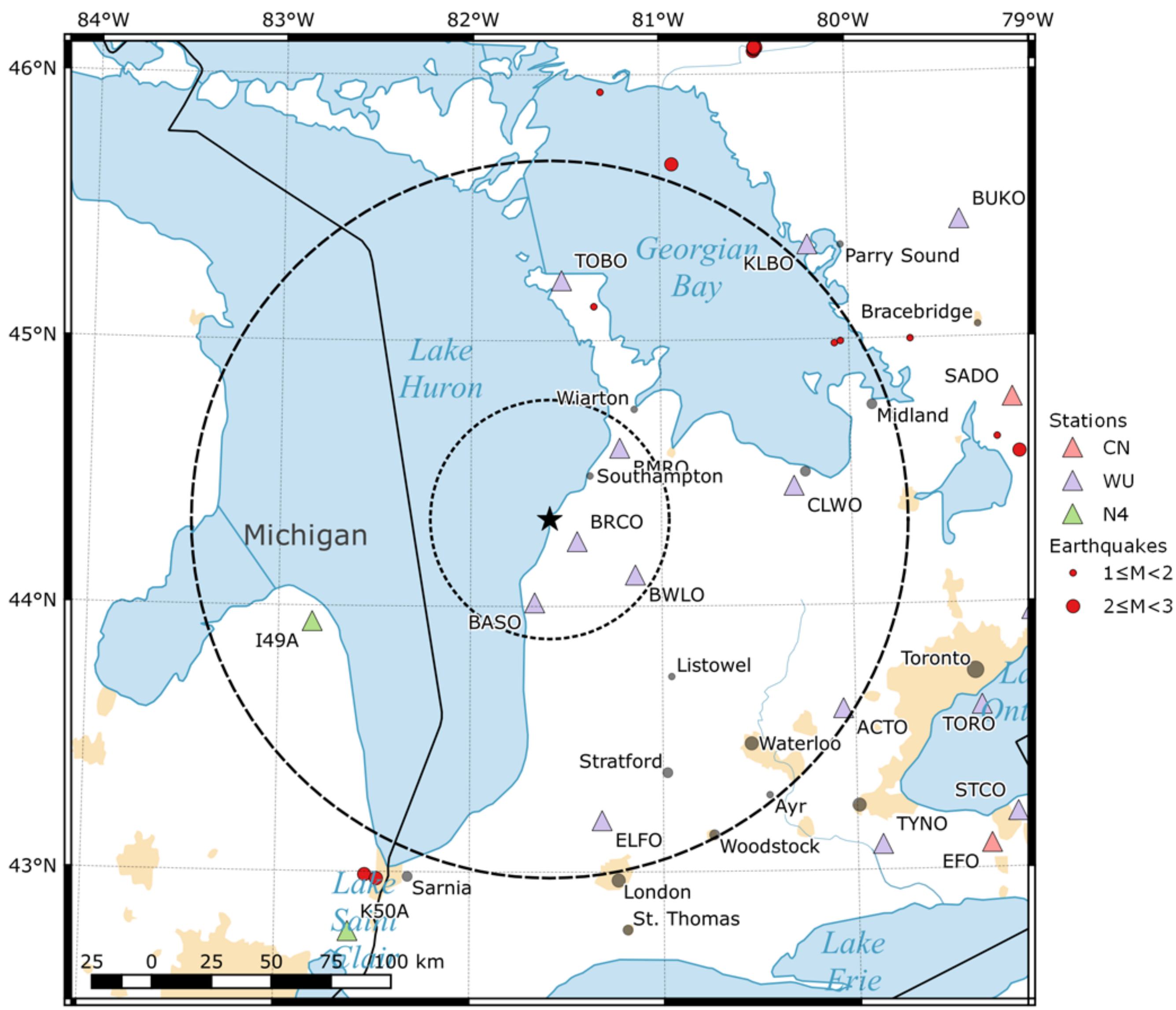

Figure 3: Earthquakes near Bruce site, 2020. Earthquakes are shown as red circles, with the size indicating the magnitude. Notes in caption to Figure 1 also apply.

The largest event in the rectangular recurrence region was a m_N 3.0 in the northeast corner that occurred on 2020-08-10. The epicentre was less than 2 km from Pembroke, but approximately 500 km from the Bruce Nuclear Site. The depth was estimated to be 6.3 km, using Regional depth phase monitoring (RDPM), Ma (2004). Although this event is within the rectangular recurrence region it occurred in the Western Quebec Seismic Zone (WQSZ). Seismicity in the WQSZ has been associated with an early Paleozoic rift zone called the Ottawa-Bonnechere Graben and the Mesozoic track of the Great Meteor Hotspot (Ma & Eaton, 2007). These are significantly different seismotectonic processes than those expected to be encountered in the southern Ontario and Bruce region. For this reason, we will propose to exclude the WQSZ from the polygonal area proposed for estimation of earthquake recurrence parameters at the Bruce site (see polygon on Figure 5 and discussion in Section 5.2).

The second-largest event in the rectangular recurrence area was a m_N 2.9 on 2020-05-19 that occurred 9 km south of Buffalo, NY, and approximately 275 km from the Bruce nuclear site. The depth of this event was estimated at 6±1 km based on regional depth phase modeling (RDPM, see Section 4.2); no crustal Rayleigh phase (Rg) was observed.

There were four other earthquakes near the aforementioned one, with m_N magnitudes between 2.1 and 2.8, and these were the next-largest events in the rectangular recurrence area. Using RDPM It was possible to estimate the depths of the two largest events. The 2.8 m_N earthquake of 2020-03-29 occurred under the southern part of Lake Ontario. The depth was determined to be 1.5 km based on clear regional depth phases on two stations, and strong Rg visible at WLVO. The m_N 2.7 earthquake of 2020-01-21, located 22 km northeast of Niagara Falls, NY, was estimated to be 6 km using RDPM based on results from two stations.

A concentration of seismicity southwest of Lake Ontario and east of Lake Erie was first noted by Basham, Weichert, & Berry (1979), as part of a mooted Niagara Falls-Attica seismic zone. Seeber & Armbruster (1993) noted that improvements to instrumentation and techniques reflected in the NCEER-91 catalogue resolved this more clearly into two clusters. They associated some of the seismicity of the Niagara Seismic Zone with rapid erosion rates, and some of the seismicity of the Attica Seismic Zone with the Clarendon-Linden Fault. Stevens (1994) cautioned that epicentres prior to 1970 are insufficiently accurate to support spatial correlations, and that between 1970 and 1991 the observed seismicity was scattered and without clear trends. Mereu et al. (2002) showed that, with the SOSN contributing more accurate epicentres, more earthquakes were being located under Lake Ontario and Lake Erie. They speculated that this seismicity could be related to water flows along southeast-dipping fissures below the lakes (Mereu et al., 2002). This is thought to explain why many events in the recurrence region occur under and south of the lakes.

Just southwest of the recurrence areas (past and proposed), on 2020-08-21, there was a m_N 3.8 earthquake at the west end of Lake Erie, felt in the US and Canada. The magnitude of the 2020 event was estimated by the USGS to be 3.2 M_{wr} using regional moment tensor inversion, with a largely strike-slip focal mechanism. This event was 35 km from the 2018 m_N 4.1 Amherstburg earthquake (Ackerley, Adams, Peci, & Halchuk, 2020). Also, there are three other events on the south shore of Lake Erie with Nuttli magnitudes equal to 2.5, 2.3 and 2.8, all at fixed depths of 5 km, and all east of the m_N 3.8 event. Although the Amherstburg earthquake, and these four 2020 events were located outside the area that this study uses to estimate recurrence, they nonetheless occurred in a similar seismotectonic setting to the Bruce nuclear site, inasmuch as it was located in the same platform province – the Michigan basin – of the same stable continental region.

