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Key Points:

- Multistation template matching finds swarms that help discern induced seismicity
- Two swarms were correlated with wastewater disposal, three with hydraulic fracturing
- Seventeen other cataloged earthquakes between 2010 and 2014 were nonswarmy, likely natural

Supporting Information:

- Tables S1 and S2

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Distinguishing induced seismicity from natural seismicity in Ohio: Demonstrating the utility of waveform template matching

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Abstract This study investigated the utility of multistation waveform cross correlation to help discern induced seismicity. Template matching was applied to all Ohio earthquakes cataloged since the arrival of nearby EarthScope TA stations in late 2010. Earthquakes that were within 5 km of fluid injection activities in regions that lacked previously documented seismicity were found to be swarmy. Moreover, the larger number of events produced by template matching for these swarmy sequences made it easier to establish more detailed temporal and spatial relationships between the seismicity and fluid injection activities, which is typically required for an earthquake to be considered induced. Study results detected three previously documented induced sequences (Youngstown, Poland Township, and Harrison County) and provided evidence that suggests two additional cases of induced seismicity (Belmont/Guernsey County and Washington County). Evidence for these cases suggested that unusual swarm-like behaviors in regions that lack previously documented seismicity can be used to help distinguish induced seismicity, complementing the traditional identification of an anthropogenic source spatially and temporally correlated with the seismicity. In support of this finding, we identified 17 additional cataloged earthquakes in regions of previously documented seismicity and away from disposal wells or hydraulic fracturing that returned very few template matches. The lack of swarminess helps to indicate that these events are most likely naturally occurring.

1. Introduction

As oil and gas well completions utilizing multistage hydraulic fracturing have become more commonplace, the potential for seismicity induced by the deep disposal of frac-related wastewater and the hydraulic fracturing process itself has become an increasingly important issue [e.g., *National Academy of Sciences (NAS)*, 2012]. While it is rare for a wastewater disposal well to induce felt seismicity, the recent increase in the number of wells and volumes injected are suspected of contributing to a substantial increase of events $\geq M$ 3 in central and eastern United States in since 2010 [e.g., *Ellsworth*, 2013]. More than 300 earthquakes with $M \geq 3$ occurred in the 3 years from 2010 to 2012, compared with an average rate of 21 events per year observed from 1967 to 2000. Arkansas, Colorado, New Mexico, Ohio, Oklahoma, and Texas have recently experienced elevated levels of seismic activity near industrial activities, raising the likelihood that these events were induced by human activity [e.g., *Frohlich*, 2012; *Horton*, 2012; *Kerenan et al.*, 2013; *Kim*, 2013; *Rubinstein and Ellsworth*, 2013]. A more thorough investigation of recent earthquakes is needed to more clearly identify and characterize induced seismicity and ultimately to determine whether human activity should be changed to reduce earthquake hazards and potential losses.

Beginning in March 2011, a series of 10 small (M ~2), shallow (~3 km depth) earthquakes were recorded and reported by the Ohio Department of Natural Resources (ODNR) near Youngstown in northeastern Ohio (Figure 1). The proximity of the Youngstown earthquake sequence (YES) to the recently activated D&L Energy Northstar 1 wastewater disposal well raised concerns of possible injection-induced seismicity. ODNR and Lamont-Doherty Earth Observatory (LDEO) deployed a local seismic network in December 2011 that more closely constrained the proximity of events to the disposal well. Injection activities were ceased on 30 December 2011. On 31 December 2011, a M 4.0 earthquake occurred with an epicenter less than 1 km from the well. Several subsequent studies of this sequence have provided additional evidence that the earthquakes were induced by wastewater disposal [*Ohio Department of Natural Resources (ODNR)*, 2012; *Kim*, 2013; *Skoumal et al.*, 2014; *Holtkamp et al.*, 2015].

Although uncommon, the YES findings are consistent with earlier cases where the injection of fluids into underground formations has induced seismicity [e.g., *Evans et al.*, 2012; *McGarr et al.*, 2002; *Nicholson and Wesson*, 1990].

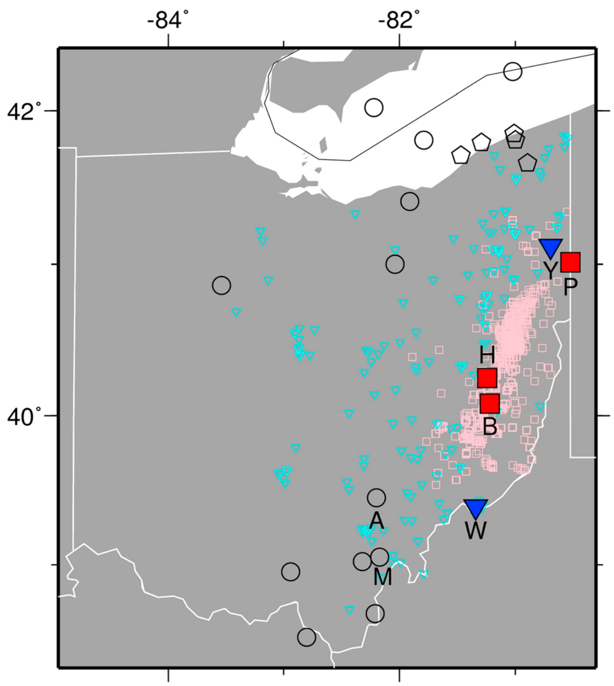

Figure 1. Map summarizing the template matching results. Some templates reveal repeating events with evidence they are induced by wastewater disposal (blue triangle) or hydraulic fracturing (red squares). Pentagons are recent earthquake templates that produced a handful of matches. Circles are recent isolated earthquake that produced 0–1 additional template matches and appear to be natural earthquakes. Pink squares and cyan triangles are all unconventional Utica wells and wastewater disposal wells active during the study time frame. Labels are B, Belmont/Guernsey Co.; H, Harrison Co.; M, Meigs Co.; P, Poland Township; A, Athens Co.; W, Washington Co.; Y, Youngstown.

Although the number of earthquakes near the Northstar 1 well reduced dramatically within a week of shut in, there is an ongoing moratorium on wastewater disposal within 7 km of the well and a small number of earthquakes, including a M ~2 event in November 2013, have continued to occur near the well [*Skoumal et al.*, 2014].

