Relationships between Pre-Existing Structure, Regional Stress Orientation, and Seismicity Induced by Wastewater Injection, Northern Appalachian Basin, USA*

James Free[1], Brian S. Currie[2], Robert J. Skoumal[2], and Michael R. Brudzinski[2]

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Abstract

Recent seismicity in the northern Appalachian Basin has been attributed to active wastewater injection operations. Current models of induced seismicity suggest that movement along pre-existing faults/fractures with orientations optimal to the regional maximum horizontal stress field is the likely source of recorded earthquakes. As part of this investigation, we evaluated the relationships between injection wells, waveform template matching-derived locations of induced earthquakes, and subsurface structures mapped using data from over 600 wells in Ohio and West Virginia. We also evaluated subsurface in-situ stress conditions determined from regional studies and local hydraulic fracturing operations to evaluate the principle stress orientations/magnitudes for comparison with the trends of identified earthquake epicenters. Study results indicate that the locations of seismic events likely induced by wastewater injection operations in Washington County, Ohio correspond to the trend of small-amplitude folds in Upper Devonian rocks close to injection well locations. Similar amplitude folds imaged in nearby seismic reflection lines are associated with basement-involved fault systems that cut the injection interval, providing a possible permeability pathway for fluid pressure increases that could initiate slip. While subsurface mapping in other parts of the basin have not yielded similar structural/epicentral relationships, the orientation of induced events throughout eastern Ohio correspond to the predicted optimal orientation of reactivated fault/fracture zones given the regional principle stress directions.

Selected Reference

Deyling, T.H., 1993, Moss Run Prospect: Structure in Laurence Township, Washington County, Ohio, *in* An Update on Ohio's Subsurface Geology: First Annual Technical Symposium, Ohio Geological Society, 17 p.

Relationships between pre-existing structure, regional stress orientation, and seismicity induced by wastewater injection, northern Appalachian Basin, USA

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Miami University, Oxford OH 45056

Outline

Introduction of recent induced seismic events in Ohio

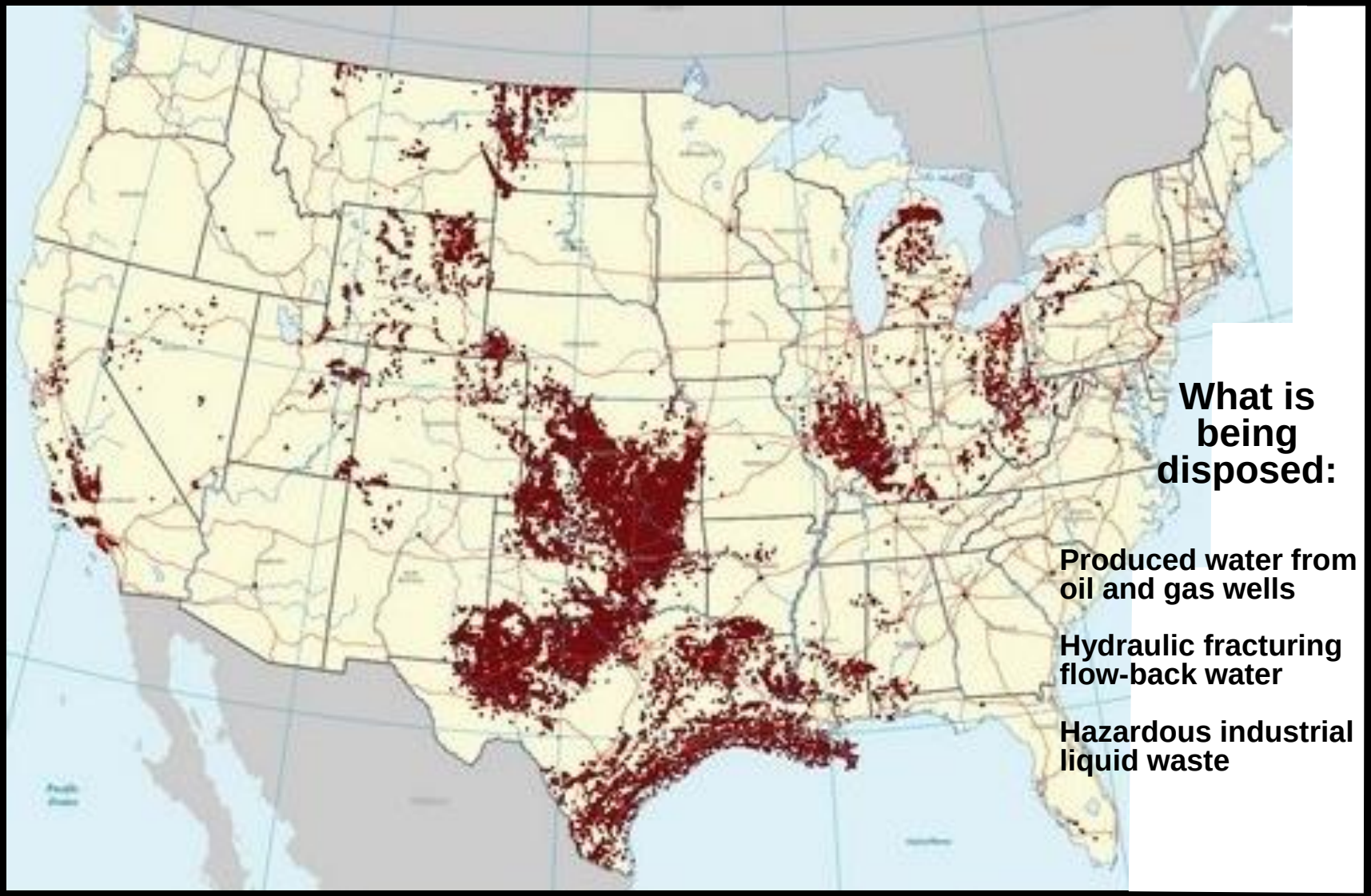
Characterization of possible induced events using seismogram-template matching

Conceptual model of induced seismicity

Evaluation of induced events in Washington County, Ohio

Wastewater Disposal Wells:

The U.S. has tens of thousands of deep wastewater disposal wells



What is being disposed:

- **Produced water from oil and gas wells**
- **Hydraulic fracturing flow-back water**
- **Hazardous industrial liquid waste**

