2022 REPORT ON

EARTHQUAKE ACTIVITY IN OHIO

compiled by Jeff L. Fox, Daniel R. Blake, and Jacqueline A. Thompson

OHIO GEOLOGICAL SURVEY
DEPARTMENT OF NATURAL RESOURCES

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STATE OF OHIO
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF GEOLOGICAL SURVEY
D. Mark Jones, Chief

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PREFACE

The 2022 Report on Earthquake Activity in Ohio continues the efforts of the Ohio Department of Natural Resources (ODNR) Division of Geological Survey's Ohio Seismic Network (OhioSeis) to present a clear and concise representation of all seismicity, natural and anthropogenic, in the state for the calendar year. This report presents the data in tables and figures, with brief discussions of significant earthquakes or seismic swarm activity. The computer program HYPOINVERSE-2000 (Klein, 2012) was used to process earthquake data in SEISAN and AQMS. The earthquake listing in Table 3 is estimated to be systematically complete above magnitude 1.5 M_L within the state for 2022. However, these data are preliminary—both the locations and magnitudes in this table are subject to revision. The catalog may include some anthropogenic seismic events not yet identified.

The Ohio Earthquake Epicenters Locator interactive map is continually updated and is available for viewing at **https://gis.ohiodnr.gov/MapViewer/?config=Earthquakes**. Seismic station lists and locations are current to the calendar year of this report only. Seismic station information can also be found on the interactive map. Station metadata is available from the IRIS Data Management Center (DMC). Station locations contained within this report are not accurate for privacy purposes. Interested scientists can obtain detailed location information for performing earthquake locations from the IRIS DMC.

A complete copy of this report, including maps and earthquake catalog, is available on the ODNR Earthquakes website at **ohioseis.ohiodnr.gov**.

Jeff Fox
Seismologist

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ABBREVIATIONS USED IN THIS REPORT

Units of Measure

kilometers . . . . km
meters . . . . m
miles . . . . mi

Other

Advanced National Seismic System . . . . . . ANSS
ANSS Quake Management System . . . . . . AQMS
Community Internet Intensity Maps . . . . . . CIIM
Incorporated Research Institutions for Seismology . . . . IRIS
Magnitude[1] . . . . M_L or M_d
Standard for the Exchange of Earthquake Data . . . . SEED
Ohio Seismic Network . . . . OhioSeis
SEISmic ANalysis software. . . . . SEISAN
United States Geological Survey. . . . . USGS

[1]Richter local magnitude (M_L) or coda magnitude (M_d) determined by OhioSeis.

EARTHQUAKE ACTIVITY IN OHIO
JANUARY 1–DECEMBER 31, 2022

During the period January 1 through December 31, 2022, the Ohio Seismic Network (seismic network code: OH) located 135 earthquakes within the Ohio region (tables 1 and 3, and fig. 1). The total includes eighteen earthquakes of magnitude 2.0 M_L or greater, one of which is greater than magnitude 3.0 M_L. During the 2022 calendar year, 10 earthquakes were reported felt by Ohioans. The largest earthquake recorded within Ohio's borders in 2022 was the M_L 3.1 earthquake on January 4 in Lake County. A cumulative tabulation of earthquakes during 2022 that were either felt in the Ohio region or for which a Community Internet Intensity Map (CIIM) was produced, or both, is available in table 2[1]. Additional information on earthquakes within the Ohio region is available from the Ohio Seismic Network online database.

[1]A CIIM summarizes the responses, and an intensity number is assigned to each ZIP code for which a CIIM questionnaire is completed. The intensity values in each ZIP-code area are averaged, and the map is updated as additional data are received. ZIP-code areas for which data have been received are color-coded according to the intensity scale below the map; other areas are gray. A CIIM is automatically made after each widely felt earthquake in the United States. The system can start receiving responses about 3 minutes after the earthquake. Internet users can also enter data for U.S. earthquakes they have experienced in the past.

TABLE 1. ***Earthquake magnitude statistics for calendar year 2022, all of Ohio***

2022 Ohio Earthquakes Summary	
Earthquakes > M_L 3.00	1
Earthquakes M_L 2.50–3.00	1
Earthquakes M_L 2.00–2.49	16
Earthquakes M_L 1.60–1.99	25
Earthquakes M_L 1.00–1.59	55
Earthquakes M_L < 1.00	37
Total Earthquakes (all magnitudes)	135

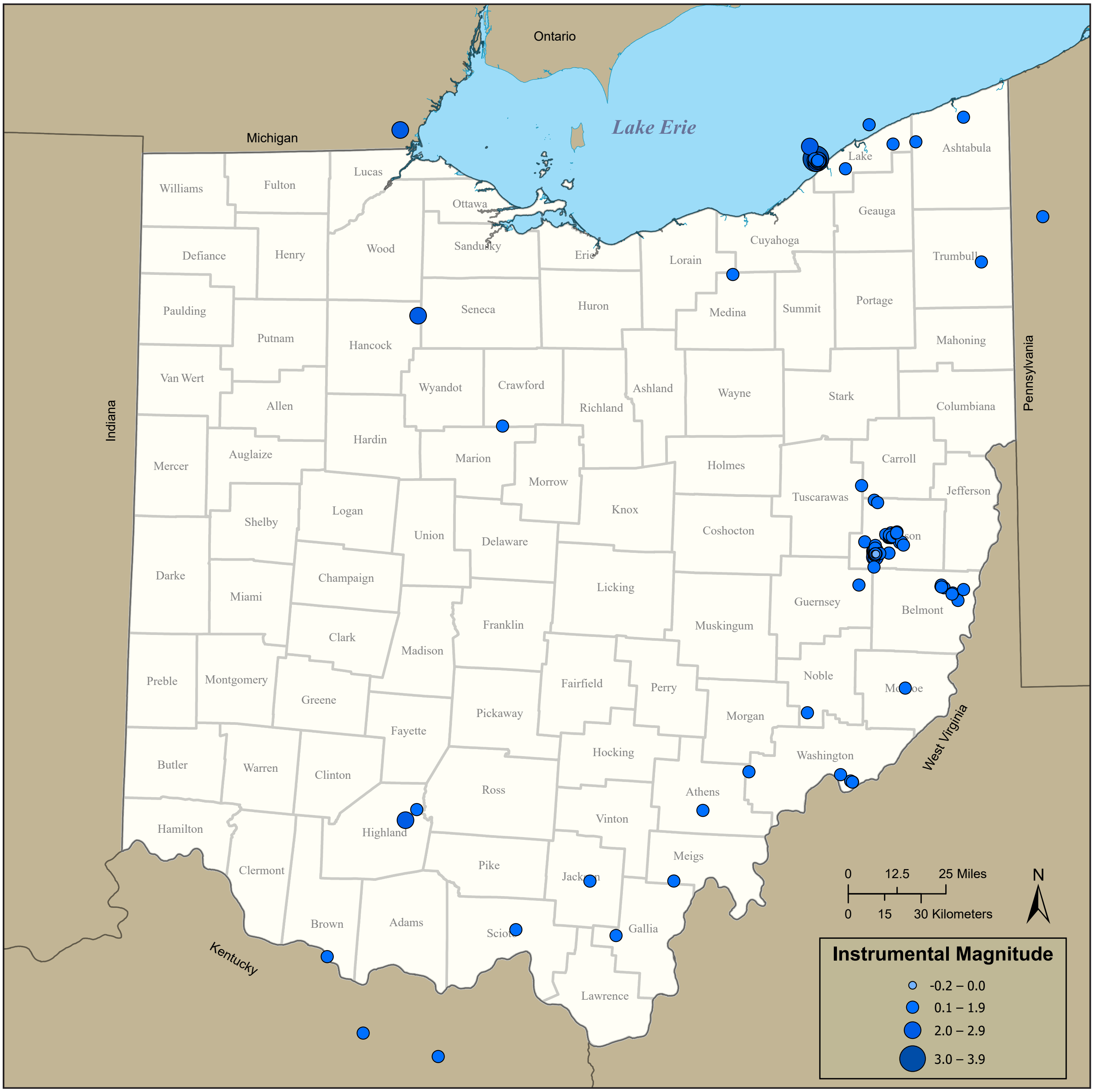

FIGURE 1. Map of earthquake epicenters located by the Ohio Seismic Network seismograph stations, January 1–December 31, 2022.

NOTABLE EARTHQUAKE EVENTS, JANUARY 1–DECEMBER 31, 2022

During the report period, there were five spatiotemporal clusters of earthquake activity (figs. 1, 2) throughout the state. For reporting purposes, we define a cluster as six or more earthquakes occurring within a 10-kilometer (km) (6-mile [mi]) radius, or within a known tectonic region.