Felt earthquakes induced by hydraulic fracturing during well stimulations are even rarer than those associated with wastewater disposal. However, due to the recent enhanced scrutiny regarding the practice and more sensitive seismic-monitoring tools, induced seismicity attributed to hydraulic fracturing has become more apparent in the past few years. While microseismicity (M <1) is an inherent component of the hydraulic fracturing process [*Warpinski et al.*, 2012], hydraulic fracturing has previously been well correlated to a handful of earthquakes sequences, including M 1.9 Oklahoma, 1979 [*Nicholson and Wesson*, 1990]; M_L 2.9 Oklahoma, 2011 [*Holland*, 2013]; M_L 3.8 British Columbia, 2011 [*British Columbia Oil and Gas Commission*, 2012]; M_L 2.3 England, 2011 [*British Geological Survey*, 2011]; and M 2.2 Harrison County, Ohio, 2013 [*Friberg et al.*, 2014].

Between 5 and 14 March 2014, a series of five earthquakes ranging from M_L 2.1 to 3.0 were recorded in Poland Township, Ohio. The epicentral locations for the Poland Township earthquake sequence (PTES) are less than 20 km southeast of the locations of the YES. Despite this proximity, there were no disposal wells operating within 10 km of the Poland Township earthquakes. However, the earthquakes occurred within 1 km of a group of recently drilled production wells in the area, one of which (Hilcorp Energy CLL2 1H) was undergoing active hydraulic-fracture stimulation at the time of the initial seismic events. Because of this proximity, the Ohio Department of Natural Resources (ODNR) halted completion operations at the Hilcorp well on the afternoon of 10 March 2014.

These two recent examples of induced seismicity have demonstrated that Ohio is a good target region for establishing how earthquake hazards may be influenced by human activities. Foremost, Ohio has a relatively low background seismicity rate with ~4 recorded events per year between 1990 and 2004. By comparison, Ohio has seen that number jump to ~10 in the past 10 years as potential cases of induced seismicity have become more prevalent. The overall low background rate helps in distinguishing induced events from tectonic events as induced sequences tend to stand out relative to the background patterns. Another key factor is that Ohio is host to both active wastewater disposal wells and horizontal drilling/hydraulic fracturing associated with the Marcellus and Utica-Point Pleasant shale plays. The majority of the disposal wells and the area of active hydraulic fracturing are concentrated in eastern Ohio, which limits the geographic extent of likely induced events. Additionally, the relatively limited number of disposal and horizontal production wells compared to other states (for example, Oklahoma) allows the effects of activities associated individual well acts to be evaluated.

Following the events of the YES, there has been a heightened concern over seismicity related to energy technologies in Ohio. The ODNR has established new regulations to identify induced seismicity before felt events occur [*ODNR*, 2014a], which could serve as a blueprint for other states. Additionally, Ohio requires detailed oil and gas and underground disposal control reports including horizontal well location surveys, completion and stimulation reports, and daily injection volume and pressure data that are publically available [*ODNR*, 2014b]. From a seismological research perspective, Ohio benefits from being served by a number of regional long-standing "backbone" seismic stations for over a decade and the studies of YES and PTES significantly benefited from early adoption of EarthScope Transportable Array (TA) stations in western Pennsylvania in late 2010.

Utilizing the data sources outlined above, we attempted to broaden the template matching efforts to other recorded seismic events across Ohio to investigate whether additional cases of induced seismicity can be identified. *Davis and Frohlich* [1993] developed three primary criteria to determine if seismicity is induced by fluid injection activities: (1) coincident timing, (2) coincident location, and (3) adequate fluid pressures. In this study, we demonstrate that the identification of repetitive and/or swarm-like seismicity from template matching can also be a criteria for differentiating induced seismicity from natural seismicity in a stable cratonic interior where seismicity is generally rare.

2. Data and Analysis

Our template matching and event characterization approach have been optimized based on studies of the YES [*Skoumal et al.*, 2014] and PTES [*Skoumal et al.*, 2015]. The ideal network consisted of stations early adoption EarthScope TA sites M54A, N54A, and O56A in both the YES and PTES. This study investigates templates with these stations (referred to as MNO templates) from the time of installation (November 2010) until the end of this study (May 2014). TA stations formally arrived in Ohio during 2012, which provided opportunities to build templates using closer TA stations for some recent earthquakes (referred to as local templates). The closer proximity of these stations to the source events typically increased the signal-to-noise ratio and led to higher numbers of matches. In one earthquake sequence, there was an event of interest that occurred just before the installation of M54A, N54A, and O56A, such that we needed to construct a template from older regional stations.

Templates were created for all earthquakes in Ohio since 6 November 2010 from the catalogs provided by the ODNR, Lamont Doherty Earth Observatory (LDEO), U.S. Geological Survey National Earthquake Information Center (NEIC), and EarthScope Array Network Facility (ANF). For the ANF catalog, we needed to identify surficial blasts related primarily to quarrying/surface mining activities based on the presence of clear R_g waves [e.g., *Kafka*, 1990]. This step is important because the blast events register an average of over 100 matches if used as templates. This highlights the fact that the majority of seismic sources in Ohio are blasts, yet there is less concern about mining activities because they represent surficial processes and rarely involve preexisting faults. While we examined waveforms to identify blasts manually, we developed a simple routine to aid this process. It involved calculating the ratio of the high-frequency (>5 Hz) to low frequency (0.4–1 Hz) mean amplitude for a horizontal component seismogram during the event and dividing it by the ratio calculated in the minute before the event. We calculated this across the 10 closest stations and found that the average was typically less than 1 for blasts due to the prominent R_g waves and greater than 5 for earthquakes.

After discarding 60 blast events, the culled catalog has 51 remaining earthquakes that were used for template matching (Table 1). As in our previous studies, waveforms were obtained using Incorporated Research Institutions for Seismology (IRIS) WebServices, interpolated to 40 samples per second, and then band-pass filtered between 5 and15 Hz. For each event, templates began 10 s before the *P* wave arrival on vertical components and 10 s before *S* wave arrival on horizontal components, with a total length of 37 s in both cases. Cross-correlation coefficients (CCC) were calculated by correlating the template with years of data by shifting one datum at a time for each station and component. We sum the CCC values across the network taking into account the lag values between different station components established in the template event arrival times. Network-normalized CCC (NNCCC) values were produced by dividing the sum of normalized CCC values for all stations and components by the number of contributing channels. We set an initial threshold of 15 times the median absolute deviation (MAD) of the daily NNCCC. Correlating a randomly generated template against a random yearlong signal at 40 samples per second would result in ~1 false positive based on what 15×MAD represents, theoretically.