210 Class I and II injection wells in Ohio

Source: Ohio DRN EPA & Division of Oil and Gas Management

10 Class I Wells

Hazardous/Industrial liquid waste

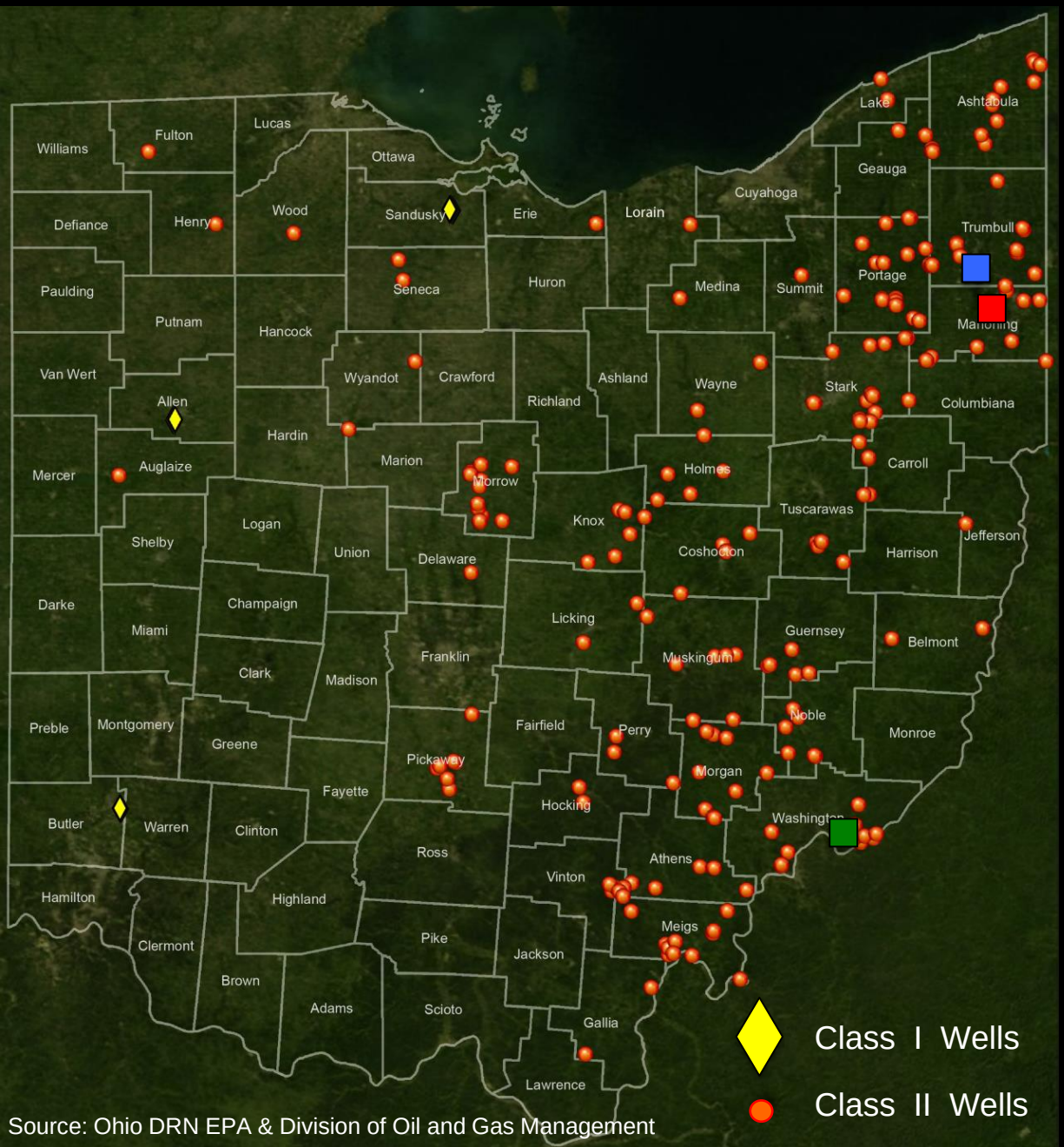
200 Class II Wells

"Salt Water" injection wells

- produced water from oil/gas wells

-"flowback water" from well completions using hydraulic fracturing

210 Class I and II injection wells in Ohio

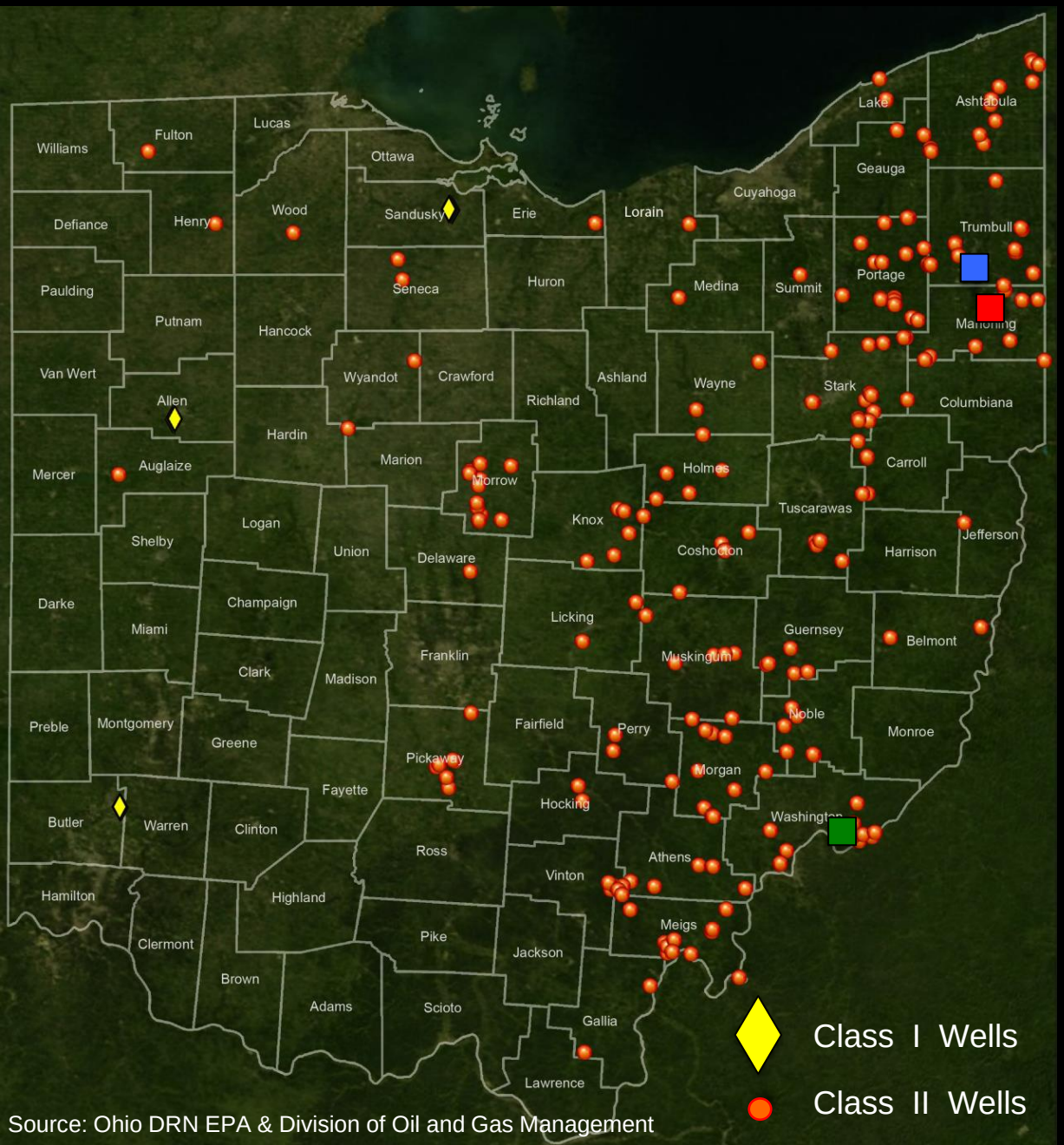


Source: Ohio DRN EPA & Division of Oil and Gas Management

Since 2011, there have been three cases where earthquakes have been recorded in close proximity to wastewater injection wells in Ohio.

- Youngstown 2010-11
- Washington County 2010-15
- Trumbull County 2014

Seismic Template Matching



Source: Ohio DRN EPA & Division of Oil and Gas Management

To more fully characterize possible induced events, we have employed seismogram template matching using data from regional seismic stations.