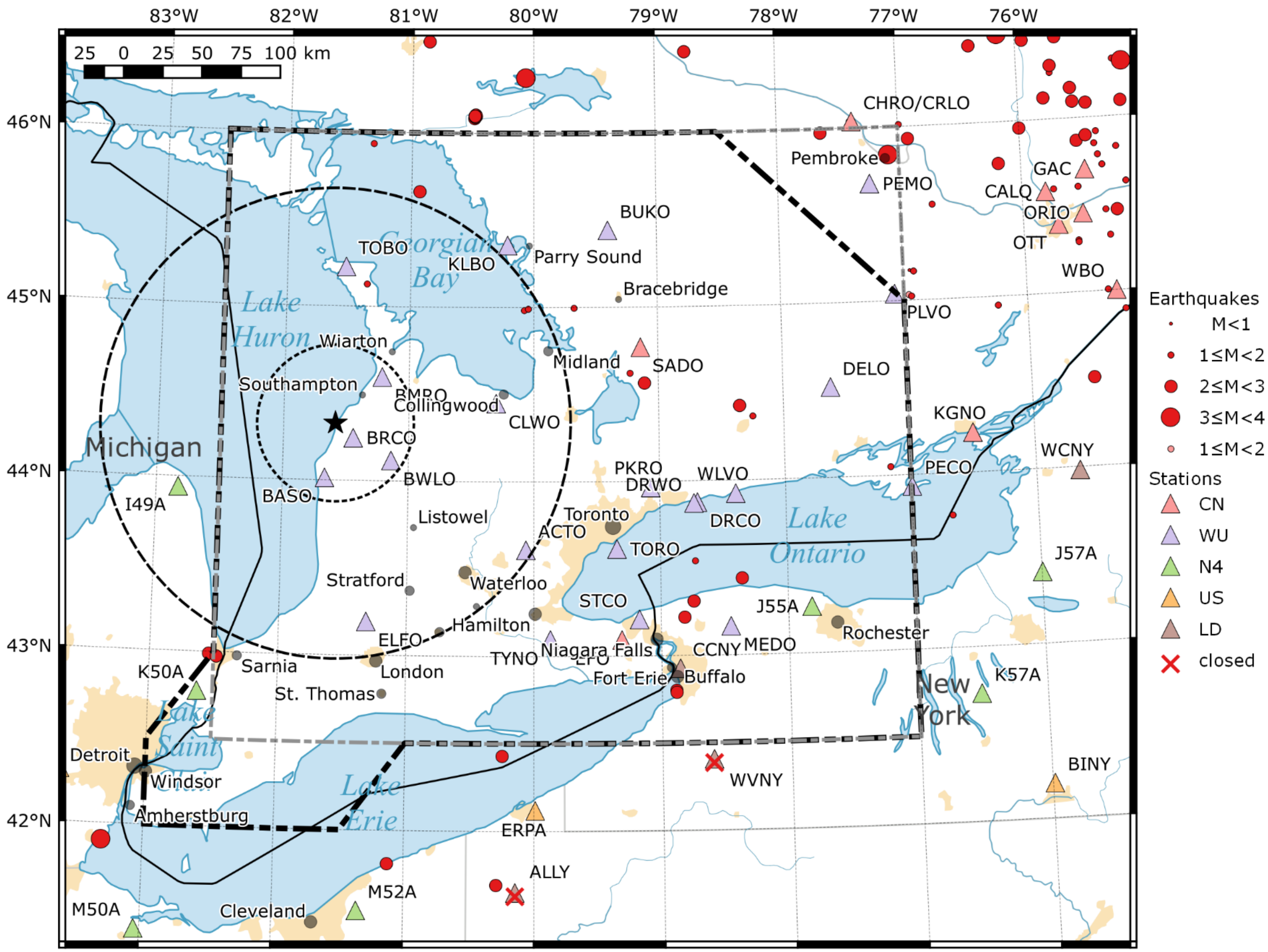

Figure 4: Earthquakes in southern Ontario, 2020. Notes in caption to Figure 3 apply.

3.2 HISTORICAL SEISMICITY

The low level of seismicity within 50 km of the Bruce nuclear site in 2020 is consistent with the lack of seismicity there in the past. However, a cluster of seismicity under Lake Huron, approximately 20 km NW of Southampton, ON, is active (see Table 2).

Using conventional event detection techniques, eight earthquakes of magnitude 1.0 or greater have been located within 50 km of the Bruce nuclear site since 2004. Note that although no events were located by CHIS prior to the events listed in Table 2, the detection threshold prior to the completion of POLARIS upgrades in 2002 was such that it is unlikely that events under magnitude 2.0 could have been detected. With the addition of the Bruce nuclear site sub-network, any event over 1.0 m_N within 50 km of the site is detectible, as long as all stations are operating. See Section 5 for more details on magnitude thresholds and completeness.

The four smallest events of 2012 that are listed in Table 2 were added to the catalogue in 2018, including one over magnitude 1.0. These events were detected by scanning 2011–2017 using matched-filter techniques, with events from 2012 and 2016 serving as templates (Ackerley, Adams, Peci, Halchuk, & Street, 2019). The magnitudes of these events were estimated using conventional techniques. The location of the largest event (1.4 m_N) was estimated by manual re-picking and travel-time inversion, while the remainder were fixed to the location of the template event with the largest cross-correlation coefficient. It should be possible to obtain relative locations and magnitudes of greater accuracy using correlation-based techniques, for events detected after the installation of the Bruce nuclear sub-network. Such careful analysis is recommended by the IAEA (2010, p. 14) for earthquakes recorded in the near region.

Table 2: Earthquakes within 50 km of Bruce site, 2000–2020

time [a] [UTC]	mag.	lat. [°N]	lon. [°W]	dep. [km]	D[b]	#[c]	stations	phases	comment	dist. to site [km]
2004-09-28 21:10	2.1 m_N	44.6333	81.5078	2	R		10	16	Lake Huron.	34
2006-09-10 17:09	2.0 m_N	44.6340	81.4568	2	R		11	20	Lake Huron.	35
2006-09-17 07:14	1.6 m_N	44.6304	81.4766	2	R		8	15	Lake Huron.	34
2008-09-14 04:50	1.2 m_N	44.6253	81.6417	18	F		6	8	Lake Huron.	33
2011-12-31 10:32	2.5 m_N	44.6287	81.5190	3.5	V	3	7	14	Lake Huron.	33
2011-12-31 11:04	1.5 m_N	44.6269	81.5208	3.5	M		6	12	Lake Huron. Aftershock.	33
2012-01-08 16:39[d]	0.6 m_N	44.6297	81.5175	2	M		3	5	Lake Huron.	34
2012-02-09 00:11[d]	0.1 M_L	44.6297	81.5175	2	M		3	4	Lake Huron.	34
2012-02-09 14:26	2.3 m_N	44.6297	81.5175	3.5	M		10	17	Lake Huron.	34
2012-02-28 08:11[d]	1.4 m_N	44.6303	81.5199	2	M		7	13	Lake Huron.	34
2012-04-12 20:45[d]	0.7 m_N	44.6297	81.5175	2	M		2	4	Lake Huron.	34
2016-08-21 07:14	1.8 m_N	44.6560	81.4897	2	R		8	15	Lake Huron.	37

The following notes apply as indicated:

[a] Times given are Coordinated Universal Time (UTC), not local times.

[b] Depth type coding "D" is as follows (see Section 4.2 for detail):

F – operator assigned
V – RDPM
R – Rg observed; assigned shallow depth
M – fixed depth based on waveform similarity

[c] "#" is the number of depth phases used in the estimating the depth.

[d] Events located by manual picking and travel-time inversion after detection using cross-correlation template-matching. See Appendix of Ackerley, et al. (2019) for details.