Table 1. Earthquakes Utilized as Templates in This Study, Grouped by Their Region

Date	Latitude	Longitude	Depth (km)	Magnitude	Source	No. of Matches	County/Region
Youngstown							
17-03-2011T10:42:20	41.11	−80.70	5	2.1	OGSO	342	Mahoning
17-03-2011T10:53:09	41.11	−80.70	5	2.6	OGSO	276	Mahoning
22-08-2011T08:00:31	41.09	−80.71	5	2.7	ISC	310	Mahoning
25-08-2011T19:44:20	41.10	−80.73	5	2.4	OGSO	249	Mahoning
02-09-2011T21:03:26	41.12	−80.69	5	2.2	OGSO	246	Mahoning
26-09-2011T01:06:09	41.12	−80.70	5	2.4	ISC	325	Mahoning
30-09-2011T00:52:37	41.16	−80.69	3.7	2.5	ISC	235	Mahoning
20-10-2011T22:41:09	41.11	−80.68	5	2.3	OGSO	320	Mahoning
25-11-2011T06:47:26	41.10	−80.69	5	2.2	OGSO	125	Mahoning
24-12-2011T06:24:57	41.11	−80.69	3.5	2.7	OGSO	271	Mahoning
31-12-2011T20:04:58	41.16	−80.73	2.2	4.0	ISC	90	Mahoning
13-01-2012T22:29:33	41.11	−80.69	5	2.1	OGSO	163	Mahoning
12-11-2013T20:12:00	41.13	−80.71	7.7	2.1	ANF	49	Mahoning
Poland Township							
10-03-2014T06:26:45	41.01	−80.54	2.5	3.0	NEIC-PDE	45	Mahoning
10-03-2014T06:42:44	41.01	−80.56	5	2.4	NEIC-PDE	64	Mahoning
10-03-2014T15:03:47	41.01	−80.53	5	2.2	NEIC-PDE	56	Mahoning
10-03-2014T15:44:06	41.01	−80.53	5	2.6	NEIC-PDE	61	Mahoning
11-03-2014T07:01:13	41.00	−80.53	5.2	2.1	NEIC-PDE	73	Mahoning
Harrison County							
02-10-2013T00:01:26	40.23	−81.22	11.2	2.2	ANF	97	Harrison
02-10-2013T01:52:46	40.23	−81.24	8.5	2.0	ANF	95	Harrison
02-10-2013T03:19:10	40.24	−81.24	7.6	2.4	ANF	107	Harrison
02-10-2013T10:06:55	40.24	−81.24	10.8	2.4	ANF	93	Harrison
05-10-2013T00:16:14	40.25	−81.24	7.4	2.6	ANF	84	Harrison
08-10-2013T06:25:46	40.24	−81.25	9.6	2.1	ANF	89	Harrison
19-10-2013T06:48:38	40.24	−81.24	8.9	2.3	ANF	86	Harrison
Belmont/Guernsey County							
18-05-2014T23:05:27	40.06	−81.25	3	2.6	ANF/TS[a]	54	Belmont
18-05-2014T23:22:45	40.06	−81.25	3	1.9	ANF/TS	45	Guernsey
18-05-2014T23:47:19	40.06	−81.25	3	1.9	ANF/TS	54	Guernsey
19-05-2014T00:18:50	40.06	−81.24	3	2.2	ANF/TS	49	Belmont
19-05-2014T05:11:57	40.06	−81.24	3	2.1	ANF/TS	51	Belmont
Washington County							
24-10-2010T08:12:45	39.39	−81.35	2	2.8	OGSO/TS	<1>[b]	Washington
31-08-2011T09:35:12	39.37	−81.37	3	2.8	ISC/TS	36	Washington
31-08-2011T17:36:02	39.37	−81.37	2	3.1	ISC/TS	31	Washington
04-09-2011T13:21:59	39.38	−81.35	5	2.6	OGSO/TS	53	Washington
29-05-2012T11:52:54	39.38	−81.34	2	2.1	OGSO/TS	6	Washington
18-09-2012T21:05:19	39.39	−81.34	4	2.1	OGSO/TS	47 (77)[c]	Washington
Lake and Ashtabula Counties							
08-03-2013T22:32:20	41.71	−81.47	5	2.1	NEIC-PDE	3 (5)	Lake
01-07-2013T07:48:43	41.79	−81.29	5	3.2	OGSO	3 (3)	Lake
06-10-2013T19:37:02	41.85	−81.01	5	2.4	NEIC-PDE	2 (2)[d]	Lake
08-04-2014T16:02:28	41.81	−81.00	5	2.2	NEIC-PDE	2 (2)[d]	Lake
17-03-2013T22:49:26	41.66	−80.89	5	2.2	OGSO	4 (8)	Ashtabula
Isolated Events							
26-04-2011T07:09:46	40.86	−83.54	5	2.4	OGSO	1	Hancock
05-06-2011T15:35:20	41.00	−82.04	0.7	3.0	ISC	2	Medina
15-06-2011T04:37:57	41.81	−81.79	5	2.0	OGSO	1	Lake Erie
13-08-2011T15:41:00	42.25	−81.02	5	2.1	OGSO	1	Lake Erie
01-12-2012T07:32:01	39.05	−82.17	20	2.6	ANF	1	Meigs
17-02-2013T04:12:55	42.02	−82.22	5	2.5	NEIC-PDE	1	Lake Erie
27-03-2013T09:10:48	38.67	−82.21	1.2	3.1	ANF	1	Gallia

Table 1. (continued)

Date	Latitude	Longitude	Depth (km)	Magnitude	Source	No. of Matches	County/Region
10-05-2013T23:22:36	39.02	−82.32	17.9	2.0	ANF	1	Meigs
11-10-2013T02:25:40	38.51	−82.80	5.7	2.2	NEIC-PDE	1	Greenup
20-11-2013T17:59:39	39.45	−82.20	8	3.5	NEIC-PDE	1	Athens
20-01-2014T06:50:18	41.41	−81.91	13	2.1	NEIC-PDE	1	Cuyahoga
27-01-2014T05:52:58	38.95	−82.94	17.2	1.9	ANF	1	Scioto

[a]TS: Locations are from this study.
[b]Numbers in less than and greater than signs represent the matches obtained with a regional set of 3 older stations.
[c]Numbers in parentheses show the number of matches obtained with a local set of three TA stations.
[d]Events that only match with each other.