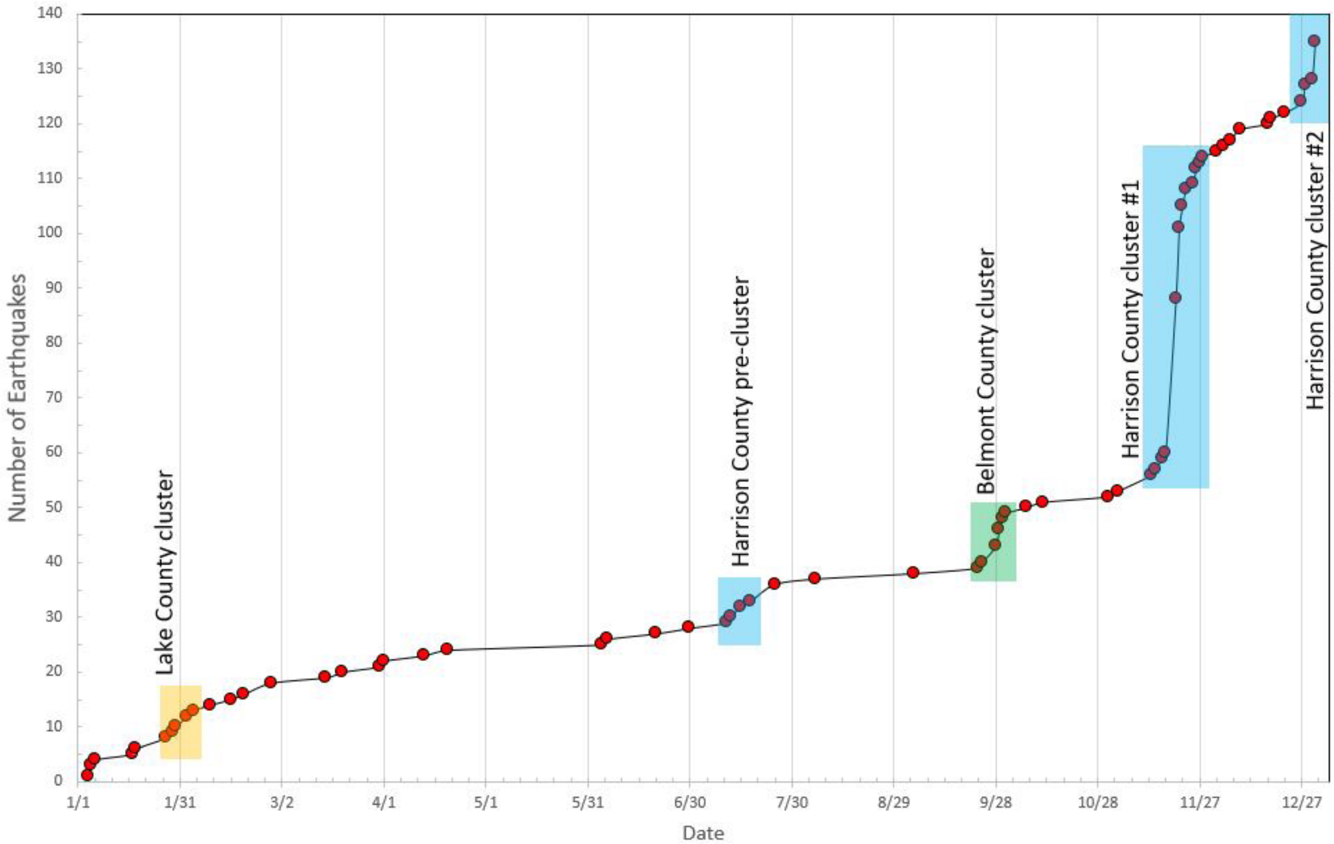

FIGURE 2. Cumulative plot of Ohio earthquakes throughout 2022. Sharp rises in the line (highlighted by colored vertical lines) indicate episodes of swarm activity or many earthquakes in a short period of time. Clusters discussed in this report are highlighted by color.

LAKE COUNTY CLUSTER

In late January, a small cluster of earthquakes occurred again near the epicenter of the 2019 M_L 4.2 earthquake in Lake County (Fox and others, 2021). This region has experienced sporadic aftershock activity since the 2019 mainshock due to isostatic readjustment of the crust and changes in the local stress field from that earthquake (Yao and others, 2021). Aftershock activity will most likely continue for some time. This year's cluster was most likely aftershock activity following 2022's largest earthquake, a M_L 3.1 event that occurred on January 4 (fig. 3). This earthquake was well recorded across the entire network and state. A focal mechanism was computed for this earthquake that fits the regional tectonic stress field and matches previous earthquakes in the region (Zoback and others, 1991, Herrman and others, 2011, Fox and others, 2021).

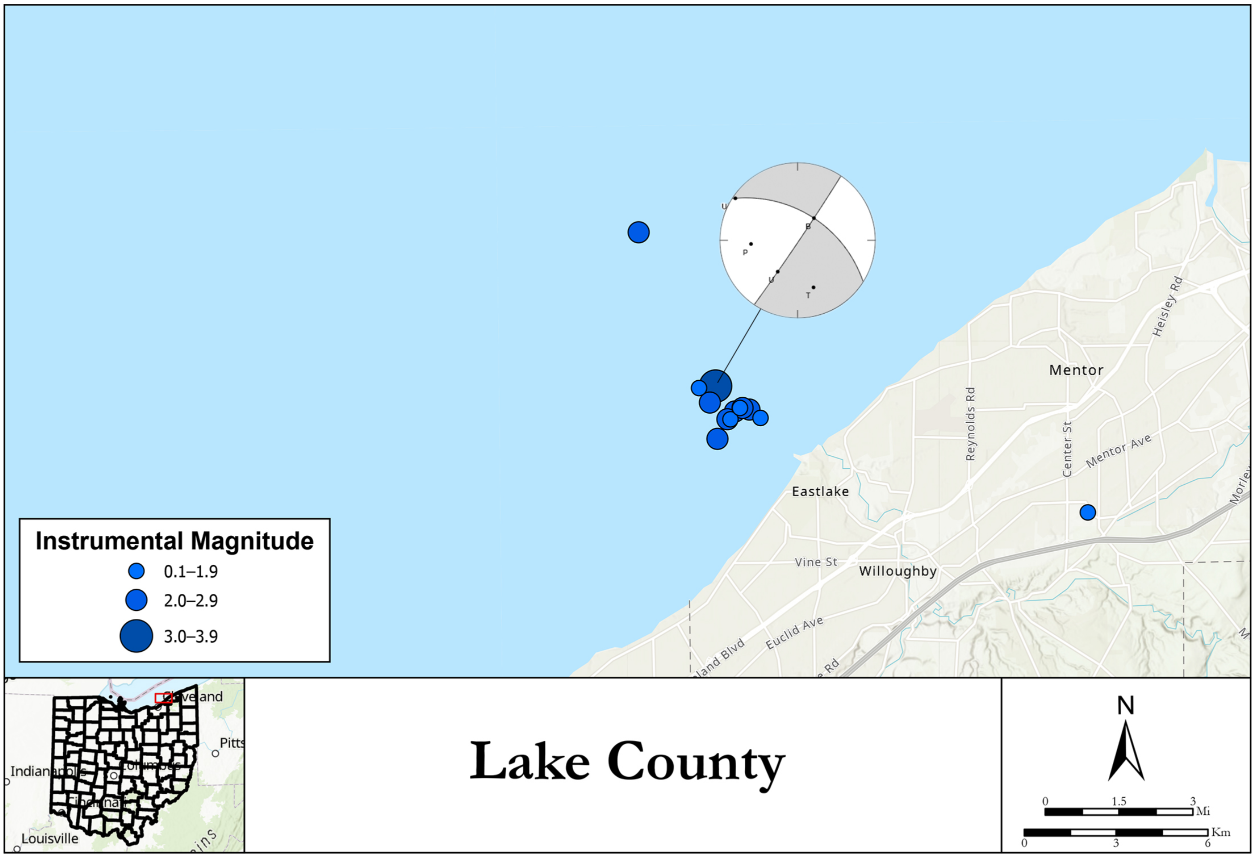

FIGURE 3. Close-up map of the January 2022 earthquake cluster in Lake County, with earthquake focal mechanism (gray-and-white circle). Shaded regions are tensional and moved away from the center (focus), while unshaded regions are compressional and moved towards the center.

BELMONT COUNTY CLUSTER

The next cluster of earthquakes occurred in late September in Belmont County (fig. 4). Beginning on September 28, eight earthquakes occurred over the next two days ranging from M_L 0.1–M_L 1.8 in magnitude. Research into the cause of this cluster is ongoing.