Figure 5 shows the historical seismicity of southern Ontario and the area surrounding the Bruce nuclear site. Events prior to 1980 are shown in yellow to differentiate them from the more recent events, as the accuracy of the earlier epicentres decreases the further back one goes in time. This is due to the varying state of the network, as well as the instruments themselves. Very early events are sometimes based solely on felt reports and their interpretation is thus highly dependent on the population distribution at the time, as well as the accuracy of the reports. Prior to the installation of local stations, larger events would have been located using phases from regional stations. Even with clear recordings on at least three stations, the data would have been mostly

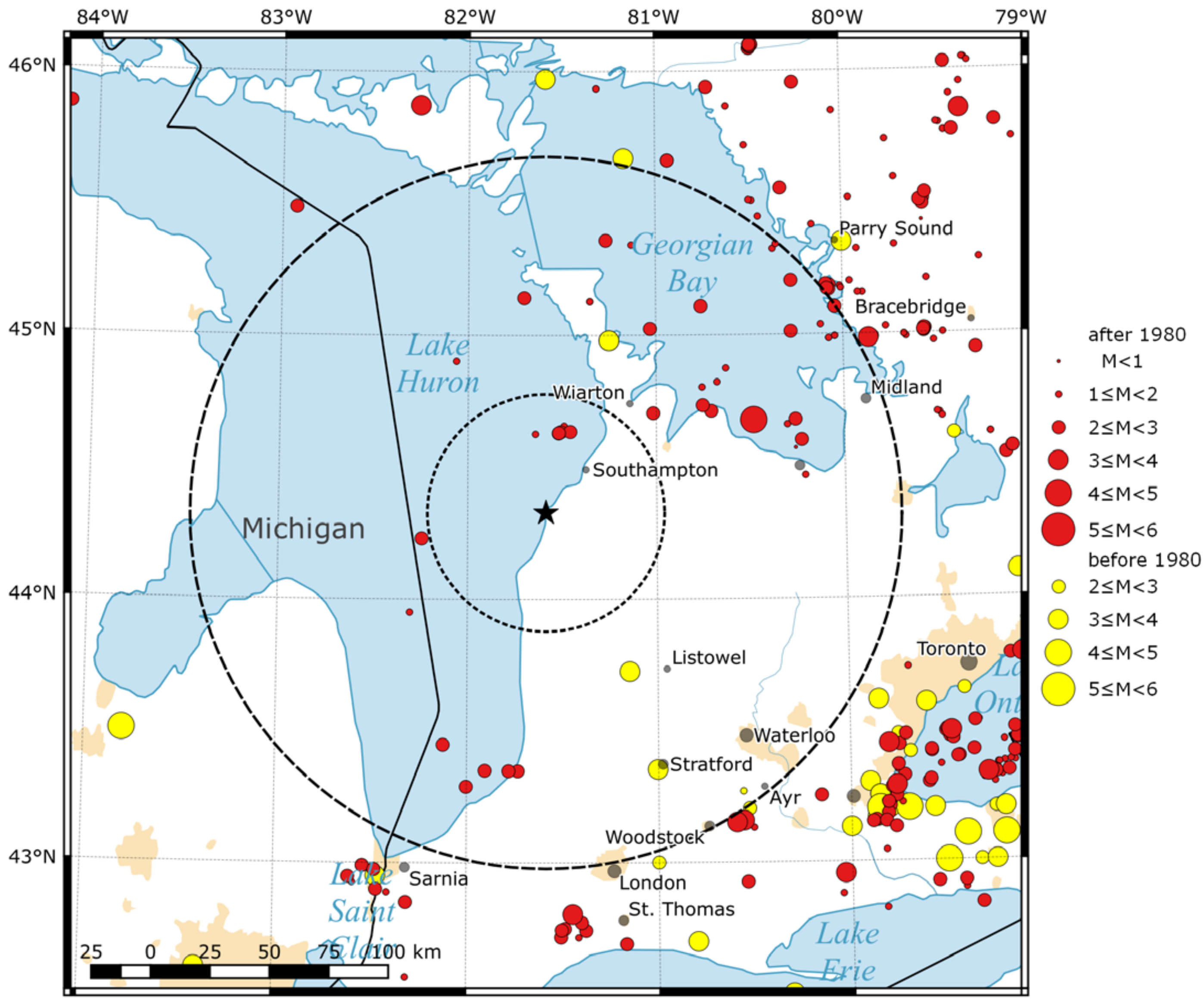

Figure 5: Historical earthquakes near within southern Ontario, 1804–2020. Yellow circles indicate earthquakes that occurred prior to 1980 and for which locations and magnitudes are less reliable. Note: the start date in the figure title should reflect the “start of monitoring” which in this case would mean the start of widespread record-keeping via newspapers, etc. However, this figure title instead indicates the year of the earliest event shown, 1804. Notes in caption to Figure 3 also apply.

from one side, and at distances of several 100 km, hence the accuracy would have been within approximately 20 km, even for reasonably sized events. Around 1980 the seismograph network was densified in the region and events began to be recorded digitally, making it easier to identify and use more seismic phases. Events after 1980 are therefore considered more reliable, within an epicentral accuracy of approximately ±10 km. Similarly, with the advent of the SOSN, the uncertainty was further reduced, to an estimated ±2 km (Mereu, et al., 2002). Note that these location error estimates are approximate, and are for earthquakes that would have been large enough to be clearly recorded by at least two or three stations. The error associated with any particular location will have changed through the years depending on exactly which stations were operational at the time, the magnitude of the event, and how clearly the event was recorded by each of the stations available (which is dependent on local noise at the time).

Since 1952, 39 earthquakes have been located between 50 and 150 km from the Bruce nuclear site (see Table 3). The largest event was a m_N 4.3 in 2005 at the southern end of Georgian Bay (Dineva, Eaton, Ma, & Mereu, 2007), felt in Owen Sound (at a distance of 37 km), Parry Sound (82 km) and up to 150 km away. The next two largest events were a m_N 3.8 (M_L 3.6) in 1957 near Stratford (felt in London) and a M_L 3.5 on the Bruce Peninsula in 1958. The latter was not based on instrumental data, but solely on felt reports.