We determined local magnitudes through a Richter scale approach:

$$M_L = \log 10[\mathbf{A}/\mathbf{A_0}]$$

For each station and component in our template, we calculated the median scale factor ($\mathbf{A}_0$) using the filtered *S* waveform amplitudes ($\mathbf{A}$) and catalog magnitudes for all events reported by the ODNR/LDEO/NEIC. For each matched event, we calculated a magnitude from the scale factor and *S* waveform amplitude at each station and component and took the median value as our final magnitude.

Following template matching, earthquake locations are compared with the OhioSeis catalog to determine whether the events occurred in a region of previous seismicity. The epicenters of events we investigated are also compared with the location of unconventional Utica wells and class II disposal wells active during our study time frame based on information available from ODNR (Figure 1). We found that there were ~850 Utica wells and ~160 wastewater disposal wells during this time frame.

3. Results

3.1. Previously Documented Cases

3.1.1. Mahoning County (Youngstown and Poland Township)

The results for these two cases are described briefly and in greater detail in *Skoumal et al.* [2014] and *Skoumal et al.* [2015]. Considering the approach applied in the present investigation is based on these previous studies, their results are included here for completeness and verification.

3.1.2. Harrison County

In October 2013, a series of seven earthquakes listed in the EarthScope catalog occurred in Harrison County, southeast Ohio (Figure 1) in an area with no previously documented seismicity. While there are nearby quarrying operations that produce frequent blasts, we have confirmed that these events lack the R_g wave characteristic of surficial blasts. There are no disposal wells within 10 km of the events, but hydraulic fracturing operations were performed from 7 September to 6 October 2013 on three wells near the earthquake

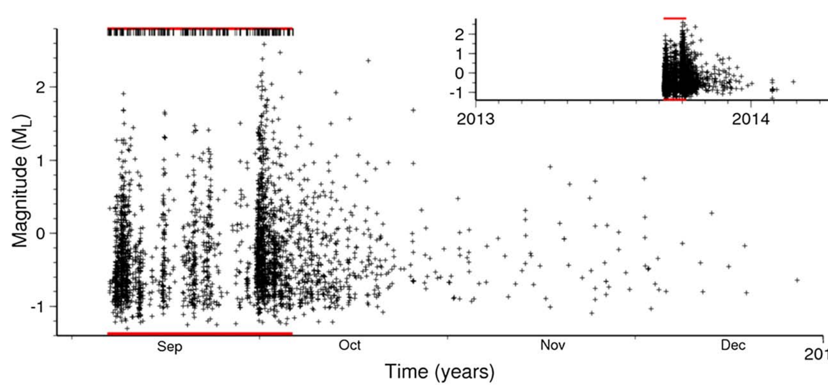

Figure 2. Magnitude of earthquakes in Harrison County (crosses) identified from template matching using nearby station O53A. Red bars indicate duration of nearby hydraulic fracturing, with black bars showing individual stages. Inset shows the entire time frame over which the template matching was performed based on nearby EarthScope station availability.

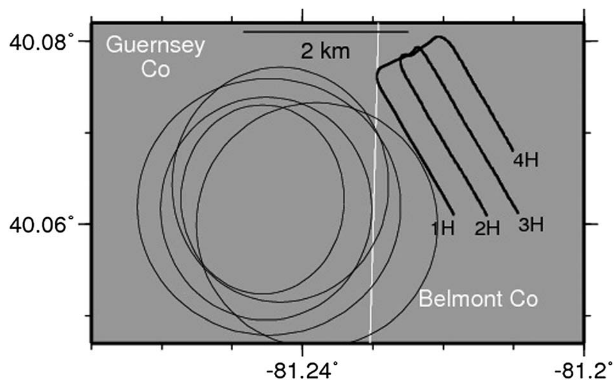

Figure 3. Map at the edge of Belmont and Guernsey Counties showing relocations and bootstrap uncertainties of 4 template earthquakes (ellipses) and the Kirkwood A horizontal wells 1H-33 through 4H-33 that underwent hydraulic fracturing around the time of the earthquakes.

hypocenters. These well-completion operations have been previously correlated to the recorded seismicity [*Friberg et al.,* 2014].

The MNO templates for the Harrison County events revealed 154 unique matching events when the results from each individual template scan were combined. However, local template scans of a station (O53A) from within 5 km of the events revealed 2788 unique matching events with a magnitude of completeness of M_L −0.6 (Figure 2). The temporal distribution of these events is similar to that of *Friberg et al.* [2014] with bursts of activity during certain stimulation stages and a gradual decay of activity after operations ceased. We note, however, that our technique identified nearly an order of magnitude more events than the earlier study with a lower magnitude of completeness (478 events, M_c 0).

3.2. New Sequences

3.2.1. Belmont/Guernsey County

A series of five small (M_L ~2) earthquakes listed in the EarthScope catalog occurred on 18–19 May 2014 in western Belmont/eastern Guernsey counties in southeast Ohio (Figure 1). The catalog epicenters were within 5 km of four horizontal wells (Kirkwood A wells 1H-4H-33), with targets in the Ordovician Point Pleasant Formation at depth of ~2475 m. These wells underwent hydraulic-fracture stimulation in April–May 2014. We relocated the four cataloged earthquakes by picking reliable arrival times and inverting for locations with *elocate* using the velocity model from neighboring Harrison County [*Herrmann*, 2004; *Friberg et al.*, 2014]. The absolute location errors were determined using bootstrapping, removing one station at a time from the location process, and using the standard deviation as the error estimate [*Efron*, 1979]. Based on drill survey reports from the ODNR, the four relocated earthquakes appear to have occurred west of the drilled laterals (Figure 3), although the location uncertainties are relatively large given the station coverage.