This technique has resulted in the identification of smaller magnitude earthquakes (< M 1.0) in each suspected case

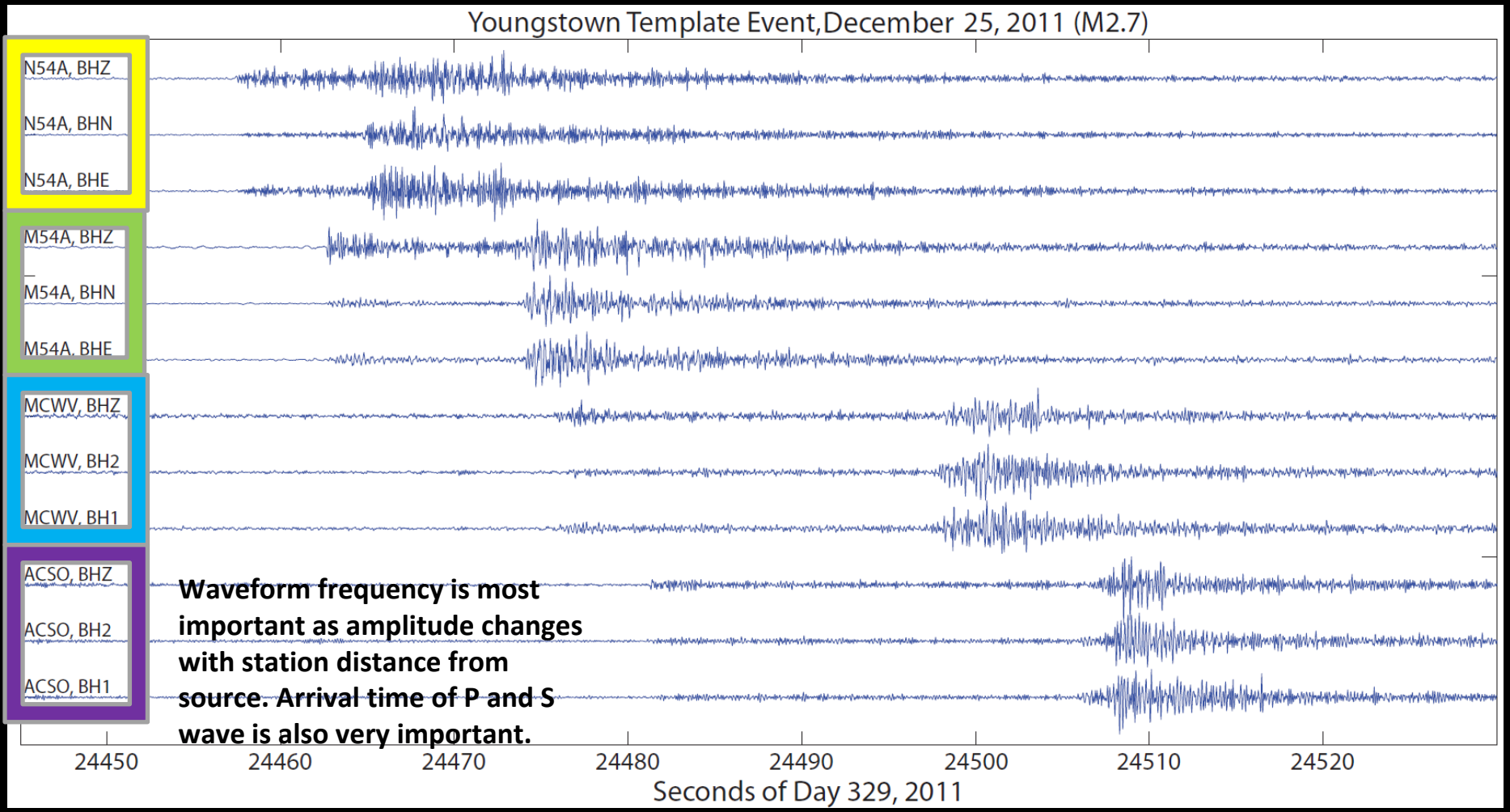
Allows a temporal/spatial evaluation of recorded seismicity in association with the history of injection pressures and volumes for each well.

- **Youngstown 2010-11**
- **Washington County 2010-15**
- **Trumbull County 2014**

Template Matching Procedure

Step 1: Template Waveform Identification From Regional or Local Seismic Stations

- **Seismic waveforms from 2.7 M event received at 4 regional stations at different bandwidths**



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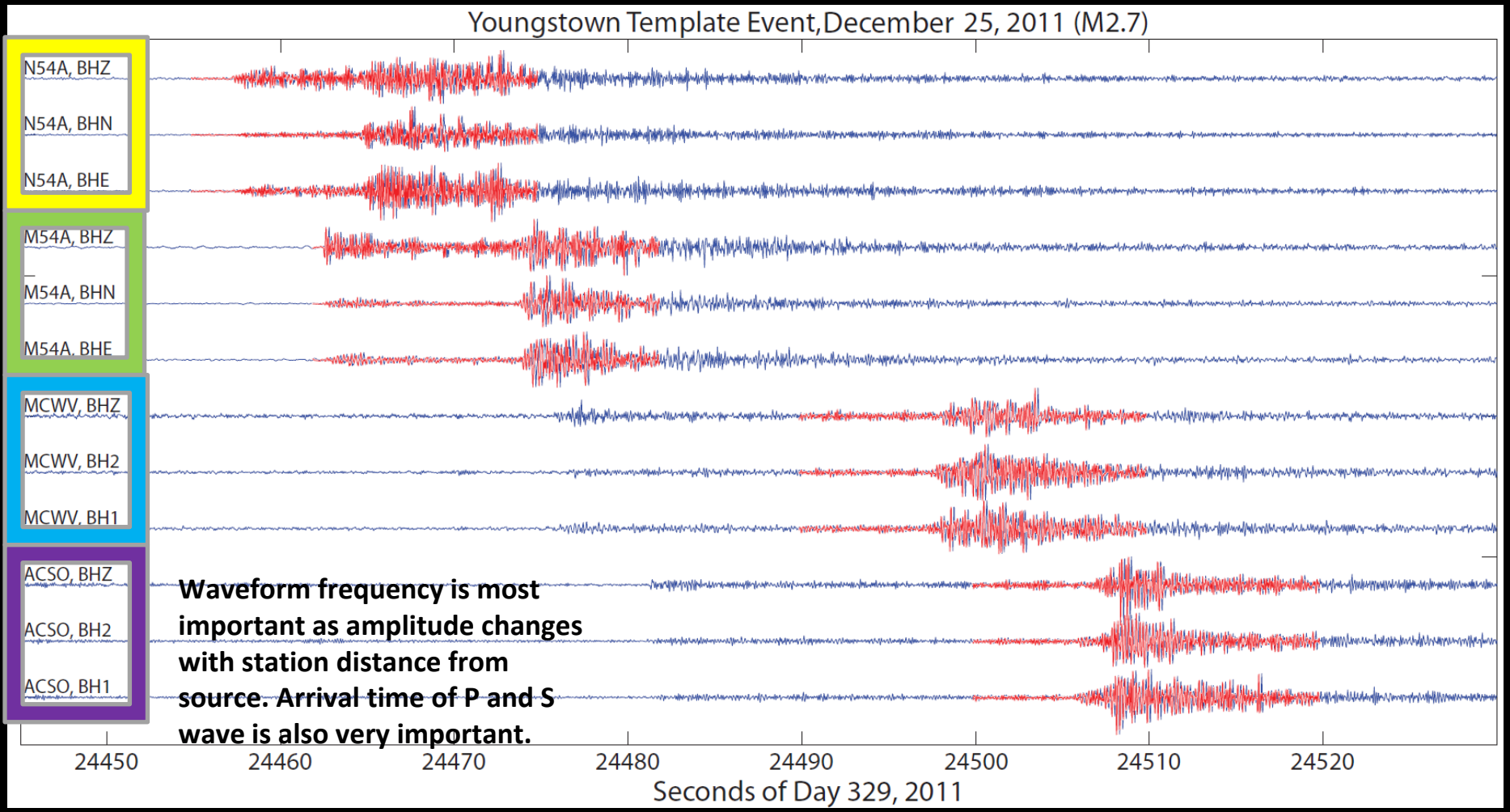
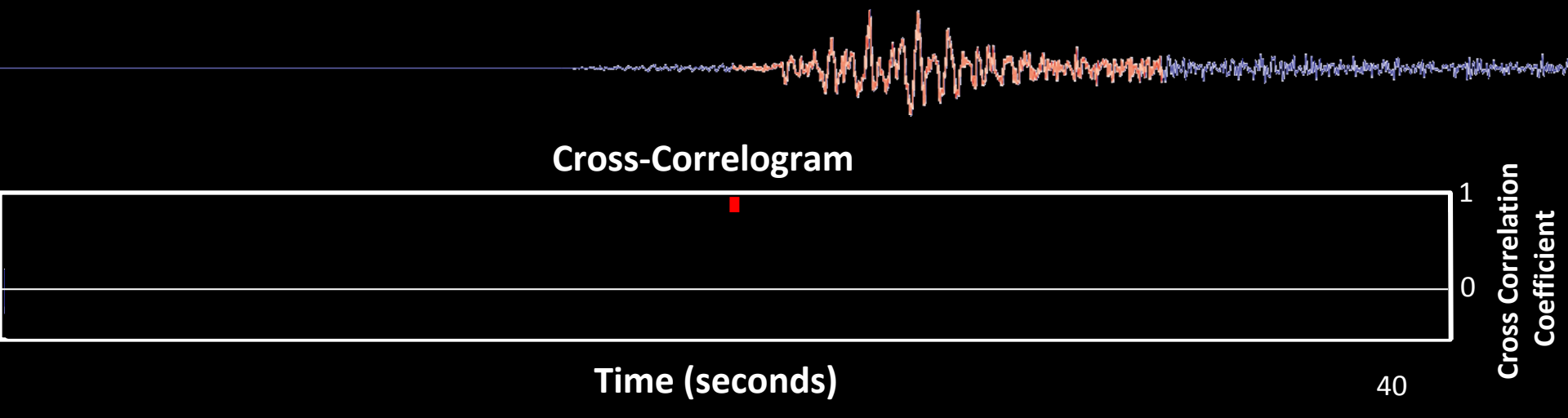