Table 3: Earthquakes between 50 and 150 km from Bruce site, 1950–2020

time [UTC]	mag.	lat. [°N]	lon. [°W]	dep. [km]	D	#	felt	stations	phases	comment	Dist. to site [km]
1952-12-25 04:28[a]	3.0 m_N	43.7250	81.1470	20				3	5	16 km W of Listowel	75
1957-06-29 11:25[a,b]	3.8 m_N	43.3530	81.0030	18			✓	5	9	4 km WSW of Stratford	117
1958-01-24 12:00[c]	3.5 M_L	44.9800	81.2500				✓	0	0	27 km N of Wiarton	77
1978-10-15 22:36[a]	1.7 m_N	43.2690	80.5590	18				7	12	9 km W of Ayr	143
1991-04-15 04:10[d]	2.5 m_N	45.1410	81.7020	18	F			6	11	Lake Huron	90
1993-12-26 15:59	2.6 m_N	44.6000	80.2280	18	F			13	19	Georgian Bay	112
1995-04-09 23:39	2.5 m_N	45.0109	80.2788	18	F			7	11	Georgian Bay	128
1995-11-11 05:42	2.8 m_N	45.0237	81.0306	18	F			14	26	Georgian Bay	89
1995-11-22 03:29	2.0 m_N	45.1087	80.7592	18	F			3	6	Georgian Bay	108
1995-12-19 05:39	2.1 m_N	45.1033	80.0428	2	R			6	9	Georgian Bay	149
1996-05-28 05:56	2.4 m_N	45.2045	80.2757	18	F			13	23	Georgian Bay	142
1996-09-30 22:02	2.2 m_N	44.7040	81.0158	18	F			5	9	12 km SE of Wiarton	61
1998-04-23 06:11	2.4 m_N	43.3472	81.7331	18	F			10	18	45 km S of Goderich	109
1998-08-10 02:33	2.1 m_N	43.3476	81.7814	18	F			10	14	45 km S of Goderich	109
2001-06-05 09:31	2.6 m_N	44.6777	80.2598	2	R			11	19	Georgian Bay	112
2003-05-25 04:34	2.0 m_N	44.7114	80.7070	18	F			7	13	Georgian Bay	81
2004-08-07 10:01	2.0 m_N	45.3591	81.2663	18	F			13	23	Georgian Bay	117
2005-10-20 21:15	2.2 m_N	44.6711	80.4845	11	M			12	21	Georgian Bay, Foreshock	95
2005-10-20 21:16	4.3 m_N	44.6766	80.4821	11	V	4	✓	16	28	Georgian Bay	96
2006-01-06 16:36	2.0 m_N	44.7330	80.7523	18	F			6	10	Georgian Bay	80
2007-04-19 14:54	1.3 m_N	45.3422	81.1296	5	F			5	7	Georgian Bay	118
2007-06-18 07:18	2.1 m_N	44.2292	82.2420	18	F			8	13	Lake Huron	53
2007-12-25 14:17	1.9 m_N	43.9492	82.3025	18	F			5	8	Lake Huron	71
2009-10-09 07:08	1.0 m_N	44.6589	80.3029	5	F			7	12	Georgian Bay	108
2010-01-16 01:30	0.9 m_N	44.5702	80.2603	5	F			4	5	Georgian Bay	108
2010-06-04 00:51	1.8 m_N	44.8736	80.6283	2	R			10	18	Georgian Bay	97
2011-05-11 05:22	1.6 m_N	45.3250	80.3721	2	R			6	12	Georgian Bay	146
2012-08-08 01:06	2.2 m_N	43.2880	82.0025	18	F			6	11	Lake Huron	120
2013-09-05 02:47	1.9 m_N	44.4657	80.2108	2	R		✓	14	24	2 km S of Collingwood	110
2014-11-04 10:04	1.8 m_N	44.8021	80.7553	18	F			9	16	Georgian Bay	84
2015-05-15 03:44	1.7 m_N	44.8215	80.6755	18	F			11	20	Georgian Bay	90
2015-06-17 07:24	1.4 m_N	45.0359	80.1193	2	R			9	18	Georgian Bay	140
2015-07-14 11:04	2.3 m_N	43.3490	81.9053	18	F			13	21	Lake Huron	111
2016-03-20 17:46	1.7 m_N	44.9017	82.0627	2	R			8	16	Lake Huron	74
2016-03-27 23:06	2.3 m_N	43.4472	82.1242	18	F			12	21	Lake Huron	106
2018-02-08 10:14	1.6 m_N	45.3428	80.3546	2	R			8	13	25 km W of Parry Sound	149
2020-01-02 02:38	1.5 m_N	45.1276	81.3516	5	F			7	13	45 km N of Wiarton, ON	90
2020-06-01 03:59	1.6 m_N	44.9831	80.0763	2	R			13	24	Georgian Bay	140
2020-08-03 06:13	1.0 m_N	44.991	-80.044	2	R			6	10	Georgian Bay	142

In addition to the notes to Table 2, the following notes apply as indicated:

[a] Epicentres and magnitudes were re-evaluated using numerical methods in the early 1990s.

[b] Initial epicentre, obtained using graphical methods, was 18 km NW of St. Thomas, ON, 156 km from Bruce site.

[c] Based on felt reports only: time is unknown and magnitude is assigned according to intensity reports.

[d] First event recorded digitally in the region.

Figure 6 shows the historical seismicity on a regional scale. Most of the events in the region are located along the southern shores of Lake Erie, in the western Lake Ontario/Niagara Peninsula region and in western Quebec. The seismicity of 2020 was consistent with this pattern.

The largest historical earthquake in the region was a 5.5 M_L event on 1929-08-12 near Attica, NY. It has been suggested that this and subsequent nearby events may be associated with the Clarendon-Linden fault (Basham, Weichert, & Berry, 1979; Seeber & Armbruster, 1993).

Just outside the recurrence regions, there is a significant cluster of seismicity on the south shore of Lake Erie. The largest event in this cluster was a 5.0 m_b event on 1986-01-31. This event occurred 12 km away from two deep wastewater disposal wells that started injection in 1975 and 1981. It has been a subject of debate ever since whether the event was natural or anthropogenic. Further to the south, many events have been more definitively been linked to hydraulic fracturing and wastewater disposal wells (Brudzinski & Kozłowska, 2019). Some of the seismicity shown in Figure 6 is therefore likely to be anthropogenic. However, Figure 6 shows that along the south shore of Lake Erie seismicity had been recorded prior to 1980, before the era of intensified hydrocarbon extraction. Brudzinski & Kozłowska (2019) review evidence suggesting that it is associated with a geological feature known as the Akron magnetic lineament and conclude that at least some of the seismicity must be of natural origin.

Although there was no dedicated seismic monitoring data for the region near the Bruce nuclear site before BRCO was installed in 1996, it is nonetheless possible to calculate the theoretical shaking from past events at the site. The five Canadian events with the strongest theoretical shaking are listed in Table 4 (the New Madrid sequence of earthquakes 1811–1812 may have produced greater shaking, but the NEDB is incomplete outside of Canada, so these events have been omitted). Two ground motion models were used to estimate the ground shaking, HBB1981 (Hasegawa, Basham, & Berry, 1981) and NGA-East (Goulet, et al., 2017). The older model overestimates shaking at distance; the newer model shows that nearby events, such as the 2005 Georgian Bay event, were likely to have produced as much shaking as the 1663 earthquake near Charlevoix. Note that these rankings are very much dependent on the choice of PGA as a measure of ground shaking intensity; the use of spectral accelerations at longer periods might be very different.

Table 4: Historical earthquakes that would have created strongest shaking at the Bruce site. Peak ground acceleration (PGA) was estimated using two ground motion models, HBB1981 (Hasegawa, Basham, & Berry, 1981) and NGA-East (Goulet, et al., 2017) for all events in the NEDB above magnitude 4, within 1500 km of the site. Of the earthquakes that occurred in Canada, only the five likely to have produced the greatest ground shaking according to NGA-East are listed below. Moment magnitude estimates are from Bent (2022), except as noted.

time [UTC]	latitude [°N]	longitude [°W]	magnitude [a]		distance [km]	PGA [g]		region and comment
			NEDB	moment		NGA-East	HBB1981	
1935-11-01	46.78	-79.07	6.2ML	6.1	336	0.58%	1.50%	Témiscaming, QC
1732-09-16	45.50	-73.60	5.8MN	6.3	644	0.18%	0.98%	Montreal, QC
1663-02-06	47.60	-70.10	7.0ML	7.0	961	0.15%	1.58%	La Malbaie, QC
2005-10-20	44.68	-80.48	4.3MN	3.8[b]	96	0.14%	0.26%	Georgian Bay, ON
1944-09-05	44.97	-74.90	5.6ML	5.8	535	0.13%	0.62%	Cornwall, ON

Note:

[a] See Section 4.1 for a discussion of the relative merits of different magnitude measures.

[b] Moment magnitude estimated from MN using $M_W = m_N - 0.5$ (Halchuk, Allen, Rogers, & Adams, 2015).