Scans using the MNO templates revealed 64 unique events down to M_L ~1 temporally restricted to May 2014 (Figure 4a). Template matching using the three closest TA stations (O53A, P53A, and O52A) showed 180 unique events restricted to 28 April to 25 May 2014 (Figure 4b), with only a single event in each of the two subsequent months. State records indicate that drilling/completion occurred during 28 April to 21 May along four horizontal wells, temporally coinciding with the seismicity we detected. We identified eight seismic

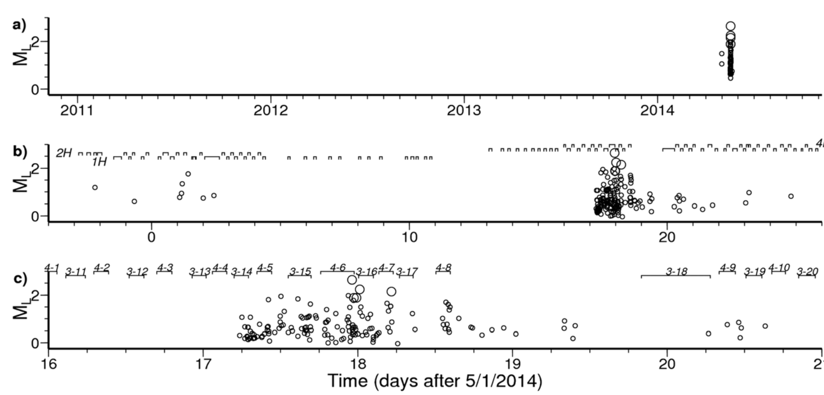

Figure 4. Magnitudes of earthquakes found through template matching in the Belmont/Guernsey County case using (a) typical three regional TA stations and (b and c) closest 3 TA stations. Large circles are templates; small circles are matches. Brackets indicate times of hydraulic fracturing stimulation at each well, and individual stages are labeled in the zoomed in view (Figure 4c).

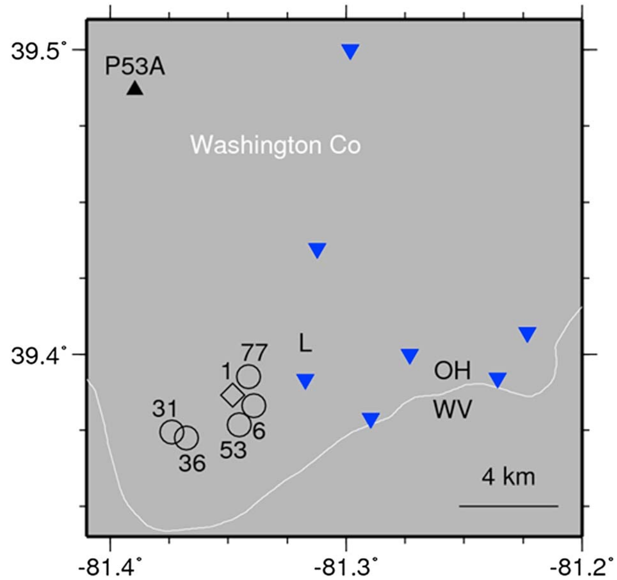

Figure 5. Map showing relocated epicenters of template events (circles), number of matches (numbers). Diamond shows the template event that used older regional data. Nearest TA station is a black triangle, and disposal wells are blue inverted triangles, where L = long-run disposal well. White line shows state boundary (Ohio River).

events during the concurrently operating Kirkwood A 1H-33 and 2H-33 stimulations, but the vast majority of seismicity occurs on 17–19 May during 3H-33 and 4H-33 stimulations. An 11 additional events were recorded on the following days when hydraulic-fracturing operations on these two wells were again active (Figure 4b). Based on the current location estimates, it appears that seismicity flourished during a set of 3H-33 and 4H-33 stages despite being further from the seismic source than 1H-33 and 2H-33.

The main cluster of seismicity started during stage 14 of well 3H-33, which does appear to be a routine stimulation based on the stimulation report available from ODNR, but the details for stage 4 of well 4H-33, which immediately preceded this, are missing in the stimulation report. The other stage that may be important is stage 6 at well 4H-33 because a "sweep" was reported during the middle of that stage, and this term typically refers to temporary reduction in the proppant concentration to avoid clogging the well. As a result, this stage lasted longer than normal, and the largest earthquake occurred at the end of that stage. This results in a day-long gap in stimulation that may have contributed to the reduced seismic activity afterward. Unfortunately, the limited stimulation reports available at this time prevent more detailed analysis of the potential relationships between operations and seismicity.

Given that the Belmont/Guernsey County events display unusual swarm behavior that temporally and spatially correlates to the hydraulically fracturing operations, and that they occurred in an area with no prior documented earthquakes, there is a strong possibility that the April–May 2014 earthquake sequence was induced.

3.2.2. Washington County

There were a series of five recorded earthquakes in Washington County (Figures 1 and 5), which we used to construct MNO templates that found 59 unique events (Figure 6). The seismicity rate based on our initial template matching decreased considerably after 2011. To further investigate this seismicity rate change, we generated a template for the three closest TA stations (P53A, P52A, and Q52A) that recorded the last cataloged event (18 September 2012). Template matching with this event produced 80 matches from 27 August 2012 to 6 May 2014, most of which were $M_L < 1$ (Figure 6a). This suggests that the seismicity in this region may have been ongoing during 2011–2012, but below the magnitude detection threshold.