Template Matching Procedure

Step 2: Cross-correlating the template

Take the template, and scan it through some continuous period of data.

When all the peaks line up (regardless of recorded amplitudes), there is a spike in the cross-correlation coefficient



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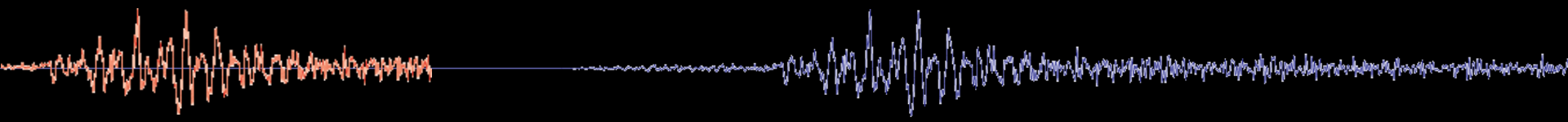

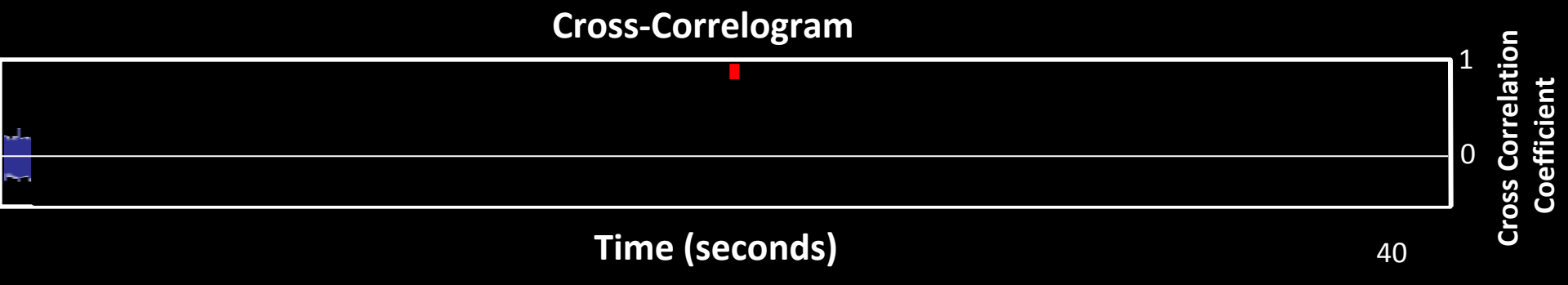

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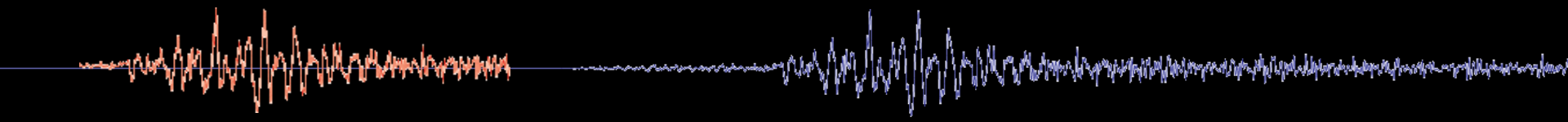

