Correlation algorithms have proven useful for helping to identify repetitive microearthquake sequences buried in vast datasets of passive seismic recordings. Multi-station waveform template matching has been particularly helpful in characterizing seismicity potentially induced by hydraulic fracturing or wastewater disposal. A swarm of many events with similar waveforms, presumably driven by localized fluid injection, can be used as criteria to help discern induced seismicity from naturally occurring seismicity. Swarm detection with template matching applied to a regional network can be done in near real-time without the requirement of local seismic deployments or industry data (e.g., injection volumes/pressures or stimulation reports), although this additional data can be utilized if available to further build support for the designation of either an induced or natural origin. An additional advantage of the scanning technique is that the cross correlations are ideally suited to perform advanced seismic source location and magnitude estimation to better characterize identified sequences. To enhance detection capability, we have developed an agglomerative clustering algorithm to help discern repetitive signals from multiple nearby source regions. The repetitive signal detector does not require a pre-existing cataloged template event, which helps to detect smaller M<2 sequences that typically precede larger M>2 induced seismicity. In Ohio, 9 recent seismic swarms have been correlated temporally and spatially with either hydraulic fracturing or wastewater injection, while nearly 20 less repetitive earthquakes were not and appear to be naturally occurring. A lack of evidence for any induced seismicity in other areas of the Appalachian Basin and Williston Basin despite nearly an order of magnitude more unconventional wells suggests that geology plays a key role in whether seismicity is induced. In particular, we identify the proximity of the basement to the target interval (either fracturing or disposal) as a key factor, suggesting the basement faults are likely needed to generate M>2 seismicity. Considering the national debate over hydraulic fracturing, we have disseminated our research to a wide range of stakeholders, including public outreach through the traditional popular press and through new opportunities such as a Reddit "Ask Me Anything" session, which became the fourth most popular in the science category ever. We have also met individually with industry and regulators to share findings and discuss operation strategies for mitigating hazard. This has led us to contribute to the StatesFirst Induced Seismicity Working Group primer document that will help shape regulations across the US.

Figure 1. Simplified geological cross-section showing oil and gas operations relative to the Precambrian basement (dark shading) in eastern Ohio (OH) and western Pennsylvania (PA). We determined the depth of wastewater injection (blue) and unconventional hydrocarbon reservoirs, Ordovician Point Pleasant Formation/Utica Shale (red) and the Devonian Marcellus Shale (green), utilizing available digital records (Cardwell et al., 2010; Patchen et al., 2006; PGS, 2015; ODNR, 2015). Small circles show depths and locations of hydraulic fracture stimulations. Stars are induced earthquake sequences in (T)rumbull Co, (Y)oungstown, and (P)oland (Skoumal et al., 2015) where operations were < 1 km from the basement.