While the initial catalog locations of the five events used as templates cover a 25 km wide area (Table 1), the similarity of matched waveforms indicates that the events occur within a much smaller source area. We proceeded to relocate these events by picking reliable arrival times and found that all template epicenters are within 4 km of one another (Figure 5). The relocations were achieved using a 1-D velocity model derived from a sonic-velocity log of the 3489 m deep Amerada Petroleum, Ulman 1 well. This well was located in southern Noble County, ~25 km north of the earthquakes. The Ulman 1 well was spudded in Pennsylvanian sedimentary rocks and drilled through the entire Paleozoic stratigraphic section to the Proterozoic crystalline basement, the top of which was encountered at depth of 3478 m. The initial model contained 12 discrete velocity layers defined by changes in rock rheology associated with key stratigraphic intervals in the basin (Table S1 in the supporting information). This initial model was reduced to four layers to reflect primary thickness-associated weighted mean velocities exhibited by local stratigraphy, with the initial velocity increase at 2.572 km depth (Table S2). The uncertainties associated with the latest cataloged events in 2012 are smallest

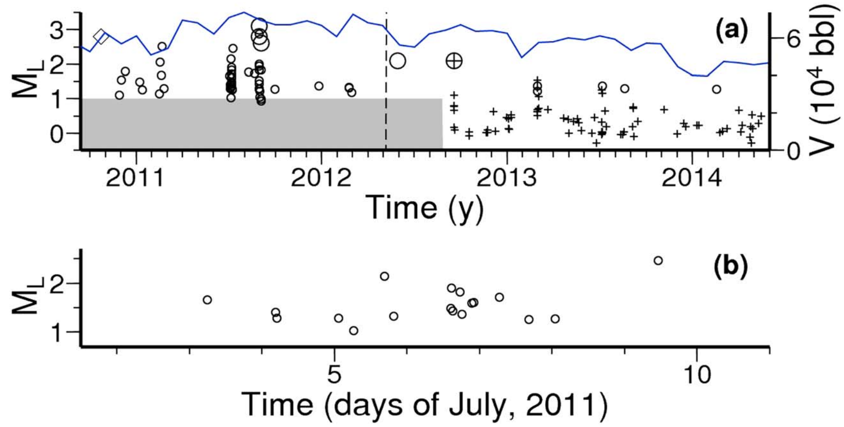

Figure 6. Magnitudes of earthquakes found through template matching in the Washington County region. Larger circles are templates; small circles are matches. (a) Events found with the traditional template stations (circles) and with the closest three TA stations using the last cataloged event in this region (crosses). Grey marks the time when the closer three TA stations were not available. Blue line is monthly injected volume at the nearest well. Dashed line is time when ownership changed at the nearest high-volume disposal well. Diamond is earliest recorded event in this region, which occurred 2 weeks before the TA stations were installed. (b) Swarm of events illustrating the lack of main shock-aftershock behavior.

due to the presence of TA stations in Ohio and a few portable instruments deployed by ODNR at that time. These best located events are less than 2 km west of a wastewater disposal well (Figure 5).

There are several wastewater disposal wells in the area of interest, but the closest to the seismicity is the Ohio Oil Gathering Corporation, Long Run Disposal Well 1. This well began injecting into the Clinton and Medina formations in September 2008 at depths of 2127–2146 m and 2170–2174 m. Since that time, the well has had one of the highest average monthly disposal volumes in Ohio. Monthly reported injected volumes have exceeded 40,000 barrel (bbl) since 2009 and reached a maximum near 74,000 bbl in 2011 (Figure 6). Maximum reported injection pressures have been approximately constant at ~1900 psi since the beginning of 2011. However, ownership of the well changed in early 2012 and monthly disposal volumes have been reduced in cooperation with ODNR. As such, the reduction in rate of seismicity $>M_L$ 1 after 2011 could be the result of reduced injected volume.

The depths of the relocated earthquakes prior to mid-2012 are not well constrained due to the lack of local data, with locations ranging in depth between 1.6 and 5.6 km. The most recent earthquake in the sequence (which is also the best located owing to more local data) has a depth of 3.6 ± 1.0 km. According to *Baranoski* [2013], the Precambrian basement depth in this location is ~3.6 km. The earthquakes could be located in the upper Precambrian basement, as seen in the better constrained induced Ohio sequences, or it could be located in the overlying Paleozoic strata. In both scenarios, the located events occurred below the Silurian injection interval. The presence of basement faults that extend upward through the Silurian in southern Washington county [*Deyling*, 1993; *Baranoski*, 2013] suggests that either scenario is plausible.

About 2 weeks prior to the installation of the MNO template stations in November 2010, one *M* 2.8 earthquake was reported, but there are no other cataloged earthquakes in Washington County since 1950. We constructed a template from three regional stations that were recording earlier (ACSO, MCWV, and BLA) but found no matches besides the template itself from 2008 to the end of our study time. To determine how effective these three different stations are as a template, we also constructed a template using these stations for the 4 September 2011 earthquake that had the largest number of matches using the MNO template stations (53). We identified about half as many matches (25), and none before November 2010. This suggests that the more regional template stations are sufficient to determine that the first event is essentially not repetitive and that there is no evidence of seismicity from when injection began at the Long Run 1 well until the October 2010 event.

3.3. Lake and Ashtabula Counties

There were four earthquakes in Lake County and one earthquake in Ashtabula County during our 2010–2014 study time frame, which was interesting since these counties hosted seismic sequences that are thought to have been induced by deep wastewater disposal as far back as 1986 [*Nicholson et al.*, 1988; *Seeber and Armbruster*, 1993;

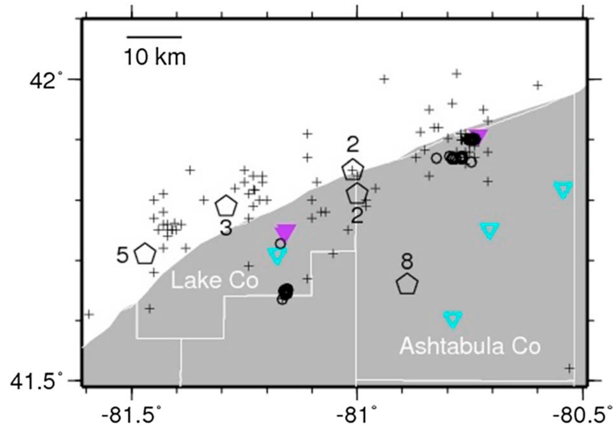

Figure 7. Map showing epicenters in the OhioSeis catalog (crosses), along with previously relocated events from the 1986 Lake Co sequence and 1987/2001 Ashtabula Co sequences (circles), and the five events analyzed by this study (pentagons). Numbers indicate how many matches found using a local set of TA stations. Inverted triangles show deep disposal wells suspected in the earlier sequences (purple) and those operating during the recent sequences (cyan).

Seeber et al., 2004; *Gerrish and Nieto*, 2005] (Figure 7). We found that all five recent earthquake templates produced matching events, but the number of matches was small (2–4), and they appear to resemble more traditional foreshock/main shock/aftershock patterns. To further investigate these cases, we created templates from closer TA stations (e.g., M53A, M52A, and L53A) as all the recent events occurred in March 2013 or later, after the TA had arrived. Despite the significantly higher signal-to-noise ratios with these stations, only two sequences were expanded, one from 3 to 5 matches and another from 4 to 8 matches.