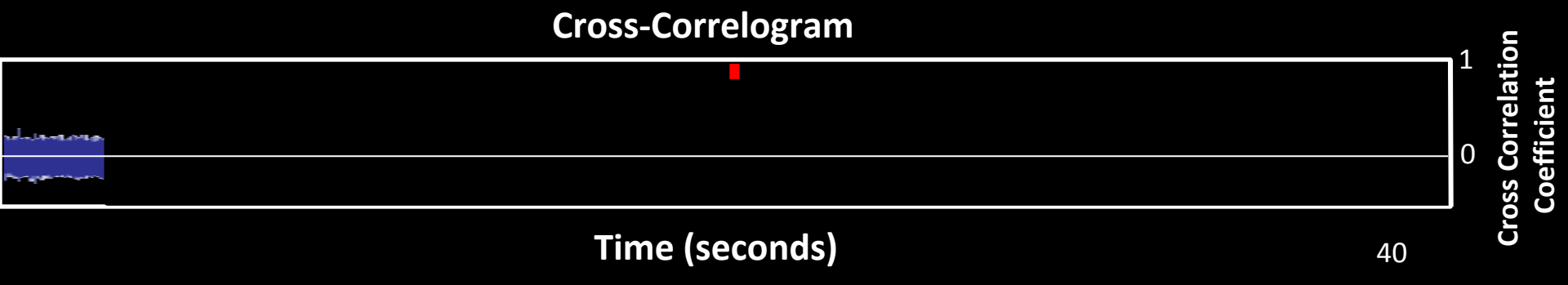

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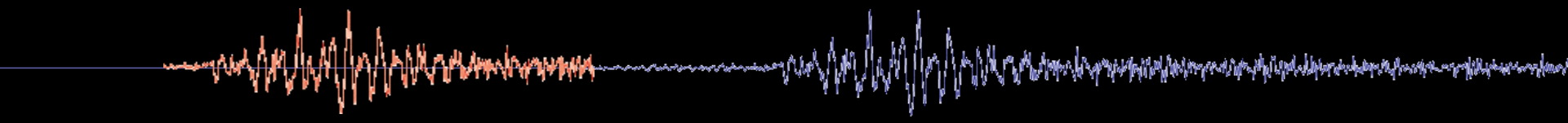
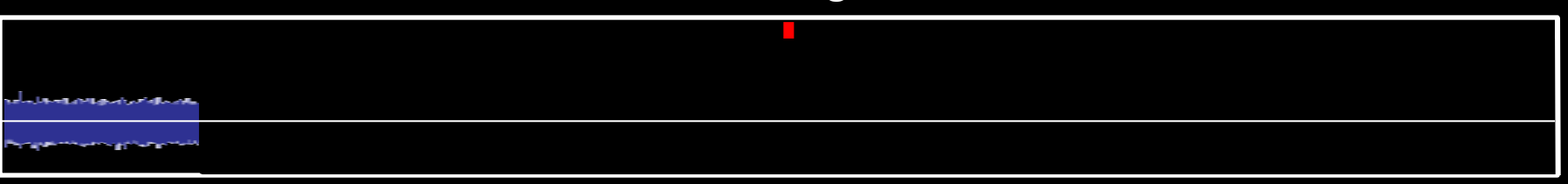


Cross-Correlogram



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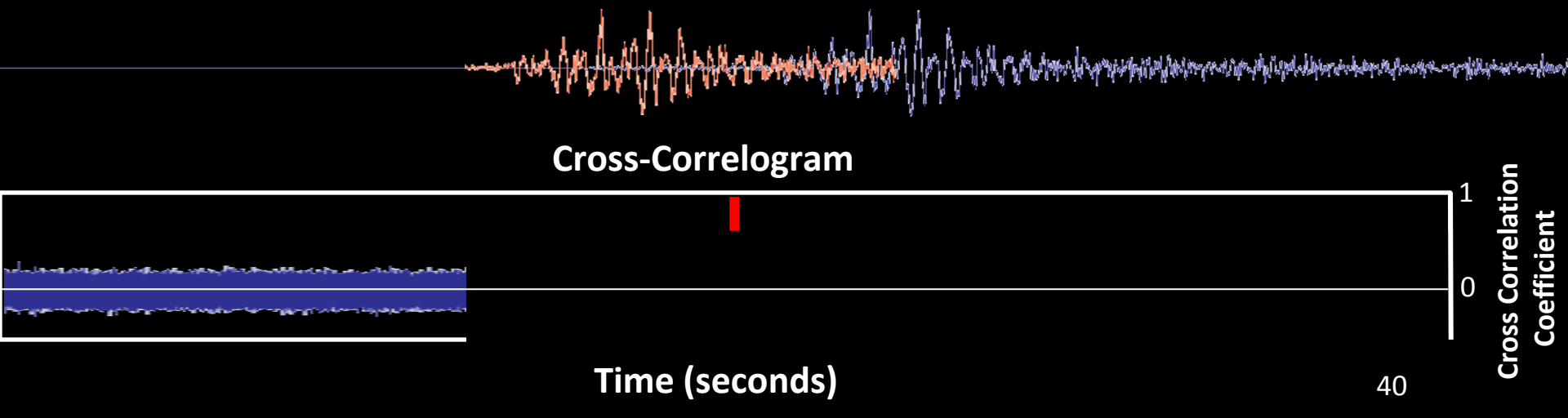

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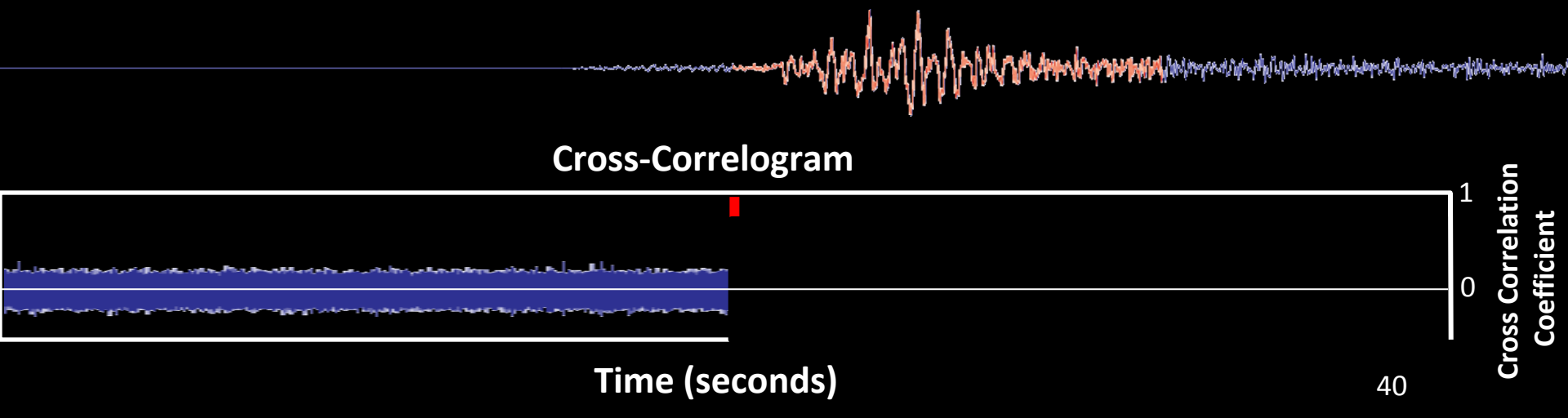