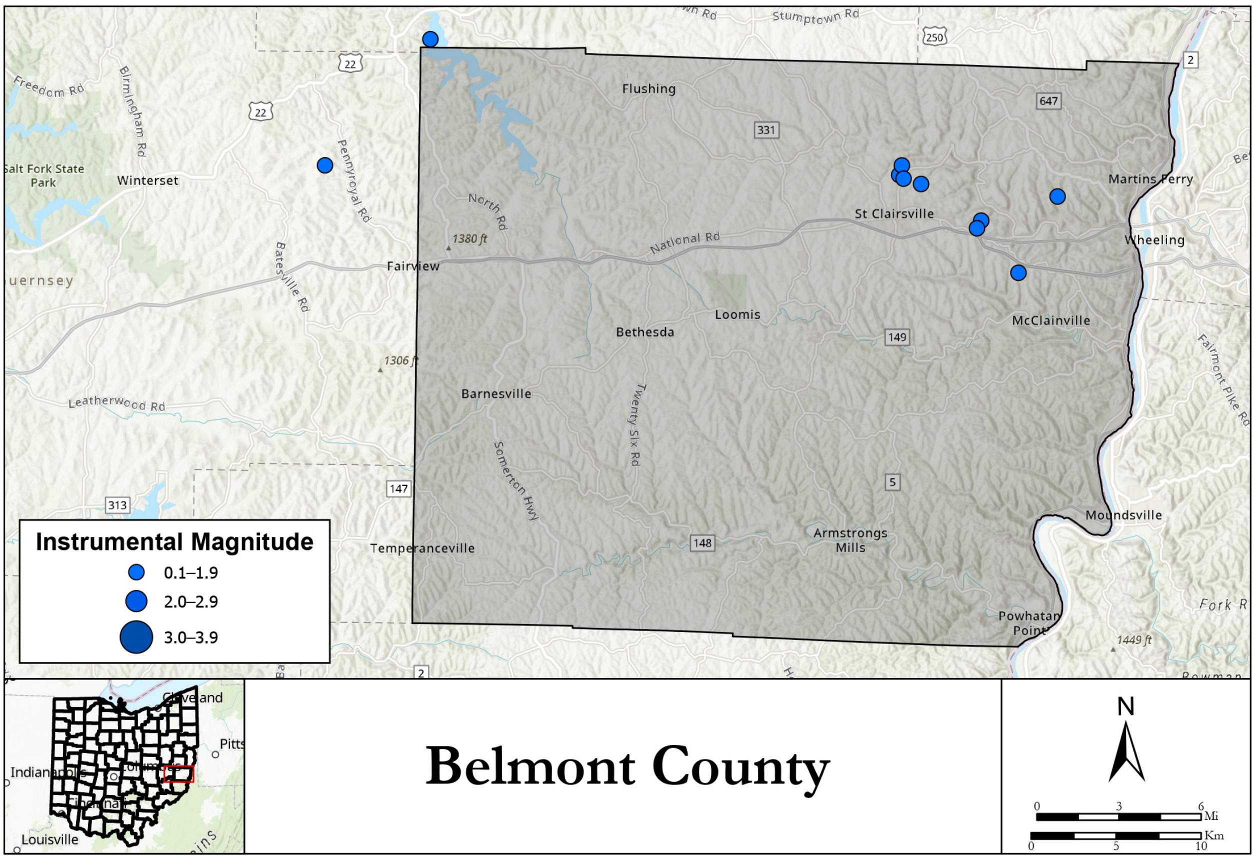

FIGURE 4. Map of earthquakes in Belmont County, 2022. This region has experienced earthquake cluster activity in the recent past.

HARRISON COUNTY CLUSTERS

Beginning in mid-November, southwestern Harrison County experienced a large cluster of earthquakes measuring M_L -0.2–M_L 2.4 (fig. 5, area noted as #1). Prior to this event, there was a “pre-cluster" (smaller cluster) in the same area in early July. In the November cluster, 62 earthquakes were detected in 19 days near the site of a previous cluster that occurred in 2013 (Friberg and others, 2014) and approximately 8 km (5 mi) southwest of the 2021 Harrison County earthquake cluster (Fox and others, 2022). An earthquake focal mechanism was calculated for the largest earthquake in the sequence (fig. 5). This focal mechanism matches the regional tectonic stress field and resembles focal mechanisms computed for the 2013 earthquakes (Friberg and others, 2014).

A second cluster of earthquakes (fig. 5, area noted as #2) occurred in Harrison County in December. Beginning on December 9 and continuing into early January 2023, approximately 35 earthquakes occurred ranging from M_L 0.0 to M_L 1.5 magnitude. This cluster was concentrated about 8 km (5 mi) northeast of the November 2022 earthquake activity. Research into these clusters is ongoing.

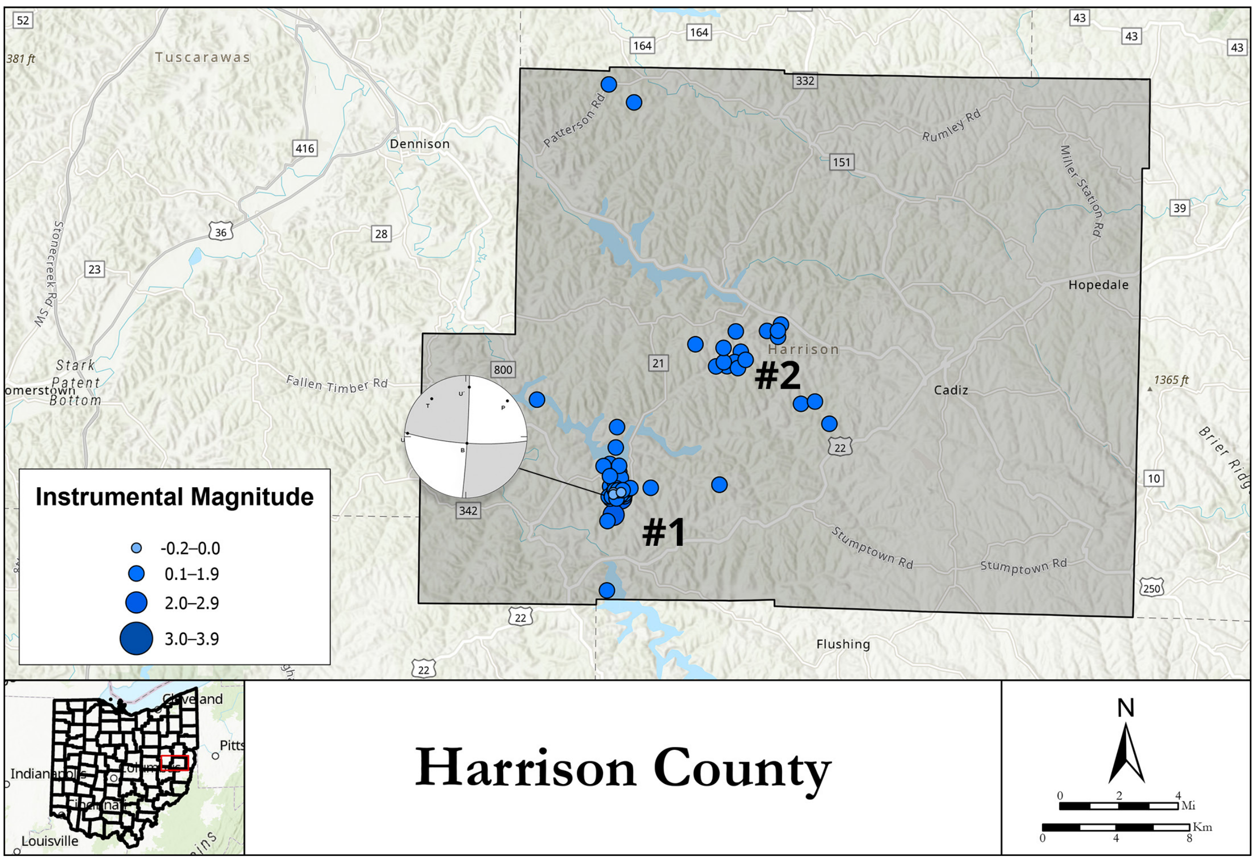

FIGURE 5. Map of Harrison County earthquake clusters (earthquakes in the area marked #1 occurred in November 2022, earthquakes in the area marked #2 occurred in December 2022), with earthquake focal mechanism (gray-and-white circle) for the November 20, 2022, M_L 2.4 earthquake in Harrison County. Shaded regions of the “beachball” are tensional and moved away from the center (focus), while unshaded regions are compressional and moved towards the center.

HANCOCK COUNTY EARTHQUAKE

A minor earthquake occurred late in the year on December 22 at 3:30 AM local time in Hancock County. This earthquake measured M_L 2.8 and exhibited strike-slip movement (fig. 6). Fault plane solutions and deformation models, as well as P-wave radiation patterns (figs. 6 a,b,c) from this earthquake further confirm association with NW–SE trending structures revealed in magnetic anomaly maps and basement structural features (fig. 7). The earthquake was felt by several Ohio residents. This earthquake is thought to be associated with NW–SE striking faults of the Outlet fault system (Baranoski, 2002).

Previous seismicity in this region has been observed to be in the M_L 2.0–M_L 3.0 range and has been documented since the 1970s. This most recent earthquake was clearly seen across the entire Ohio seismic network and was widely felt, receiving dozens of reports on the USGS's "Did You Feel It?" (DYFI) earthquake reporting web page.