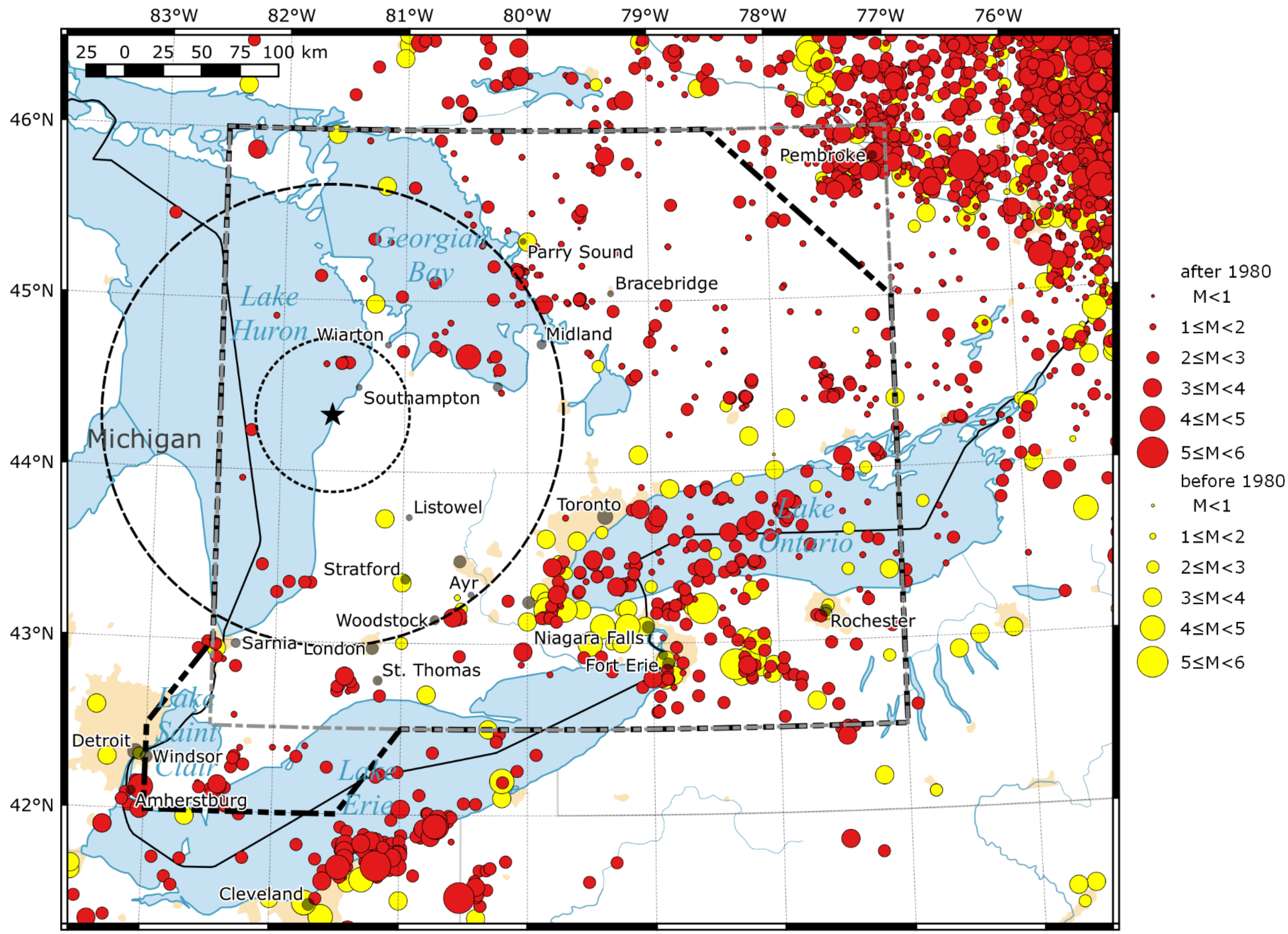

Figure 6: Historical earthquakes in southern Ontario, 1823–2020. Notes in caption to Figure 5 apply.

4 EARTHQUAKE CHARACTERISATION

4.1 MAGNITUDE ESTIMATION

Earthquake magnitude scales attempt to estimate energy release, and there are numerous different scales used. All magnitude scales are logarithmic, so that one unit of magnitude corresponds to a factor of ten of ground shaking amplitude.

Almost all earthquakes in this series of annual reports will have magnitudes calculated using the Nuttli scale, and will be formally written as m_N. This is a regional magnitude based on Lg amplitudes, similar to m_{bLg} (Bormann & Dewey, 2014). In eastern Canada, m_N is the magnitude used by CHIS for moderate-sized earthquakes.

Prior to the introduction of the Nuttli scale in the 1970's, the Richter scale (M_L) was used in eastern Canada, so historical events that have not been re-evaluated will still have an M_L magnitude. The M_L scale is also sometimes used for small events when the magnitude cannot be read from at least one station more than 50 km from the epicentre.

Two other magnitude types that sometimes appear in the earthquake database for eastern Canada are body wave magnitude m_b (Bormann & Dewey, 2014) and coda duration magnitudes M_C (Bormann, Wendt, & DiGiacomo, 2013). These magnitude types are not routinely used at CHIS, but are sometimes available from other agencies.

The most accurate assessment of energy release is via moment tensor inversion that yields a moment magnitude (M_w), but this is only possible for larger earthquakes, typically events with m_N > 4.5. Bent (2011) suggests that for Nuttli magnitudes above approximately 3.0, the post-1995 relationship is $M_w = m_N - 0.53$, so as an approximation this relation could be applied to the smaller m_N magnitudes in this report.

4.2 DEPTH ESTIMATION

There is uncertainty with respect to the actual depth of earthquakes in this region due to the low levels of seismicity and the relatively short history of dense seismograph monitoring. Except for the immediate vicinity of the Bruce sub-network, there is no part of southern Ontario where depth estimation via direct phases is possible.

In most of eastern Canada, the default depth is generally assumed mid-crust, i.e. 18 km, except in a few regions, such as the Appalachians, where the default is assumed to be shallower, at 5 km, in the absence of evidence to the contrary. Experience elsewhere in Southern Ontario suggests most earthquakes are shallower than 18 km (Ma & Atkinson, 2006; Ma & Eaton, 2009), and occur at similar depths as in the Appalachians.

For events with good signal-to-noise ratio at seismographs in the range 60–600 km the Regional Depth Phase Modeling (RDPM) method (Ma, 2004) can sometimes be used to estimate the depth of events. This method relies on the difference in travel time between an arrival which travels directly from source to receiver and an arrival which reflects off the surface just after leaving the source. Diminishing signal-to-noise ratios with distance and difficulties inherent in phase identification mean that this method is only reliably applicable for events larger than approximately m_N 3. Ideally estimates are available from multiple stations, and their distribution can indicate the uncertainty in the depth estimate. Studies of shallow ground-truth mining events in northern Ontario have shown that RDPM depth estimates are generally consistent with a nominal uncertainty of ±1 km (Ackerley, Peci, Adams, & Halchuk, 2021).

The only events in the local study area that have been large enough to calculate depths using RDPM were the 4.3 m_N in 2005 located in Georgian Bay and the 2.5 m_N event located under Lake Huron in 2011. The depth estimated by CHIS for the 2005 Georgian Bay earthquake method was

11 km, which concurred with Dineva et al. (Dineva, Eaton, Ma, & Mereu, 2007). The depth estimate for the 2011 Lake Huron event was 3.5 km (Halchuk, et al., 2013). No other events large enough to apply this method have occurred within 150 km of the Bruce nuclear site, nor has any small event occurred close enough to the Bruce sub-network to allow estimation of depth using direct phases.

An alternative method of depth determination involves the observation and/or modeling of the relatively long-period crustal Rayleigh wave (Rg). Rg is developed more strongly from shallower events. This has been demonstrated using controlled blasts (Myers, Walter, Mayeda, & Glenn, 1999) and is believed to hold true for natural earthquakes (Kafka, 1990). Since Rg amplitudes are depth dependant while Sg is largely independent of depth, below a certain depth Rg is simply not observable (Båth, 1975). The critical depth below which Rg is not observed is variously estimated as being between 4 km (Kafka, 1990) and 5 km (Tibi, Koper, Pankow, & Young, 2018).

Prior to 2016, the practice at CHIS was to assign a 5 km depth when Rg is observed (or 1 km when Rg is particularly pronounced). This practice was problematic because these depths are also assigned when no other depth estimate is available. For example, 5 km is the default for earthquakes in some regions, and 1 km is the default for underground mining events. Furthermore, it is misleading to fix the depth at the maximum likely depth, rather than somewhere in the middle of the range. For these reasons, since 2016, the practice across eastern Canada is to assign a 2 km depth below sea level when Rg is observed, with an implicit ±3 km uncertainty. The -3 km uncertainty allows for events that occur below the ground surface but above sea level.

In all, four earthquakes within 50 km of the Bruce nuclear site have depth estimates based on the observation of Rg phases.

A final method used to assign depths to earthquakes is based on waveform similarity. Waveform similarity can be assessed qualitatively in the time domain, using different narrowband filters at several stations. Template-based cross-correlation techniques offer an objective means of assessing waveform similarity (Ackerley, Adams, Peci, Halchuk, & Street, 2019). When two earthquakes are determined to have similar waveforms, and the larger event permits depth estimation, but the smaller event does not, the smaller event may be assigned the depth of the larger event. A common application is the assignment of aftershock depths to be the same as the mainshock. Events detected using matched-filter techniques in this study were assigned the depth of the template event.