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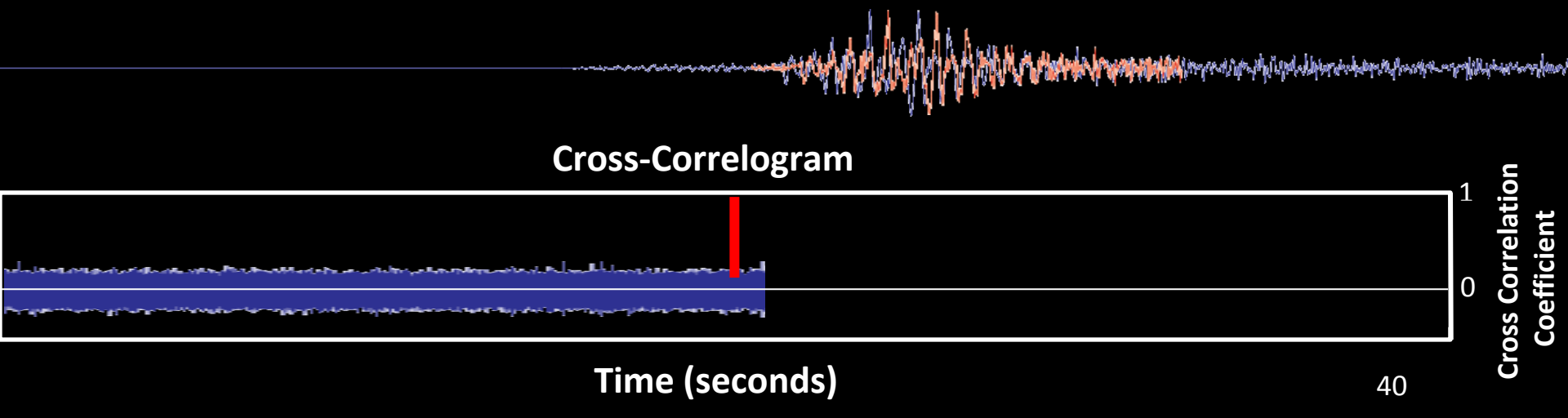
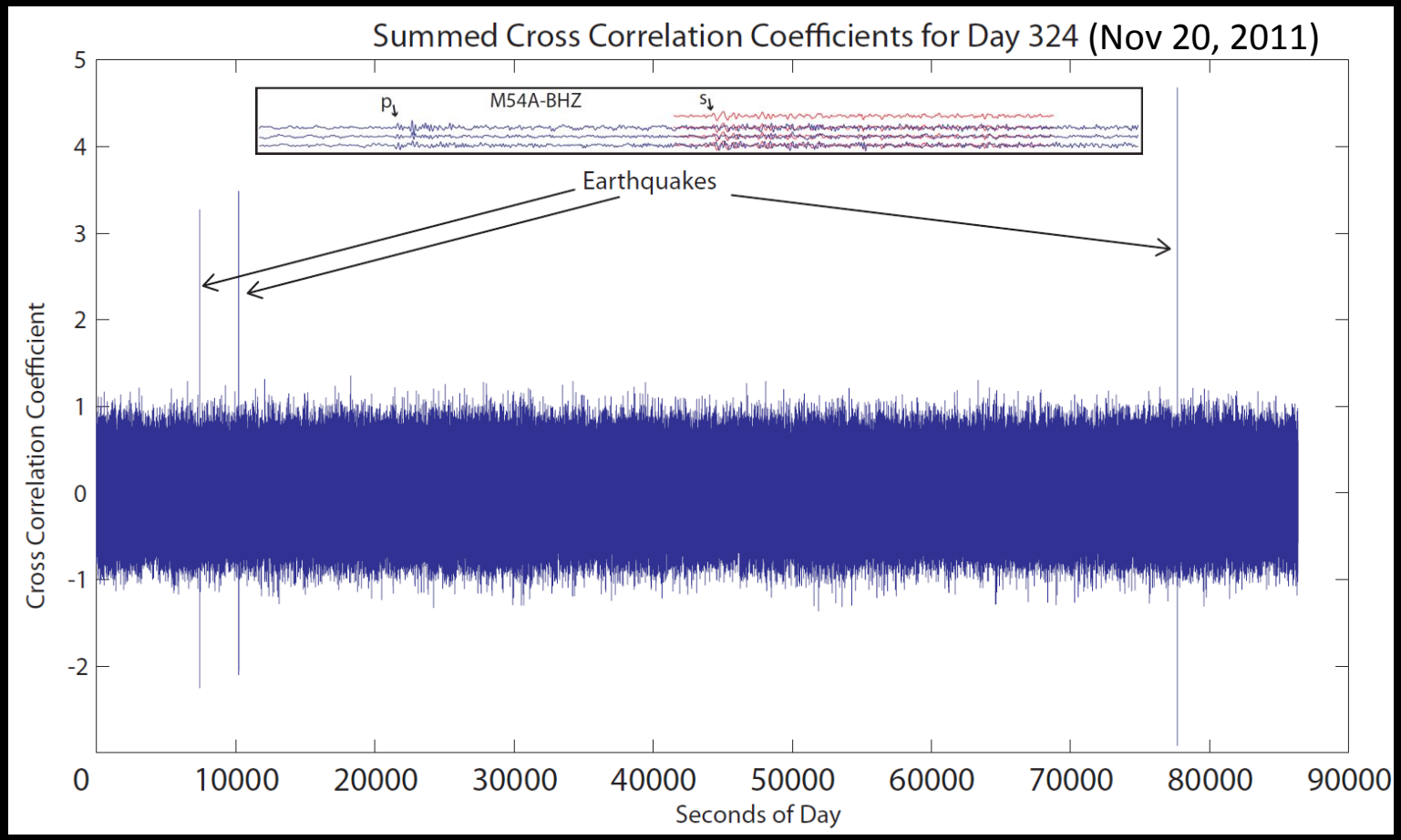
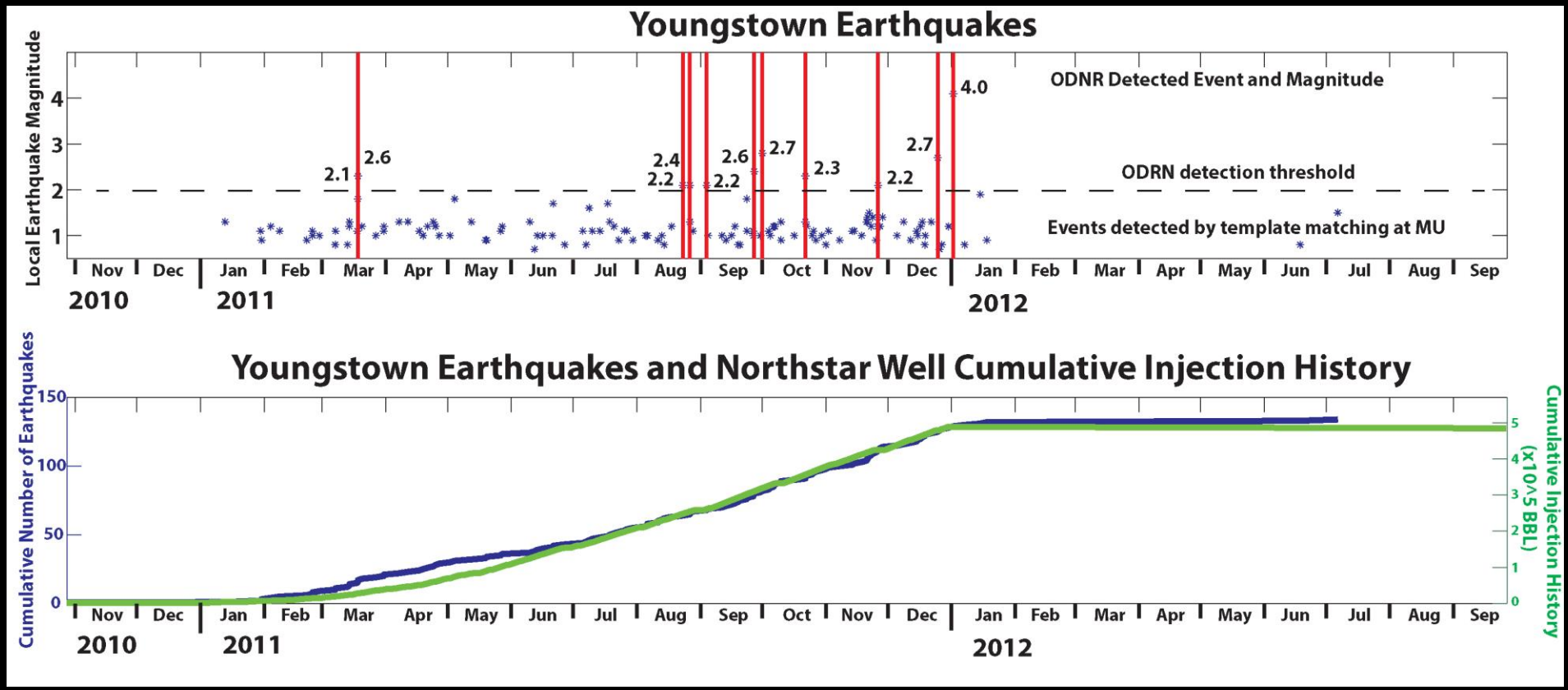


Template Matching Procedure

- **Step 3: Evaluate long time periods on data from different seismic stations and different channels**
  - **e.g., for one day, the cross correlation technique yields:**



Technique has identified >560 in the Youngstown example, the first of which occurred ~2 weeks after the initiation of injection



Hundreds of events matched below the ODNR detection threshold.