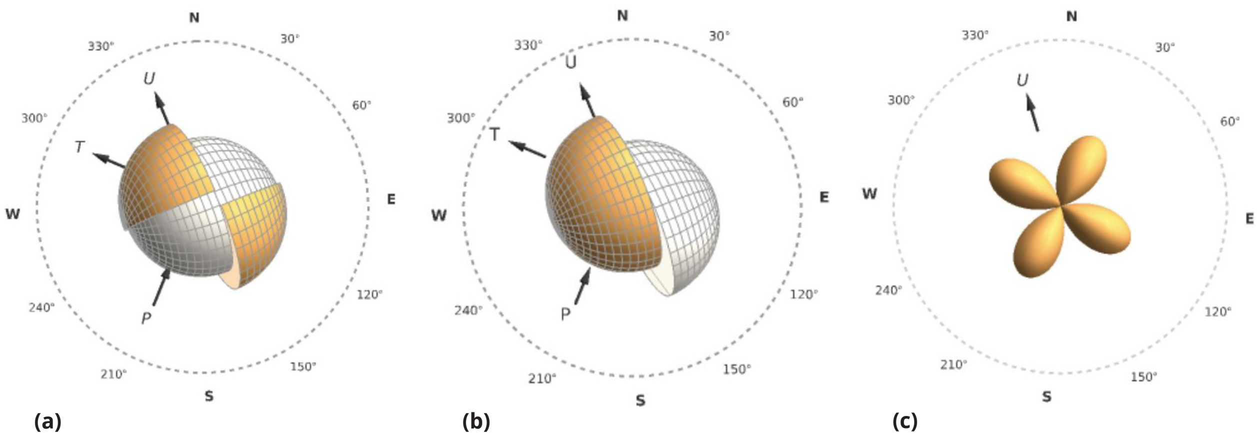

FIGURE 6. (a) Deformation model at the focus (center) of the December 22 Hancock County earthquake. (b) Faulting style shows right-lateral strike-slip movement to the northwest and southeast. (c) P-wave radiation patterns emanating from the focus of the earthquake derived from waveform first-motion polarities. "U" represents the direction of the primary plane or fault plane. "T" represents the tension axis of the focal mechanism, or the part of the fault that moves away from the focus. "P" represents the pressure axis or the part of the fault that moves towards the focus. Regional maximum horizontal stress bisects the angle between these two axes.

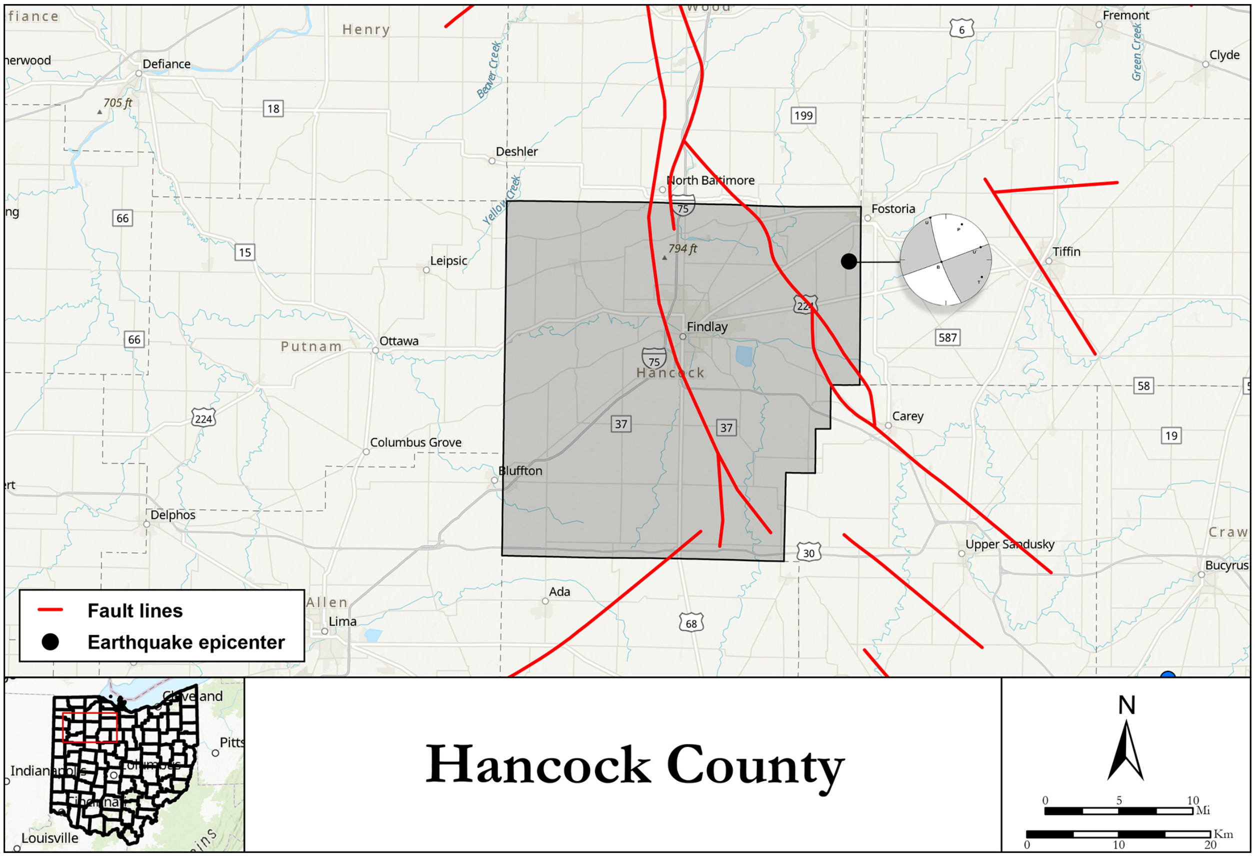

FIGURE 7. Location map of northwestern Ohio showing the epicenter of the December 22 Hancock County earthquake near the Outlet Fault system. Faults are indicated by red lines. This focal mechanism (gray-and-white circle) "beachball" shows strike-slip movement along the NW–SE oriented fault line. Shaded regions are tensional and moved away from the center (focus), while unshaded regions are compressional and moved towards the center.

FELT EARTHQUAKE EVENTS, JANUARY 1–DECEMBER 31, 2022

For earthquakes M_L 3.0 and larger in the Ohio region, the U.S. Geological Survey (USGS) automatically posts a Community Internet Intensity Map (CIIM) on its "Did You Feel It?" web page at **http://earthquake.usgs.gov/earthquakes/dyfi/**. Earthquakes of smaller magnitude that are felt and those reported by regional seismic networks will also be posted to the USGS CIIM pages. We encourage anyone who feels an earthquake to report their observations on this interactive website. Felt information is available by zip code on the CIIM site or can be obtained directly from OhioSeis.

TABLE 2. ***Earthquakes felt and/or generating a Shakemap in the Ohio region, January 1–December 31, 2022.***

DATE	TIME[1]	FELT INFORMATION[2]	LATITUDE	LONGITUDE	MAGNITUDE (M_L)[3]
Jan 4	08:20 EST 13:20 UTC	USGS ShakeMap. CIIM. Felt (III) at Eastlake, Wickliffe, Mentor, and Willoughby, OH and (II) at Cleveland and Euclid, OH.	41.695 N	81.478 W	3.1
Jan 5	05:25 EST 10:25 UTC	USGS ShakeMap. CIIM. Felt (II) at Eastlake, OH.	41.685 N	81.473 W	2.0
Jan 27	03:53 EST 08:53 UTC	USGS ShakeMap. CIIM. Felt (III) at Eastlake, OH.	41.683 N	81.457 W	2.3
Jan 27	13:10 EST 18:10 UTC	USGS ShakeMap. CIIM. Felt (III) at Eastlake, OH.	41.679 N	81.447 W	2.4
Jan 29	01:23 EST 06:23 UTC	USGS ShakeMap. CIIM. Felt (III) at Eastlake, OH.	41.688 N	81.464 W	2.0
Feb 1	20:37 EST 01:37 (Feb 2 UTC)	USGS ShakeMap. CIIM. Felt (III) at Eastlake, OH.	41.688 N	81.468 W	1.3
Feb 4	16:14 EST 21:14 UTC	USGS ShakeMap. CIIM. Felt (III) at Eastlake, OH and (II) at Willoughby, OH.	41.690 N	81.480 W	2.4
Feb 27	10:30 EST 15:30 UTC	USGS ShakeMap. CIIM. Felt (II) at Eastlake, OH and Willoughby, OH.	41.688 N	81.467 W	2.0
Jul 11	12:49:17 EDT 16:49:17 UTC	USGS ShakeMap. CIIM. Felt (III) at Temperance, Erie, and Monroe, MI and (II) at Toledo, OH.	41.817 N	83.512 W	2.4
Dec 22	03:30 EST 08:30 UTC	USGS ShakeMap. CIIM. Felt (III) at Findlay, OH and (II) at Fostoria and Bowling Green, OH.	41.112 N	83.441 W	2.7

[1]Times are listed both as Local Time—Eastern Standard Time (EST) or Eastern Daylight Time (DST)—and as Coordinated Universal Time (UTC).
[2]CIIM is Community Internet Intensity Map (http://earthquake.usgs.gov/earthquakes/dyfi), compiled by the U.S. Geological Survey (USGS); ShakeMap indicates the availability of computer-generated maps of ground shaking (https://earthquake.usgs.gov/earthquakes/search/), produced by the OhioSeis Seismograph Stations (OH). Roman numerals correspond to the Modified Mercalli intensity scale (see fig. A-13). Unless otherwise indicated, felt information is from the USGS (1) CIIM reports and/or (2) PDE Monthly (or) Weekly Listing Files (http://earthquake.usgs.gov/data/pde.php).
[3] Richter local magnitude (M_L) or coda magnitude (MC) determined by OhioSeis.

A catalog of all recorded earthquakes in Ohio for 2022 can be found in Table 3. Earthquakes are listed in chronological order.