While these numbers are still small relative to the previously discussed cases, the fact that they are not isolated events without any matches may simply be related to the increased prevalence of seismicity overall in this so-called Northeast Ohio Seismic Zone. There have been over 100 felt events since the early 1800s in this region, greater than any other area of Ohio [*Hansen*, 2012]. The seismicity correlates with the prominent Akron magnetic lineament, likely reflecting different lithologies in the Precambrian basement, and a first-order structural boundary interpreted from reflection data [*Seeber and Armbruster*, 1993]. It seems reasonable that this apparent deep fault zone could host several sets of similar small earthquakes that would explain the small number of matches we observed in this region. The recent earthquake epicenters are all greater than 10 km from active wastewater disposal wells and the older wells suspected to have induced seismicity in the 1980s, which suggests that the recent events are likely to be of the same natural origin as those that date back to the 1800s.

3.4. Isolated New Cases

Template matching was performed on the remaining 12 cataloged earthquakes that were generally isolated and scattered around Ohio (Figure 1). Only 1 of the 12 templates (Medina County) found a match, which was a smaller apparent aftershock that occurred 45 days following the template event. As such, none of the 12 cataloged events appears to be part of a repeating sequence, but there has been previously recorded or historical seismicity in each of the counties where these events occurred. One of the events without any matches was a widely felt M_L 3.5 event recorded in Athens County in 2013 (Table 1). This earthquake has been analyzed in detail by ODNR and determined to have a depth of 8 km and was not considered to be induced (ODNR, personal communication, 2014).

Only 1 of the template epicenters occurred within 10 km of a disposal well. This exception is located in Meigs County, where a 2012 earthquake occurred ~7–10 km from a set of five low volume wells that had been injecting for decades into the shallow (640–975 m depth) Devonian Ohio and Marcellus Shale formations, with only two still active 10 km away by the time the earthquake occurred. The low porosity/permeability of these units suggests that the wells were injecting into fractured reservoirs likely related to fault zones interpreted to intersect the injection interval in the area [*Baranoski and Riley*, 2013]. The recorded seismic event, however, is listed as having a hypocentral depth of 20 km and so there appears to be a large vertical offset between the earthquake hypocenter and the depth of the injection interval. Moreover, the Meigs County event did not produce any matches above the 15×MAD threshold.

3.5. Swarminess of Matched Earthquake Sequences

To gain perspective on the results of our template matching analysis, we sought to evaluate the degree to which the resulting sequences follow traditional main shock -aftershock patterns common to natural earthquakes or whether they demonstrate the swarm-like patterns common to those in previous induced sequences such as Rocky Mountain Arsenal [*Healy et al.*, 1968]. One way to quantify swarminess of a sequence

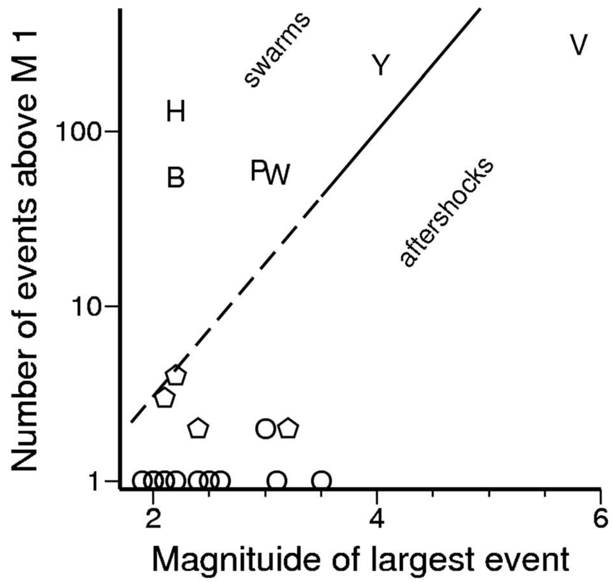

Figure 8. Swarminess of earthquake sequences analyzed in this study. Labels are those from Figure 1, with V added for the 2011 Virginia earthquake sequence. Solid line marks the proposed boundary between swarms and main shock-aftershock sequences [*Vidale and Shearer*, 2006; *Holtkamp and Brudzinski*, 2011], and the dashed line is an extension following the same slope.

is to compare the magnitude of the largest event in a sequence to the overall number of events above a level of magnitude completeness [*Vidale and Shearer*, 2006; *Holtkamp and Brudzinski*, 2011]. Plotting all of the sequences identified in this study in this way illustrates that five sequences (Youngstown, Poland Township, Harrison Co., Belmont/Guernsey Co., and Washington Co.) are significantly more swarm-like than the other investigated events (Figure 8). The 2011 M_w 5.8 Virginia earthquake sequence is also plotted as a reference for main shock-aftershock sequences in the eastern U.S. [*McNamara et al.*, 2013]. Additional characteristics of swarms are found in the 5 Ohio sequences that distinguish them from traditional main shock-aftershock sequences including (1) the largest earthquake occurring later in the sequence and (2) the largest event not being a full magnitude unit larger than other events [*Vidale and Shearer*, 2006; *Holtkamp and Brudzinski*, 2011]. For example, a portion of the Washington Co. sequence in July 2011 shows that the largest event occurs later in the sequence and the largest event is only 0.3 magnitude units greater than the next largest event (e.g., Figure 6).

4. Discussion

The general approach to classifying induced seismicity has been to identify (1) an appropriate anthropogenic source that is potentially influencing the effective stress on a fault, (2) a correlation in timing of the human activity with the seismicity, and (3) a correlation in location between the potential source and the earthquake hypocenters [e.g., *Davis and Frohlich*, 1993]. In this study we have sought to demonstrate that these criteria can be complemented by evidence for swarminess, which can be established through template matching. Table 2 summarizes the criteria, and a few others that may be complementary, for the Ohio earthquakes examined in this study.