Rise in number and magnitude of seismicity as injection proceeded.

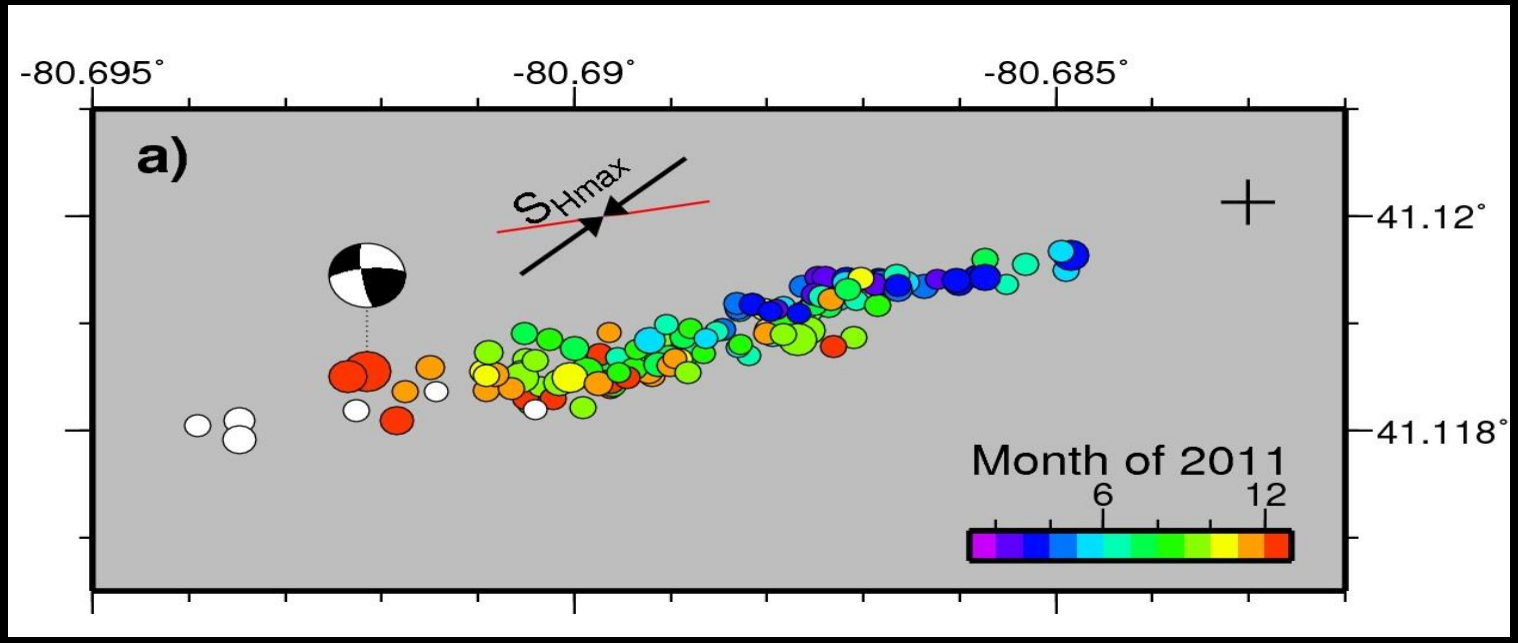
Extremely close correlation between injection volumes and seismic activity.

Youngstown Earthquake Locations

Located earthquakes plot <1 km from well and define E-NE oriented fault zone; Initiation of slip migrated to the SW over time.

Orientation consistent with the fault plane solution and is close to the optimal orientation for fault/fracture reactivation for the regional stress field.

Youngstown, 2010-12



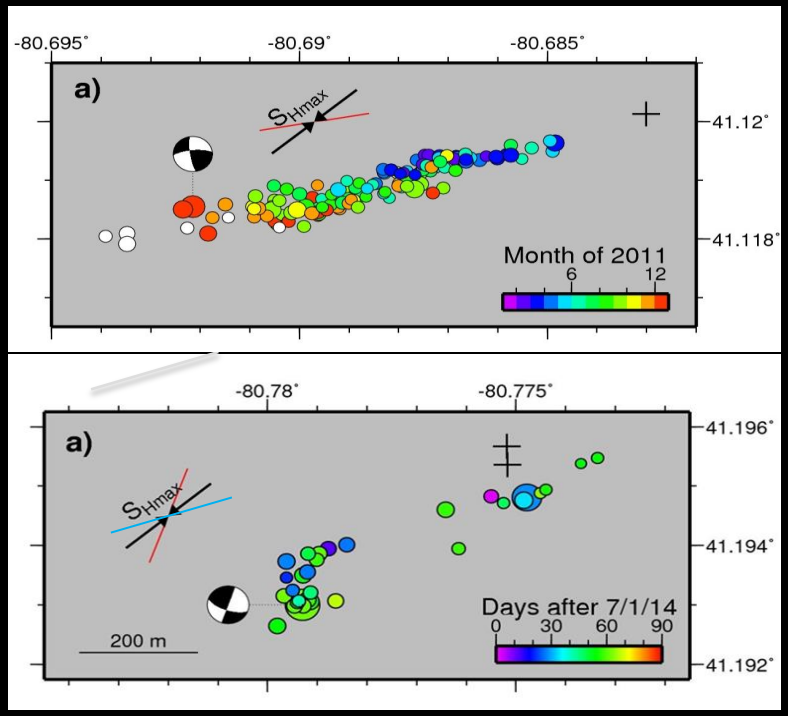
Wastewater Injection and Induced Seismicity: Conceptual Model

Injected fluids increase fluid pressure in pre-existing faults/fractures that have orientations optimal to the regional maximum horizontal stress (S_{Hmax}) orientation (~20°- 30° from S_{Hmax}).