TABLE 3. ***Catalog of all earthquakes in Ohio in 2022***[1]

Year	Month	Day	Hour[2]	Minute	Second	Latitude	Longitude	Depth[3] (km)	Mag
2022	January	4	13	20	45.90	41.695	-81.478	2.3	3.1
2022	January	5	10	25	43.26	41.685	-81.473	2.7	2.0
2022	January	5	14	4	45.10	41.840	-80.744	2.2	1.5
2022	January	6	8	21	20.43	40.480	-81.274	2.7	1.5
2022	January	17	3	16	52.60	41.302	-80.670	8.3	1.0
2022	January	18	3	40	37.49	41.685	-81.472	2.1	1.4
2022	January	27	8	53	0.89	41.687	-81.470	1.9	2.3
2022	January	27	18	10	5.46	41.679	-81.447	7.4	2.4
2022	January	29	6	23	21.45	41.688	-81.464	4.5	2.1
2022	January	30	14	27	14.51	41.694	-81.484	2.4	1.8
2022	February	2	1	37	34.68	41.688	-81.468	6.2	1.3
2022	February	2	14	19	12.40	39.380	-81.336	1.9	1.5
2022	February	4	21	14	14.85	41.690	-81.480	2.6	2.4
2022	February	9	9	26	12.80	41.818	-81.232	4.6	1.2
2022	February	15	12	35	2.03	38.816	-82.467	25.2	1.6
2022	February	19	2	34	43.60	39.408	-81.393	3.0	0.6
2022	February	27	15	30	10.74	41.688	-81.467	6.5	2.0
2022	February	27	20	21	34.37	41.685	-81.460	6.5	1.5
2022	March	15	13	4	23.19	39.018	-82.192	11.4	1.0
2022	March	20	18	27	32.66	39.240	-83.471	4.8	2.0
2022	March	31	23	40	37.42	40.425	-81.213	7.5	1.3
2022	April	1	7	54	37.47	40.416	-81.197	6.7	1.2
2022	April	13	14	33	25.66	39.639	-81.548	5.0	1.6
2022	April	20	1	8	31.25	38.730	-83.825	9.8	0.8
2022	June	4	9	29	37.74	41.268	-81.892	10.0	1.6
2022	June	6	19	14	26.33	39.422	-81.831	7.7	1.3
2022	June	20	5	9	23.87	39.018	-82.591	13.6	0.2
2022	June	30	2	43	31.14	38.448	-83.660	9.8	0.6
2022	July	11	16	49	17.00	41.817	-83.512	2.4	2.4
2022	July	12	21	42	33.90	40.226	-81.208	2.7	0.2
2022	July	15	1	2	5.80	41.465	-80.363	5.2	0.5
2022	July	15	7	42	29.17	38.364	-83.305	32.9	0.9
2022	July	18	3	56	7.90	40.257	-81.075	4.4	0.8

Year	Month	Day	Hour[2]	Minute	Second	Latitude	Longitude	Depth[3] (km)	Mag
2022	July	18	4	55	31.90	40.267	-81.093	0.1	1.3
2022	July	18	22	12	33.00	40.268	-81.084	3.2	1.0
2022	July	25	11	16	4.30	39.726	-81.077	2.0	0.4
2022	August	6	23	19	19.60	39.384	-81.345	3.0	0.8
2022	September	4	4	2	50.58	39.280	-83.418	8.3	1.2
2022	September	23	4	13	13.79	41.740	-81.507	8.6	2.0
2022	September	24	10	16	36.12	40.706	-83.019	4.7	1.5
2022	September	28	4	10	57.64	40.088	-80.788	6.7	0.1
2022	September	28	17	27	47.71	40.106	-80.895	1.0	1.4
2022	September	28	18	1	1.40	40.096	-80.882	3.2	1.4
2022	September	29	3	55	43.90	40.099	-80.894	2.0	1.2
2022	September	29	14	21	59.05	40.072	-80.844	2.4	0.6
2022	September	29	23	5	42.84	40.101	-80.897	1.0	1.8
2022	September	30	0	21	28.92	40.048	-80.816	2.8	1.1
2022	September	30	11	7	25.98	40.076	-80.841	4.1	0.7
2022	October	1	6	0	3.55	41.745	-81.095	3.6	1.7
2022	October	7	16	55	55.96	38.837	-82.942	9.7	0.6
2022	October	12	3	35	2.61	41.752	-80.982	2.1	1.7
2022	October	31	11	44	46.34	39.280	-82.052	9.3	1.6
2022	November	3	4	22	47.17	40.111	-81.293	4.7	1.1
2022	November	13	19	44	20.00	40.227	-81.203	3.3	0.9
2022	November	13	22	17	29.40	40.224	-81.208	3.0	1.8
2022	November	13	23	49	55.30	40.226	-81.206	2.7	1.7
2022	November	14	0	11	50.00	40.226	-81.206	3.3	1.5
2022	November	14	6	30	25.60	40.226	-81.206	2.6	1.1
2022	November	16	2	18	12.20	40.224	-81.207	3.1	1.6
2022	November	16	23	10	9.50	40.223	-81.217	1.4	1.0
2022	November	17	9	31	44.11	40.271	-81.262	9.8	1.5
2022	November	20	4	26	7.47	40.224	-81.211	2.7	2.1
2022	November	20	4	58	8.79	40.222	-81.209	2.4	2.0
2022	November	20	5	12	14.86	40.238	-81.210	4.8	1.2
2022	November	20	5	46	31.20	40.222	-81.212	2.6	0.4
2022	November	20	6	24	21.30	40.226	-81.211	2.3	0.2
2022	November	20	6	24	25.80	40.227	-81.212	1.0	1.0
2022	November	20	6	55	7.00	40.224	-81.214	1.4	0.8
2022	November	20	7	10	56.00	40.225	-81.212	2.1	2.4
2022	November	20	7	14	39.64	40.227	-81.209	2.6	1.7

Year	Month	Day	Hour[2]	Minute	Second	Latitude	Longitude	Depth[3] (km)	Mag
2022	November	20	7	17	50.20	40.223	-81.215	1.4	0.5
2022	November	20	7	19	32.95	40.257	-81.211	11.7	1.4
2022	November	20	7	40	41.38	40.232	-81.211	4.3	1.7
2022	November	20	7	46	9.76	40.225	-81.207	2.6	1.7
2022	November	20	7	47	18.80	40.224	-81.214	1.0	-0.1
2022	November	20	7	47	53.60	40.224	-81.212	1.9	0.7
2022	November	20	9	27	46.90	40.224	-81.212	1.9	1.4
2022	November	20	9	36	23.46	40.235	-81.210	4.5	1.6
2022	November	20	12	24	46.13	40.223	-81.210	2.8	1.6
2022	November	20	12	31	35.70	40.223	-81.213	2.8	1.6
2022	November	20	12	49	50.03	40.211	-81.218	0.3	1.9
2022	November	20	13	15	10.30	40.226	-81.213	1.5	0.4
2022	November	20	13	29	33.10	40.224	-81.213	1.4	1.3
2022	November	20	15	12	51.99	40.228	-81.146	4.5	1.5
2022	November	20	16	1	28.00	40.225	-81.214	1.0	0.0
2022	November	20	17	6	21.74	40.236	-81.213	3.3	2.2
2022	November	20	17	26	56.50	40.224	-81.209	2.5	0.5
2022	November	20	17	58	56.31	40.227	-81.210	3.6	2.1
2022	November	20	20	55	20.95	40.230	-81.213	4.4	1.2
2022	November	21	1	28	36.80	40.223	-81.207	2.1	1.9
2022	November	21	1	28	49.00	40.224	-81.213	1.7	0.8
2022	November	21	1	29	13.10	40.223	-81.215	1.7	0.5
2022	November	21	1	47	1.35	40.225	-81.210	2.6	1.6
2022	November	21	1	48	32.20	40.226	-81.205	2.8	1.8
2022	November	21	5	7	17.80	40.223	-81.212	2.3	0.5
2022	November	21	7	10	2.57	40.225	-81.212	3.1	2.2
2022	November	21	7	11	11.60	40.225	-81.209	2.3	-0.2
2022	November	21	7	36	2.00	40.228	-81.146	4.7	1.2
2022	November	21	8	10	23.14	40.213	-81.214	0.8	2.0
2022	November	21	8	43	20.40	40.225	-81.214	1.8	1.1
2022	November	21	19	43	9.46	40.230	-81.211	3.7	1.5
2022	November	22	18	11	50.01	40.239	-81.216	5.2	1.4
2022	November	22	20	0	51.11	40.232	-81.209	3.2	1.2
2022	November	22	20	5	16.34	40.247	-81.212	5.6	0.5
2022	November	22	21	37	39.52	40.233	-81.216	4.4	0.8
2022	November	23	5	40	34.03	40.228	-81.216	3.1	1.7
2022	November	23	5	55	28.01	40.225	-81.212	2.1	1.1