Table 2. Summary of Criteria to Distinguish Induced Seismicity in Ohio

Sequence	Suggested Induced Source	Distance to Source[a]	Time Delay[b]	Swarm-Like Nature[c]	Previous Seismicity[d]	Induced?
[e]2011–2012 Youngstown	Waste disposal	<1 km	2 weeks	Yes	No	Likely Induced
[f]2014 Poland Township	Hydraulic fracturing	<1 km	<1 day	Yes	No	Likely Induced
[g,h]2013 Harrison Co	Hydraulic fracturing	<1 km	<1 day	Yes	No	Likely Induced
[h]2014 Belmont/Guernsey Co	Hydraulic fracturing	< ~5 km	<1 day	Yes	No	Likely Induced
[h]2010–2014 Washington Co	Waste disposal	< ~2 km	2 years	Yes	No	Probably Induced
[h]2010–2014 Isolated (section 3.4)	None	>10 km	N/A	No	Yes	Unlikely Induced
[h]2012–2013 Lake Co	None	>10 km	N/A	No	Yes	Unlikely Induced
[h]2013 Ashtabula Co	None	>10 km	N/A	No	Yes	Unlikely Induced

[a]Three-dimensional distance from industry operations to closest earthquake.
[b]Time delay between start of wastewater disposal or hydraulic fracturing and the first recorded earthquake.
[c]Swarm-like nature, lacking traditional main shock/aftershock pattern (Figure 8).
[d]Region of suspected induced events has prior reported seismicity.
[e]*Skoumal et al.* [2014].
[f]*Skoumal et al.* [2015].
[g]*Friberg et al.* [2014].
[h]This study.

Recent studies have shown that the Youngstown, Poland Township, and Harrison County cases have earthquakes less than 1 km from either wastewater disposal or hydraulic fracturing and display a close temporal correlation between the initiation of wastewater disposal or certain hydraulic fracturing completion stages [*Skoumal et al.*, 2014, 2015; *Friberg et al.*, 2014]. These studies also identified an unusual swarm-like behavior lacking traditional foreshock/main shock/aftershock sequences. While not typically used as such, we suggest that this swarminess characteristic could be applied as a criterion to help distinguish induced seismicity. In this study we demonstrated that all three sequences are swarm-like based on the large number of events relative to the largest magnitude (Figure 8). Additional evidence for swarminess can be found in the lack of a leading largest-magnitude main shock followed by significantly smaller aftershocks decaying over time (e.g., Figure 2). Finally, we draw attention to the fact that each of these sequences occurred in areas lacking previously documented seismicity. A region that has a significant number of naturally occurring events would not exclude the possibility of an induced earthquake sequence, but the determination of an induced sequence can be supported by a lack of previous seismicity in the region. Overall, we argue that there appear to be four criteria that support the notion that these cases should be classified as likely induced seismicity (Table 2).

The Belmont/Guernsey County case identified in this study follows the pattern of the three previous cases such that we classify it as "likely induced seismicity." This includes hydraulic fracturing that was spatially and temporally correlated with the seismicity, swarm-like behavior, and no previously documented earthquakes in this region. The results from the Washington County case are not quite as definitive. The seismicity is swarm-like and occurred in an area with no prior documented seismicity. However, the closest identified event may have occurred at a larger distance from the nearest wastewater disposal well (~2 km) than the previously discussed cases, and the first identified event was ~2 years after disposal operations began at the nearest well. Yet it may be that both of these two features could be explained by the seismogenic fault simply being further from the disposal well, especially considering that this well is injecting into a reservoir over 1 km above the basement. Considering that this situation is not as clear as the previous cases, we classify this case as probably induced.

In contrast to these cases, we also found 12 earthquakes that show no evidence of swarminess and do not appear to be spatially or temporally related to wastewater disposal wells or hydraulic fracturing. These events occurred in counties where previous seismicity has been documented, although much of it is historical. We see no reason to believe that any of these 12 earthquakes are induced and have classified them as unlikely induced, consistent with the notion that the low number of matches from template matching is indicative of natural seismicity. The 5 earthquakes in Lake and Ashtabula Counties that we analyzed produced a few more matches (2–8) but are not as swarm-like as the likely induced cases that all produced over 50 matches (Figure 8). These 5 catalogued events in Lake and Ashtabula Counties were greater than 10 km from active wastewater disposal and hydraulic fracturing as well as some older waste disposal wells that were previously proposed to have induced seismicity. Considering that this has historically been one of the most seismically active regions in Ohio, these events were unlikely to have been induced.

We note that our study has identified two sequences induced by wastewater disposal wells and three sequences induced by hydraulic fracturing. When compared with the ~160 wastewater disposal wells and ~850 hydraulically fractured wells, we can estimate the fraction of operations that have induced seismicity. We find that ~1.3% of disposal wells and ~0.35% of unconventional wells have induced seismicity large enough to be detected by the OhioSeis catalog (nominally $M > 2$). While these are simple approximations, the order of magnitude larger incidence of induced seismicity from disposal wells suggests that they have a higher risk of producing seismicity than hydraulic fracturing. This is consistent with the findings of the National Academy of Sciences that the very low number of induced seismicity cases from hydraulic fracturing is likely due to the shorter duration of injection of fluids and the limited fluid volumes used in a small spatial area. [*NAS*, 2012].

5. Conclusions

This study sought to investigate the pervasiveness of induced seismicity in Ohio while also investigating the utility of multistation waveform cross correlation to help discern induced seismicity. Application of template matching to all Ohio earthquakes cataloged since the arrival of nearby EarthScope TA stations detected three previously documented cases (Youngstown, Poland Township, and Harrison County) and provided evidence that suggested two additional cases of induced seismicity (Belmont/Guernsey County and Washington County). All earthquakes that were within 5 km of fluid injection activities in regions that lacked previously documented seismicity were independently found to be swarmy. This supports the notion that swarminess and lack of previously documented seismicity can be used to help distinguish induced seismicity, complementing the traditional identification of an anthropogenic source spatially and temporally correlated with the seismicity. Moreover, the larger number of events produced by template matching for these swarmy sequences helps to establish more detailed temporal and spatial relationships between the seismicity and fluid injection activities. In support of using swarminess as an indicator of induced seismicity, we identified 17 additional cataloged earthquakes in regions of previously documented seismicity and away from disposal wells or hydraulic fracturing that returned very few template matches. The lack of swarminess helps to indicate that these events are most likely naturally occurring.

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