The method of depth estimation used for each event in this study is indicated in Tables 2 and 3.

Many authors have proposed using the Rg/Sg spectral ratio to estimate depths (Båth, 1975; Kafka, 1990; Tibi, Koper, Pankow, & Young, 2018). In particular, Ma and Motazedian (2012) estimate depths of small shallow events in eastern Canada and suggest that resolution better than 0.5 km can be achieved. This method may result in improved depth resolution for events where Rg has been observed, however we advise some skepticism as this remains to be proven in the study area. As such, these methods have not entered routine practice, in part because it is difficult to justify transplanting heuristics from one region to another.

Note that some ambiguity remains in the database as far as whether the zero depth reference is sea level or surface elevation. For depths computed by direct phases (of which there are none in the study area) the reference is sea level, because the seismograph elevation is taken into account. In contrast, for depths obtained by RDPM, Rg or from mine operators, the depth is relative to the surface. The catalogue depth is intended to be relative to sea level, which means that some depths will be negative (below ground surface but above sea level). Strictly speaking, any mine-reported, RDPM, or Rg-derived depth should be adjusted for the ground elevation to get its depth relative to sea level. Although this is not yet done, in part because for routine analysis the differences in surface elevation in eastern Canada are small relative to other uncertainties, it remains a long-term goal. For precise work – say locating micro-events relative to a shallow-dipping fault or stratum – a consistent depth datum is of course essential.

4.3 EVENT TYPE DISCRIMINATION

Much of the work of characterising seismic events in eastern Canada is discriminating earthquakes from anthropogenic events, including blasts, rockbursts and other events induced by industrial activities. In particular, in southern Ontario, the main concern is discriminating earthquakes from blasts, typically related to quarrying or construction. This discrimination can sometimes be difficult when based solely on the waveforms, so verification from the blasting source, such as a quarry operator is important. Construction blasts are particularly difficult, as the sources are consistent neither in location from year to year, nor in time from season to season.

Without a contact at the site, time of day (surface blasts are required to occur during daylight, and because explosives may not be left overnight, the charges tend to be loaded in the morning and set off in the afternoon) and repetition (same time and place) are good clues that certain events are blasts. Moreover, the ripple firing (i.e. many smaller blasts detonated milliseconds apart, rather than one large blast) used for most blasts produces a waveform with a less sharply defined P- and S-phase (Ackerley, Bird, Kolaj, Kao, & Lamontagne, 2022).

Furthermore, a blast will exhibit a very strong Rg phase. Since blasts are right at or near the surface, and because Rg amplitudes decrease with depth, a blast tends to produce a stronger and more distinct Rg phase than shallow earthquakes, which can also excite Rg waves.

In the earlier years of this study, many blasts in the region were located after the new Bruce nuclear site sub-network was installed, to help establish a pattern for blasting events in the region. With experience, events from these sources are dismissed and no effort is put into locating them unless they are large or unusual in some way.

Figure 7 is a map of southern Ontario showing the earthquakes and anthropogenic events of 2020, compared with previous years. Other than the few underground mines, the mapped “mines” within the regional study area are in fact large quarries, and many smaller quarries are not mapped, even though they produce catalogued blasts. The only rockbursts mapped in Figure 7 are to the north of the regional study area, associated with underground mines in the Sudbury mining district. Anthropogenic events generally outnumber earthquakes, but most are recognized and dismissed by an analyst without being located. In 2020, just 14 blasts were located within 150 km of the Bruce nuclear site.

In the earthquake database for southern Ontario, there are a handful of events from the early 1980s near Gobles, ON, approximately 15 km east of Woodstock, which Mereu, Brunet, Morrissey, Price, & Yapp (1986) concluded were likely induced or triggered by fluid injection related to unconventional oil and gas extraction. There has been no seismicity in the area since the end of fluid injection. In 2022 these events were finally relabeled as “induced” in the database.

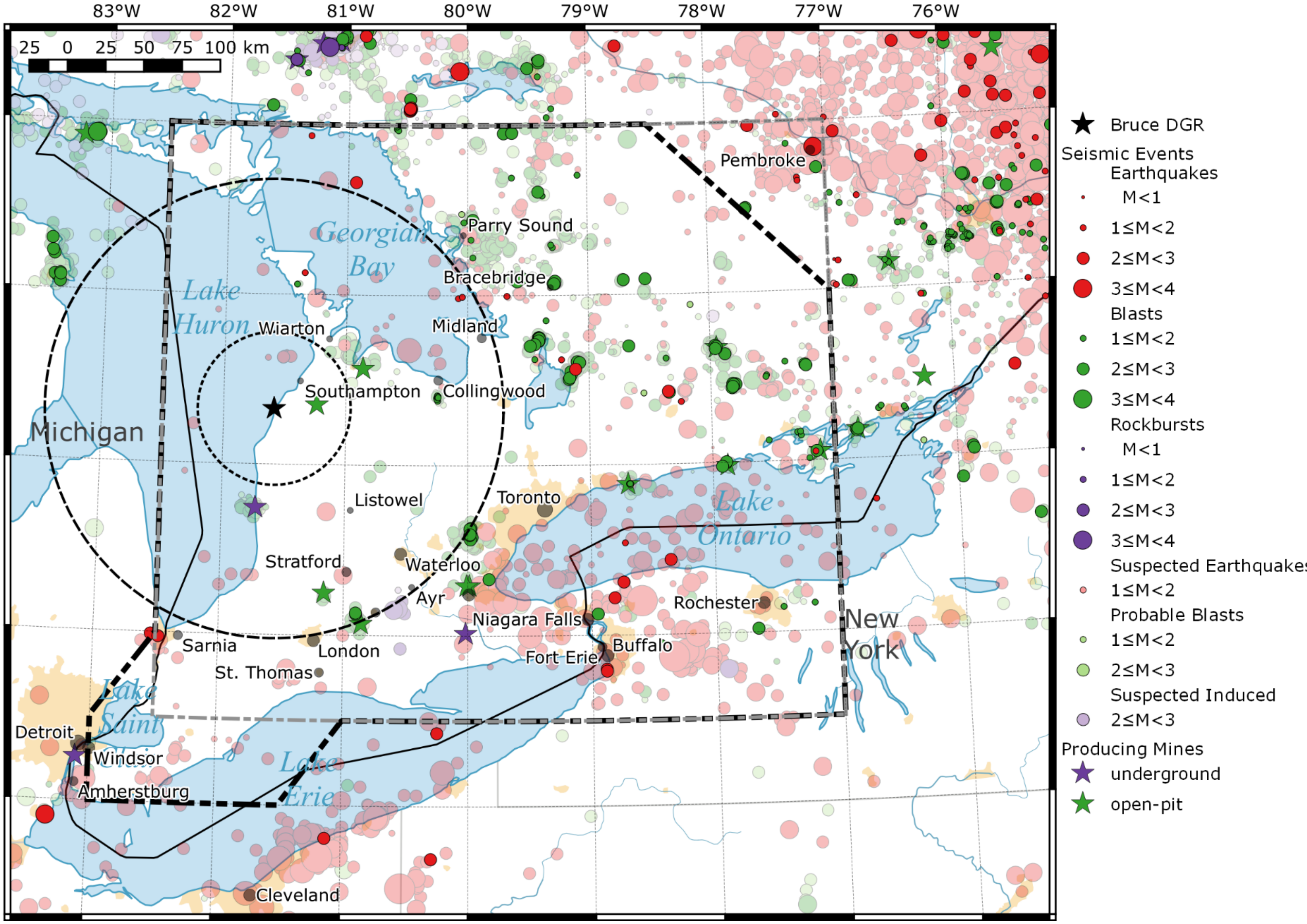

Figure 7: Seismic events in southern Ontario, 2020. Seismic events are shown as circles, with the colour indicating the type of event and the size indicating the magnitude. Events from 2020 have black outlines; events prior to 2020 have grey outlines and are semi-transparent. Mines from the Atlas of Canada (Lands and Minerals Sector; National Energy Board, 2020) are shown as stars, green for open-pit and purple for underground. Notes from caption of Figure 1 apply.