Year	Month	Day	Hour[2]	Minute	Second	Latitude	Longitude	Depth[3] (km)	Mag
2022	November	23	10	26	28.65	40.238	-81.220	4.7	1.2
2022	November	25	0	13	56.90	40.225	-81.213	1.9	1.1
2022	November	26	0	58	7.50	40.226	-81.208	2.4	1.5
2022	November	26	9	49	20.71	40.232	-81.214	4.3	1.5
2022	November	26	14	36	2.60	40.222	-81.216	1.4	1.0
2022	November	27	9	21	21.90	40.225	-81.213	2.7	1.3
2022	November	28	23	53	25.50	40.227	-81.190	3.0	0.4
2022	December	2	7	57	42.80	40.225	-81.211	1.8	0.7
2022	December	5	1	54	6.99	41.656	-81.332	4.5	1.2
2022	December	6	21	57	13.50	39.380	-81.337	1.6	0.6
2022	December	9	7	19	11.01	40.297	-81.160	0.5	1.3
2022	December	9	7	19	44.37	40.177	-81.219	5.0	0.6
2022	December	17	19	18	1.91	40.285	-81.133	5.0	1.3
2022	December	18	6	47	14.23	40.287	-81.140	5.0	1.4
2022	December	22	8	30	20.04	41.113	-83.436	1.1	2.8
2022	December	27	19	25	28.78	40.286	-81.147	5.0	1.4
2022	December	27	20	8	4.00	40.288	-81.142	5.0	1.3
2022	December	28	4	46	36.61	40.293	-81.131	5.0	1.4
2022	December	28	12	57	17.19	40.303	-81.134	5.0	1.5
2022	December	28	20	45	24.91	40.295	-81.142	2.8	1.2
2022	December	30	17	56	59.79	40.289	-81.128	5.0	1.2
2022	December	31	10	18	4.25	40.288	-81.135	5.0	1.3
2022	December	31	16	46	16.89	unknown*	unknown*	unknown*	0.0
2022	December	31	16	55	33.88	40.303	-81.114	2.4	1.5
2022	December	31	17	54	21.12	40.306	-81.105	5.1	1.3
2022	December	31	19	5	44.21	unknown*	unknown*	unknown*	0.0
2022	December	31	21	42	12.95	40.303	-81.107	2.7	0.9
2022	December	31	22	23	49.95	40.300	-81.107	3.2	1.1

[1] Earthquakes listed in chronological order. All magnitudes are M_L unless denoted otherwise.
[2] UTC: Coordinated Universal Time. All earthquake origin times are given in UTC time by hour. UTC is similar to GMT (Greenwich Mean Time). To convert to local time, subtract 5 hours for Eastern Standard Time (EST) and 4 hours for Daylight Saving Time (DST).
[3] Earthquake depth listed in km below datum.
* Earthquakes with “unknown*” in the Latitude, Longitude, and Depth boxes were too small to locate reliably; however, data indicate these earthquakes did originate within Ohio.

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- Ohio Department of Natural Resources, Division of Oil & Gas Resource Management
- Incorporated Research Institutions for Seismology

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APPENDIX

Seismic Network Discussion

Network Performance for 2022

Seismic network performance can be summarized by the availability of the data that it produces to end-product users. There are many reasons seismic data may not be available from a seismic station, mainly due to communication problems. However, weather related issues from flooded vaults, lightning strikes, and other power disruptions can also cause outages. Each seismic station has methods of backing up data during power or communication losses such that it can be sent again once these links are reestablished. OhioSeis uses tools available from the IRIS DMC to monitor and grade overall network state of health and performance. Figure A-1 provides information on network data availability during 2022. Overall, the OhioSeis network exceeded its goal of 80% network data availability for the year with a rating of 93% data availability.

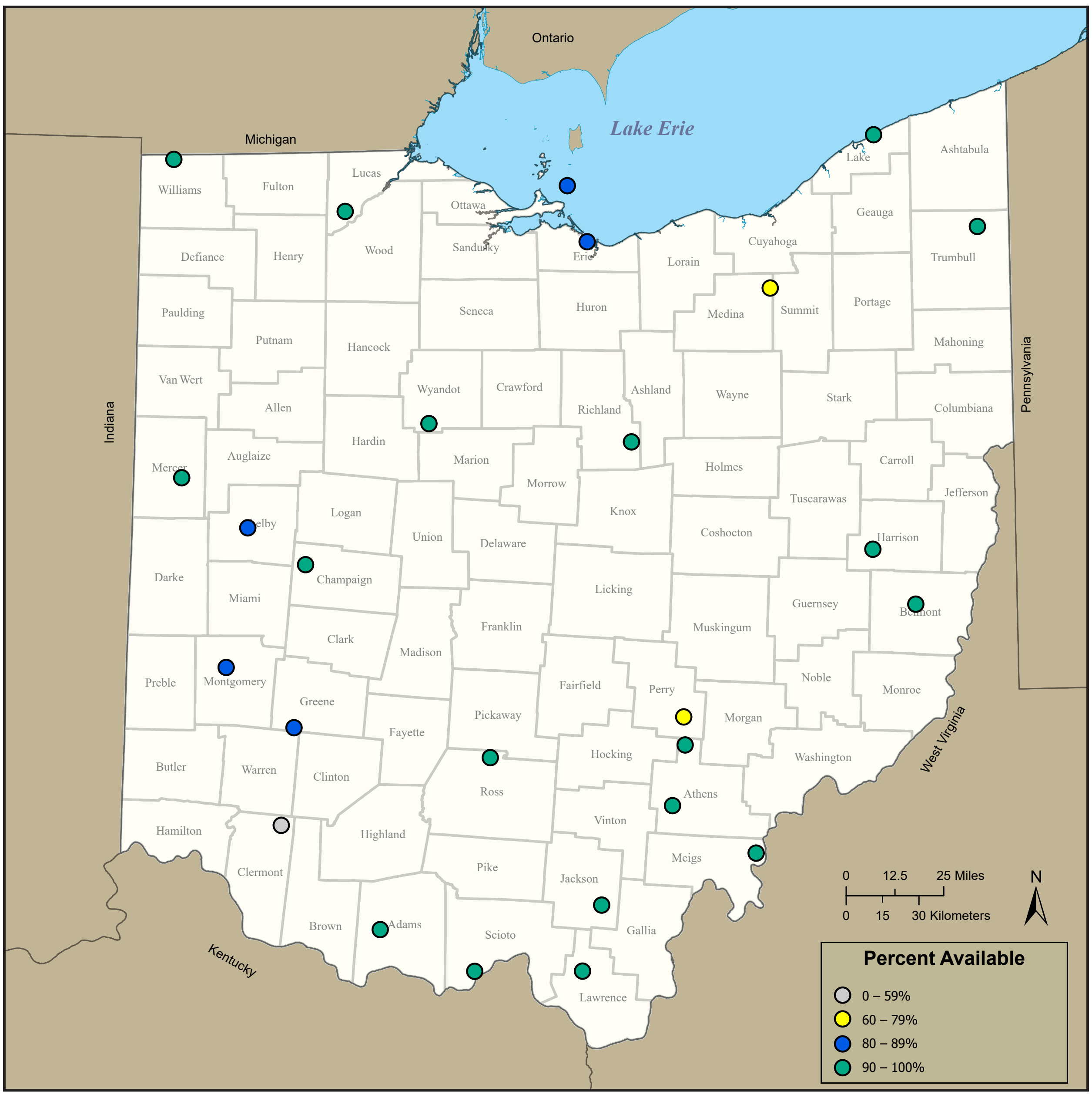

FIGURE A-1. Map of percentage of data availability from each OhioSeis seismic station during 2022.

Maintenance Performed

The OhioSeis team had another busy year maintaining the existing network. Plans to install more posthole seismometer stations were delayed due to supply-chain issues. Though equipment installation was delayed until 2023, siting and Memorandums of Understanding were processed, and station infrastructure was built in 2022 for installations in 2023.

Network maintenance focused on routine tasks and ensuring the equipment survived the previous winter. Batteries were replaced and many stations received new and reconfigured cellular antennas and masts. Staff discovered that the original design/layout of the antennas recommended by the manufacturer was not optimal for transmitting large amounts of seismic data. The new design adds a stronger omni-directional antenna as well as a directional antenna. These two antennas were placed on a tall pole and separated by approximately three feet due to their polarizations (fig. A-2).

FIGURE A-2. Old style antennas and orientation on left was comprised of two small omni-directional antennas. The new style antennas consisting of a stronger omni-directional and directional antenna in their new orientation shown on the right.

Other maintenance included replacing the seismometer vault at Sycamore State Park (fig. A-3) and repairing the solar panel pole at Mercer Wildlife Area. The cement had deteriorated, and the pole began to lean. The vault there was also replaced after being hit with lawn mowing equipment (fig. A-4).

Firmware updates and SD card replacements were performed at each of the borehole stations that were installed in 2021. The station XML (eXtensible Markup Language) files were fixed so that the response files within the metadata were corrected (fig. A-5).

FIGURE A-3. New seismometer vault at Sycamore State Park.

FIGURE A-4. Massive overgrowth of briars at Mercer Wildlife Area, left, and after cleanup and resetting of solar panel mast, right.

FIGURE A-5. Updating firmware at station VLOH in Shelby County, left, and at station HINO in Medina County, right.

Some larger projects for 2022 included the removal of station P52A in Perry County (fig. A-6) and the replacement of the broken solar panels at KIOH on Kelleys Island (fig. A-7). Station P52A was a legacy station from the original Transportable Array (TA) Network that was established in Ohio back in 2012. The station was adopted by OhioSeis in 2016 and recorded earthquakes continuously for 10 years. However, the site was located on private property and new landowners were no longer interested in hosting the station. There are plans to relocate the instrumentation to a new site in the future.

The solar panels at station KIOH (Kelleys Island) were vandalized shortly after their installation in 2021. Though they still partially provided voltage to the system, OhioSeis staff were able to revisit the site and replace the panels in late summer 2022. The conduit housing the sensor cable from the borehole (which could not be buried in the solid limestone bedrock at the ground surface) was replaced. The new conduit is lined with steel and should provide much more security and resistance from damage due to vandalism or animals (fig. A-7).

FIGURE A-6. Disassembly and removal of OhioSeis/TA station P52A.

FIGURE A-7. Damaged solar panels at OhioSeis station KIOH (Kelleys Island, Ohio) were replaced in August of 2022.

In early October, OhioSeis staff assisted the seismic program at Miami University (MU) out of Oxford, Ohio with upgrading their seismic network in Harrison County (fig. A-8). A new seismic vault was installed at the site in Harrison County and batteries were replaced. At the site in Guernsey County, general maintenance was performed and problems with the charge controller were fixed. This site also had its power system batteries replaced.

Also in October, station O53A in Harrison County was visited to check the status of the site, trim overgrowth, and replace batteries and the bilge pump. There was a small amount of water in the bottom of the vault due to the faulty pump (fig. A-9).

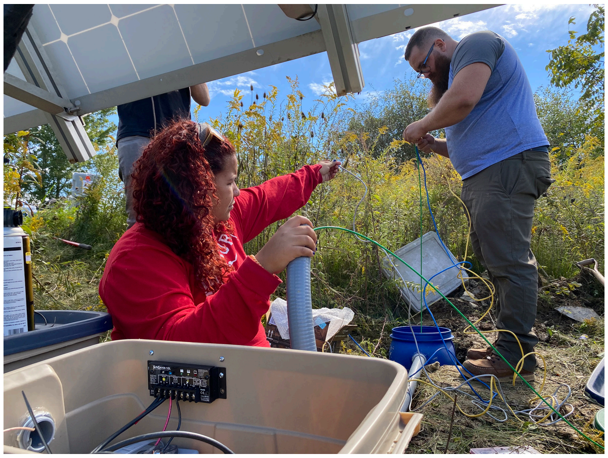

FIGURE A-8. OhioSeis staff and MU grad students upgrading Miami University (Oxford, Ohio) seismic station MUH1 (left) in Harrison County, Ohio, and MUG1 (right) in Guernsey County, Ohio in October 2022.

FIGURE A-9. ODNR intern assisting with field work maintenance of O53A in Harrison County, left, site overview on right. Seismometer is in tube at intern's feet.

Research on Lake Erie Earthquakes

OhioSeis staff co-authored a research paper which was published in Seismological Research Letters (SRL) in the summer 2022 titled, "Seismicity around Southern Lake Erie during 2013–2020 in Relation to Lake Water Level" (Yao and others, 2022), investigating whether seismicity rates are influenced by water loading (fig. A-10). Lake Erie experienced record-high water levels in 2019 and lake levels have remained high for several years (fig. A-11). This research investigated whether the loading from the weight of the extra water within Lake Erie increased stresses enough on faulted rocks to trigger earthquakes. The work was done on data collected from a temporary seismic network the University of Michigan positioned around the west end of Lake Erie as well as from the Ohio Seismic Network.

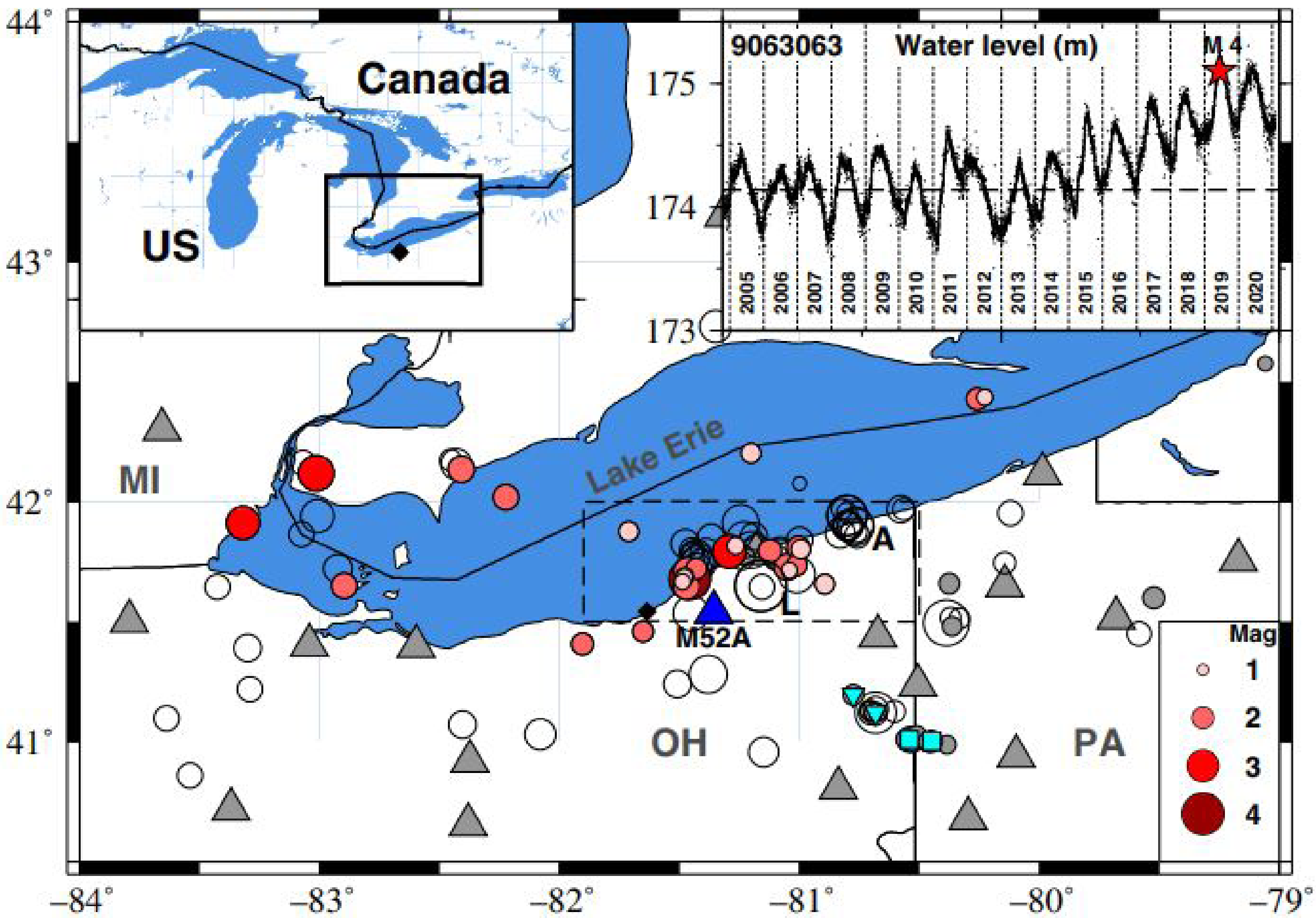

FIGURE A-10. Map showing the study region from Yao and others, 2022. Filled color-coded circles (based on magnitudes) are 27 cataloged earthquakes used in this study, and the open circles are nearby seismicity (2013–2020) within the study area (dashed box). Background earthquakes (1980–2013) are shown with open circles outside the dashed box. Gray triangles are nearby seismic stations, whereas the continuously recording station M52A is shown with the blue triangle. Cyan squares and triangles are locations of induced earthquakes by hydraulic fracturing and wastewater injection. The 1986 M_L 5.0 Lake County earthquake epicenter is labelled with the letter L, and the Ashtabula sequences (1987–2003) are labelled with an A. The water level recording (Cleveland station 9063063) between 2005 and 2020 is plotted in the top right inset.