5 EARTHQUAKE RECURRENCE

The annual frequency of earthquakes of a given magnitude normally follows a log-linear relationship called the Gutenberg-Richter law (Weichert, 1980). The observed magnitude recurrence curve is assembled by binning earthquakes by magnitude, estimating the annual incremental rates, and plotting logarithmic cumulative rate versus magnitude. The most reliable rate estimates are obtained by considering earthquakes over the longest possible duration.

Since the original study area is small (within a radius of 150 km), is in a region with little historical seismicity, and has only been closely monitored since 2004, the resulting catalogue is too small to get reliable recurrence rate data. Therefore, since the inception of this series of reports (Hayek, et al., 2008) a larger, regional, study area was defined to include a larger portion of southern Ontario. This simple rectangle is shown on Figure 6 as a dash-dotted outline. This area is not centered on the Bruce nuclear site, because otherwise it would have to include a portion of Michigan where earthquake monitoring has historically been poor. Instead, it is shifted to the west, to include areas more uniformly monitored by CHIS and its predecessors. Although the rectangle was intended to include only regions with similar seismotectonics, in fact it includes part of the Western Quebec Seismic Zone (WQSZ) (Ma & Eaton, 2007), well to the northeast of the Bruce site. Thus, we propose that future reports should use a polygonal regional study area, shown with a dash-dot-dotted outline in Figure 6. In order to make earthquake counts in the two recurrence regions comparable, the area was maintained approximately the same by adding the south-westernmost part of Ontario to compensate for the removal of the WQSZ in the northeast.

In order to estimate earthquake occurrence parameters, there must be a degree of certainty that all events down to a given magnitude have been detected and located. A catalogue will include many events below this “magnitude of completeness”, and they are useful in the imaging of potentially seismogenic structures, but their incompleteness will cause the observed earthquake magnitude-frequency distribution to deviate from the expected power law.

Factors affecting the spatiotemporal variation of the magnitude of completeness are discussed in Section 5.1, before earthquake recurrence parameters for the two regional study areas (rectangular and polygonal) are compared in Section 5.2.

5.1 MAGNITUDE OF COMPLETENESS

The minimum detectible amplitude at a station depends on the level of background noise at the site (which can be affected by the geology of the area, as well as the geographic location), and the instrument used. The amplitude of ground motion due to an earthquake diminishes rapidly with distance, so that a magnitude 4 at 100 km may produce the same amplitude as a magnitude 3 at 10 km. Thus, since a minimum of three stations are required for a location, the minimum detectible magnitude also depends on the station density of a network, more specifically on the distance to the third-nearest station.

The CNSN was initially designed to capture all events of magnitude 3.0 and above in the southern, more populated regions of Canada. The only CNSN stations in the study region are SADO in Sadowa near Orillia, and EFO in Effingham near St. Catharines; however, many of the more distant stations in the Ottawa valley region would easily detect an earthquake of magnitude 3.0 within the study region.

UWO (network code WU) has operated stations, mainly close to Lake Ontario, since the 1990’s. In 2002 many of these stations were upgraded to POLARIS type installations, at which point in time the data became available continuously in real-time at CHIS. This POLARIS network was augmented in 2003 and again in 2004, improving the completeness threshold to approximately magnitude 2 in southwestern Ontario, which includes the Bruce nuclear site.

The installation of the Bruce sub-network (see Section 2) was designed to improve the location threshold and to capture all magnitude 1 and above events within 50 km of the site. As well, a fraction of the activity smaller than magnitude 2 out to 150 km from the site is also captured. The threshold will be higher in the western part of the study area due to the lack of stations in Lake Huron and northern Michigan state. However, it was still possible to locate the 2008 Lake Huron event, which was a m_N 1.2, using 7 stations and 12 phases, as this event was within 50 km of the Bruce nuclear site, albeit outside of the sub-network.

With time, as the quality of the network has improved, the location threshold has dropped. Therefore, to establish the recurrence curve for southern Ontario we considered that the data set for M>1.8 was complete since 2004, but that the dataset for M>3 has been complete since 1980, thereby giving an additional 24 years of data for the less-common larger earthquakes. In order to make use of as much of the historical catalogue as possible the magnitude of completeness as a function of time must be estimated. Our best estimates are tabulated in the inset to Figure 8.

Two stations in southern Ontario were decommissioned in 2017: Bancroft (BANO, September 26) and Pelee Island (PLIO, September 27). PLIO in particular was a very quiet station with few nearby stations, north of the border (see Figure 4). Its loss will have a negative effect on detection thresholds in the southwestern corner of the region used for recurrence rate estimation. The decommissioning of these stations is expected to have little effect on the magnitude of completeness within 150 km of the Bruce nuclear site, however, as long as the rest of the network is operating normally.

5.2 RECURRENCE PARAMETER ESTIMATION

Figure 8 shows the magnitude-recurrence curves for the regional study areas shown on Figure 6, for 1850–2020. The best-fit recurrence parameters and the standard deviations of the slope (b-value) were estimated using Weichert (1980), based on the observed rates in each magnitude bin. The confidence interval in each bin is plotted at ±1 standard deviation. The upper and lower curves have slopes at ±1 standard deviation, and intercept the confidence bounds of the lowest-magnitude bin. The maximum magnitude (Mmax) assumed, 7.3±0.3, is that used in the 5th Generation seismic hazard model for Canada (Halchuk, Allen, Adams, & Rogers, 2014) and in the model adopted for the 2015 National Building Code of Canada. The assumed completeness table is inset.

The best-fit slope of the rectangular area is 1.004 ±0.004, and the slope of the polygonal area is 1.017±0.003, both typical of what is observed globally. Clearly, the change in recurrence area does not dramatically affect the slope of the magnitude-recurrence curve for the regional study area.

The deviation of the recurrence data for both areas from the straight-line fit at about 1.8 m_N in Figure 8 confirms the assumed magnitude of completeness for the region in the most recent era, from 2004 to present. That is, all the earthquakes of magnitude 1.8 or larger in the region since 2004 have been located. Although some events smaller than magnitude 1.8 have also been located, the data points fall away from the curve at this magnitude, indicating that the dataset beyond this point is incomplete (i.e. some events of magnitude less than 1.8 have not been detected and located). This is why at the smallest plotted magnitude class (the 0.95-1.04 class, plotted at 0.95) the data falls significantly below the calculated curve, and flattens out (note the semi-transparent data points in Figure 8). At magnitude 1.0 only about one-third of the expected earthquakes are located.

Above the magnitude of completeness, the observed recurrence rates deviate slightly but systematically from the straight-line fit. Although the deviation is unlikely significant, it is worth considering some of the factors which may affect the straightness of an observed recurrence curve.

The use of heterogeneous magnitude types (see Section 4.1) can result in deviations from linearity when different magnitude types are used in different magnitude ranges. However, in this case, the vast majority of magnitudes are of one type, $m_{N.}$ The second most common magnitude type, M_L, has been treated as equal to m_N for seismic hazard calculations, for simplicity, and because it a conservative choice, in that inferred seismic hazard will not be underestimated (Halchuk, Allen, Rogers, & Adams, 2015). The lone M_C (a coda magnitude) is a magnitude 1.9 event whose significance is negligible because small events are numerous. An event near Buffalo in 1966 had previously been assigned a preferred magnitude of 4.7 m_b. Upon review of the available magnitude estimates, it was discovered that an estimate of 4.7 m_N was available, so this was made the preferred magnitude in the database. With this change we believe the effect of heterogeneous magnitude types to have been minimized.