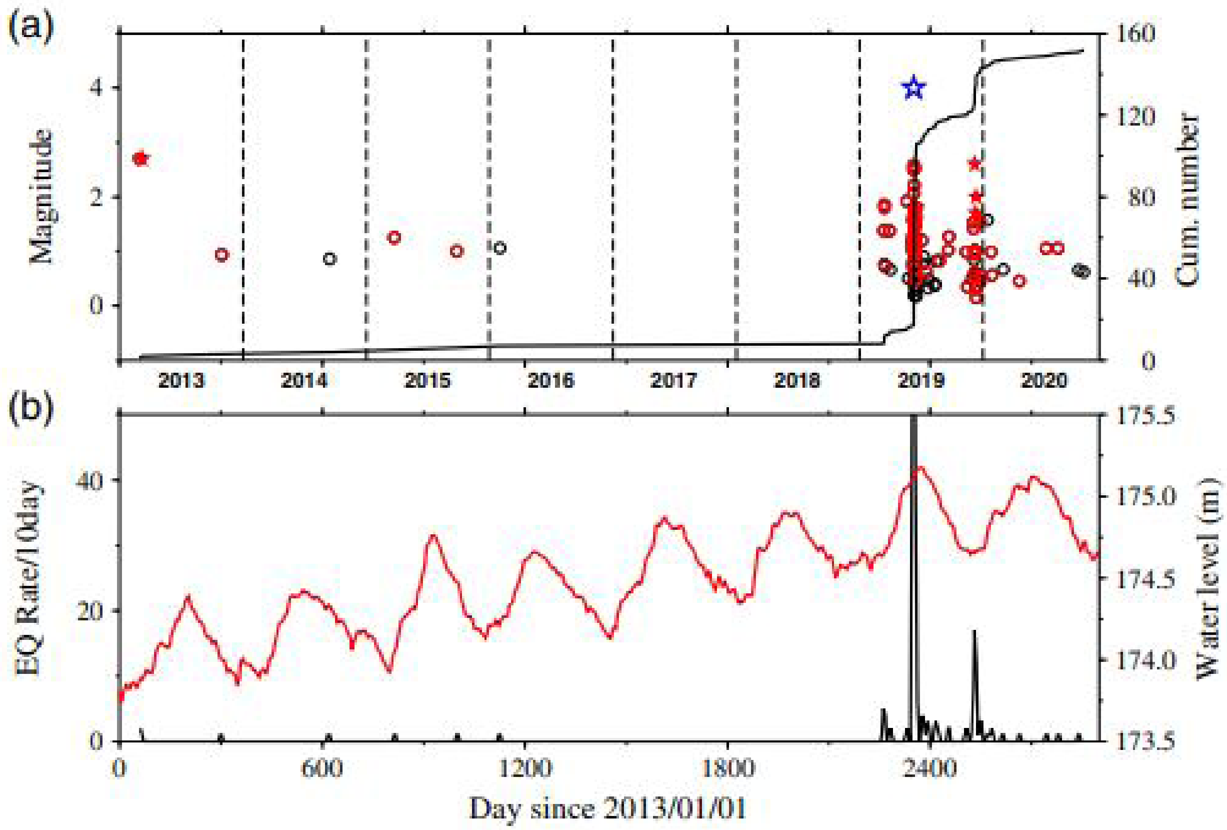

FIGURE A-11. Main earthquake cluster around the 2019 Ohio mainshock from Yao and others, 2022. (a) Magnitude versus time for events within this cluster. Symbols are like those in figure A-10. The cumulative number of earthquakes is shown with the solid black curve. (b) Earthquake rate (black line, averaged every 10 days) versus water level (red curve).

TABLE A-1. ***Ohio Seismic Network operating seismograph stations as of December 31, 2022***

STATION NAME		COUNTY	INSTALLED	SENSOR	DIGITIZER	MODEM
BCOH	Blue Creek Metro Park	Lucas	2019	GURALP CMG-6TD	Onboard	RV50
BGOH	BGSU Firelands	Erie	2019	GURALP 40T-PH	MINIMUS	RV50
BSPO	Barkcamp State Park	Belmont	2018	GURALP CMG-6TD	Onboard	RV50
CHWO	Cooper Hollow State Nature Preserve	Jackson	2018	GURALP CMG-6TD	Onboard	RV50
CPOH	Chaparral Prairie State Nature Preserve	Adams	2019	GURALP CMG-3T	RefTek 130	RV50
DSFO	Dean State Forest	Lawrence	2021	GURALP 40T-PH	MINIMUS	RV50
FOXO	Fox Lake State Park	Athens	2021	GURALP 40T-PH	MINIMUS	RV50
HINO	Hinkley Reservation	Medina	2021	GURALP 40T-PH	MINIMUS	RV50
KDOH	Killdeer Plains Wildlife Area	Wyandot	2019	GURALP CMG-6TD	Onboard	RV50
KIOH	Kelleys Island	Erie	2021	GURALP 40T-PH	MINIMUS	RV50
KLOH	Kiser Lake State Park	Champaign	2019	GURALP CMG-6TD	Onboard	RV50X
LEBO	Lake Erie Bluffs Metro Park	Lake	2016	GURALP CMG-6TD	Onboard	RV50
LLSO	Lake La Su An Wildlife Area	Williams	2021	GURALP 40T-PH	MINIMUS	RV55
M53A	Farmdale, OH	Trumbull	2018	SERCEL L223D	RefTek 130	RV50
MFOH	Malabar Farms State Park	Richland	2019	GURALP CMG-3T	RefTek 130	RV50
MWLO	Mercer Wildlife Area	Mercer	2018	GURALP CMG-6TD	Onboard	RV50
O53A	Freeport, OH	Harrison	2018	STRECKEISEN STS-2	Q330	RV50
P51A	Williamsport, OH	Ross	2018	NANOMETRICS Trillium 240	Q330	RV50
P52A	Corning, OH	Perry	2018	STRECKEISEN STS-2	Q330	RV50
SLSO	Stonelick State Park	Clermont	2018	GURALP CMG-6TD	Onboard	RV50
SVWO	Spring Valley Wildlife Area	Warren	2021	GURALP 40T-PH	MINIMUS	RV50X
SROH	Shade River State Forest	Meigs	2019	GURALP CMG-3T	RefTek 130	RV50
SSF2	Shawnee State Forest	Scioto	2016	GURALP CMG-6TD	Onboard	RV50
SSPO	Sycamore State Park	Montgomery	2019	GURALP CMG-6TD	Onboard	RV50
VLOH	Vernon A. Luthman Tecumseh Wildlife Area	Shelby	2019	GURALP 40T-PH	MINIMUS	RV50
WODO	Wallace H. O'Dowd Wildlife Area	Athens	2021	GURALP 40T-PH	MINIMUS	RV50X

(red)	Station that was decommissioned in August 2022. First installed in 2012 and adopted into the OhioSeis network in 2016.

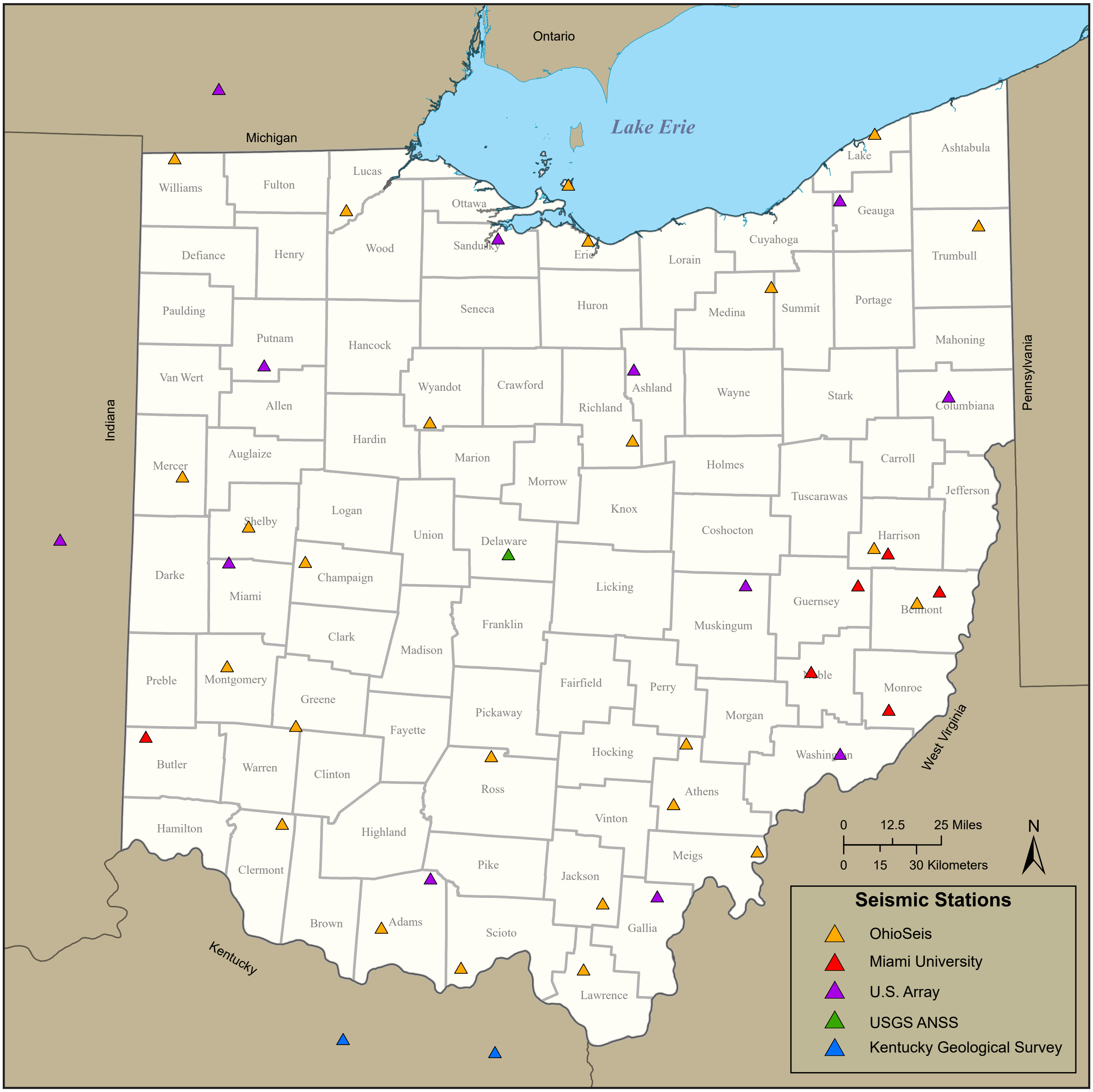

FIGURE A-12. Map of OhioSeis and other seismic station locations in Ohio and adjacent states for 2022.

Intensity	Shaking	Description/Damage
I	Not felt	Not felt except by a very few under especially favorable conditions.
II	Weak	Felt only by a few persons at rest,especially on upper floors of buildings.
III	Weak	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV	Light	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Moderate	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Strong	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	Very strong	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII	Severe	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	Violent	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Extreme	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

FIGURE A-13. The Modified Mercalli Intensity Scale for earthquake shaking.

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