Two other effects related to the assumed completeness table should be noted, although further investigation is beyond the scope of this report. First, it may be that the assumed magnitude of completeness for some time-periods is slightly over- or underestimated. This can be tested by jackknife resampling of the catalogue. Second, it may be that the completeness years and magnitudes assumed do not fully capture the spatiotemporal variability. That is, while the table may be correct for one region, if it is not correct for the sub-regions with the highest occurrence rates, this can cause the recurrence curve to deviate from linearity. This can be tested by estimating recurrence parameters for different sub-regions. It is recommended that future work include detailed study of these effects.

In general, events that are suspected of being related to industrial activity should be removed from the catalogue before estimating recurrence parameters. Such events may be a legitimate part of the short-term seismic hazard, but given that induced seismicity tends to cease after fluid injection or extraction stops, they cannot be part of the long-term hazard. Of the events near Gobles, ON in the early 1980s that were recently relabeled as “induced" (see Section 4.3), two are above the completeness threshold.

According to the best-fit curves, on average, one magnitude 5.0 event is expected to occur every 120 or 145 years, in the rectangular or polygonal area, respectively. In other words, the exclusion of the WQSZ by the polygonal recurrence area results in a reduction of the rate of M>5 events by 17% with respect to the rectangular recurrence area. It must be noted the uncertainty associated with these estimates is greater than the difference between them. Since we do not have hundreds of years of data, for larger magnitudes, the sub-catalogues from which rates are estimated become quite small, and the error bars therefore become much larger. Specifically, ±1 standard deviation on the slope results in a range of +64%/-47% for M>5 events. Although the rate of M>5 events in the polygonal area is not tremendously different from that of the original rectangular area, nonetheless we recommend the polygonal area for future recurrence estimates because it is more seismotectonically uniform.

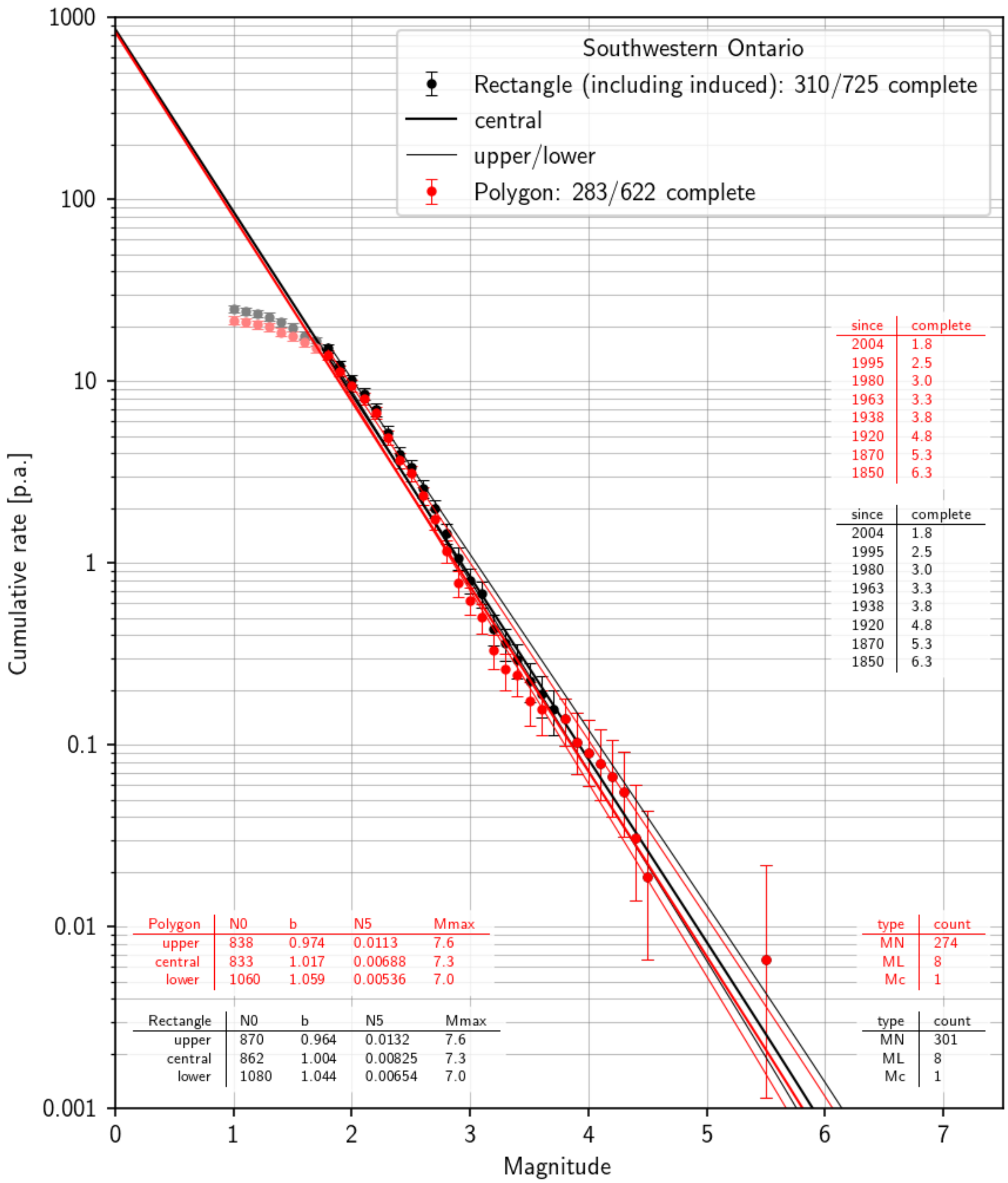

Figure 8: Magnitude recurrence curve for southern Ontario region, 1850–2020. Red and black data correspond to polygonal and rectangular recurrence areas, respectively. The years since which the catalogue is considered complete to a given magnitude are tabulated on the right. Magnitude types and counts for events above the completeness threshold are in the lower right. Yearly earthquake occurrence rates in 0.1 magnitude unit wide bins are shown as points with error bars (note that above magnitude 3.7 the rate estimates for the two recurrence areas are the same), while fitted curves are shown as lines. Occurrence rates below the minimum magnitude of completeness are shown in semi-transparent. Standard fit statistics are tabulated in the lower left, including the fitted slope b-value and the assumed maximum magnitude Mmax. The thick middle line represents the best-fit curve, while the thinner outer lines are upper and lower bounds on this estimate.

6. CONCLUSIONS

In 2007, three borehole stations were added to the already existing CNSN and POLARIS networks, with the aim to detect and locate all earthquakes of magnitude 1.0 and above within 50 km of the Bruce nuclear site. For the year 2020, data availability from the Bruce nuclear sub-network was very close to 100%, thanks in part to network refurbishment undertaken by Nanometrics, Inc. in 2017.

Some earthquakes of magnitude less than 2.0 m_N were located prior to the installation of the Bruce nuclear sub-network, however, the recurrence curve for the southern Ontario region suggests that the earthquake catalogue for the region was only complete to just under magnitude 2.0 m_N prior to the installation of the sub-network.

In 2020, there were three earthquakes recorded within 150 km of the Bruce nuclear site, all less than or equal to m_N 1.6. The low rate of events in the study area for 2020 is consistent with historical findings of few earthquakes, and the assessment of this area as representing a low seismic hazard region stands.

Since 2004, 12 earthquakes have been catalogued within 50 km of the site. These events have all been very small, ranging in magnitude from 0.1 M_L to 2.5 m_N, and grouped in a single cluster under Lake Huron, approximately 34 km to the north of the site. More work is needed to relocate these events accurately with respect to one another, to find out, for example, if they resolve into a linear structure.

A new polygonal recurrence region is recommended, one which excludes the WQSZ in the northeast corner of the rectangular recurrence region previously used. The best-fit recurrence curve using the new recurrence area gives an estimate of the rate of M>5 events which is 17% lower, but this estimate is to be preferred because the region it covers is more seismotectonically uniform.

There are concerns that the decommissioning of stations in southern Ontario and upstate New York may have an impact on detection thresholds in the region used for estimating earthquake occurrence rates in southern Ontario. It is unlikely, however, that the loss of these stations will have any effect on the completeness of the catalogue within 150 km of the Bruce nuclear site or southern Ontario.

ACKNOWLEDGMENTS

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