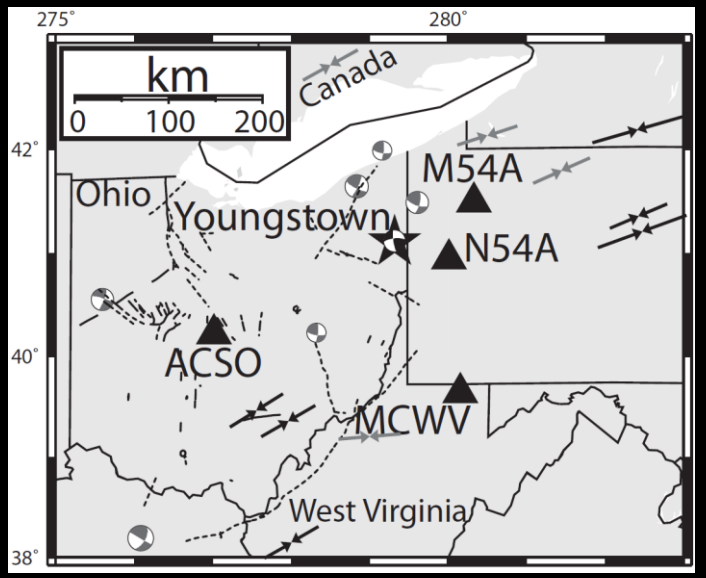
Increased pore-fluid pressure reduces effective normal stress acting on the fault-fracture surface allowing slip to occur.

Focal mechanisms from Youngstown and Trumbull Co. indicate near-vertical faults with strike- slip displacements.

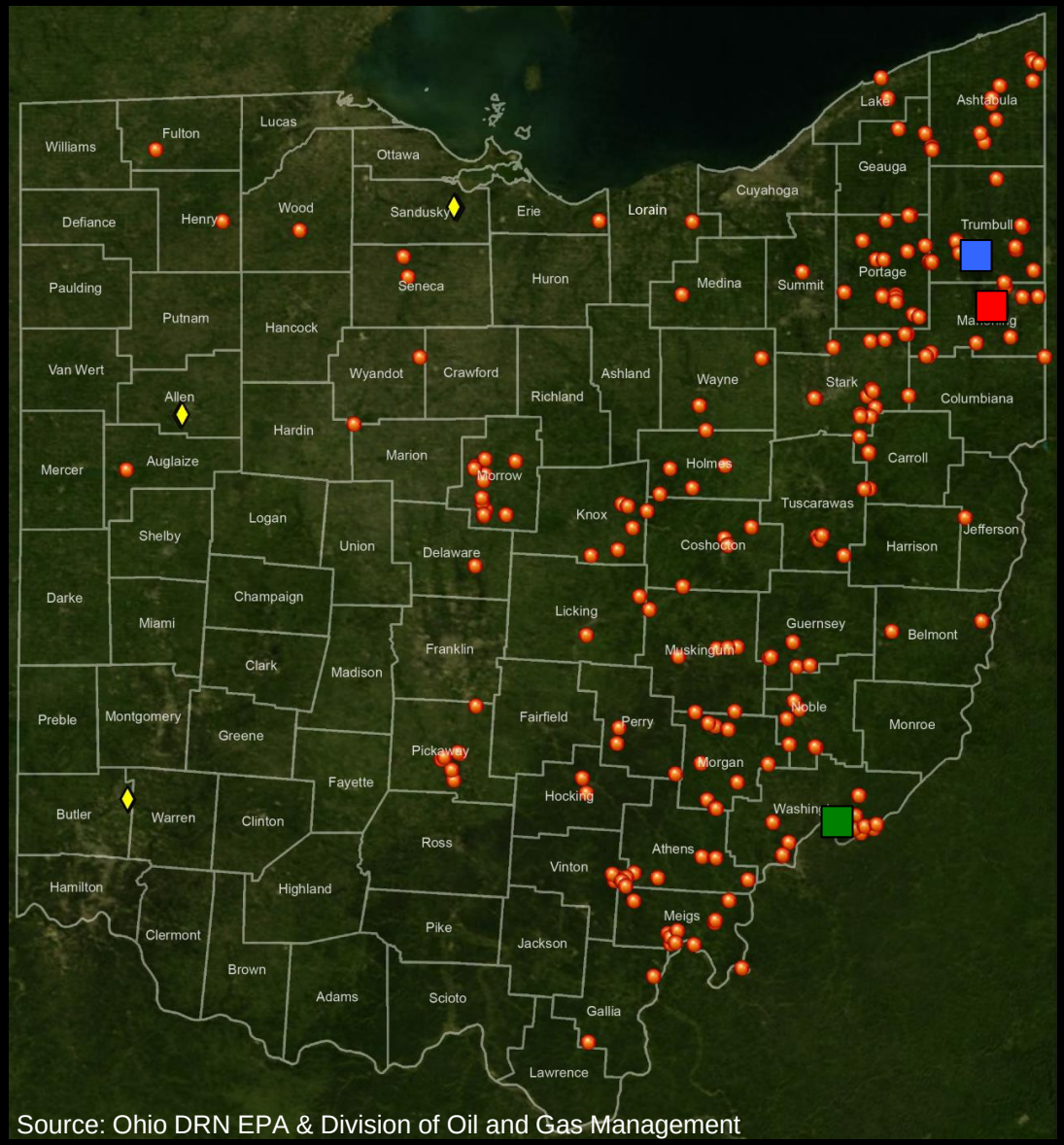
Youngstown 2010-12



Trumbull Co. 2014



Washington County Events

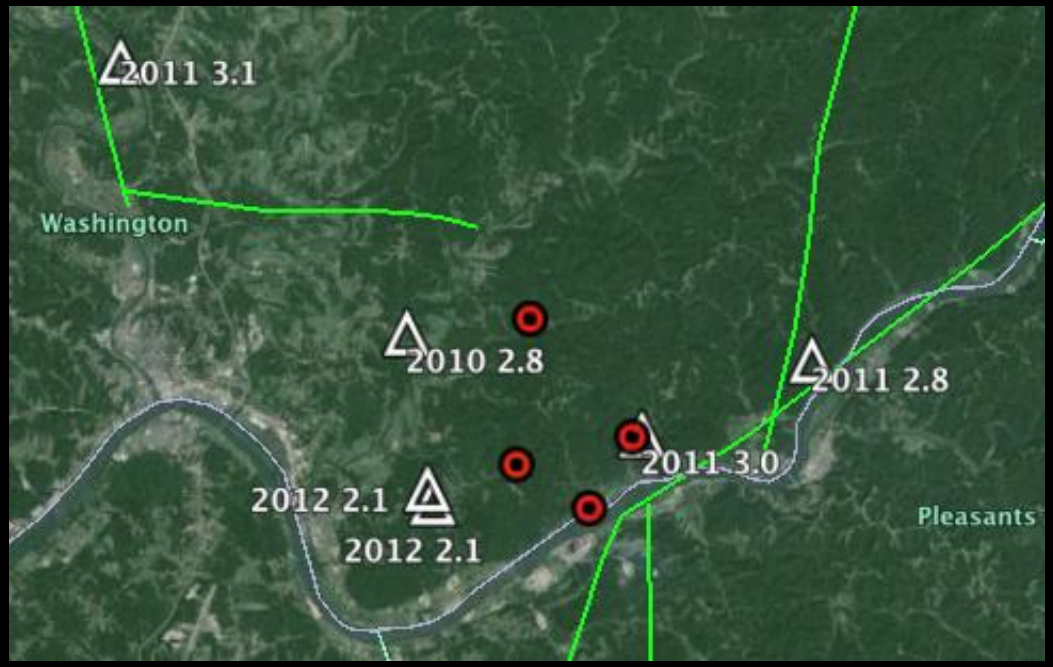


Source: Ohio DRN EPA & Division of Oil and Gas Management

Between 2010-12, six 3.1-2.1 M earthquakes were recorded near wastewater injection wells in Washington County, Ohio.

- Youngstown 2010-11
- Washington County 2010-12
- Trumbull County 2014

2010-2015 Washington County, SE Ohio Earthquake Sequence



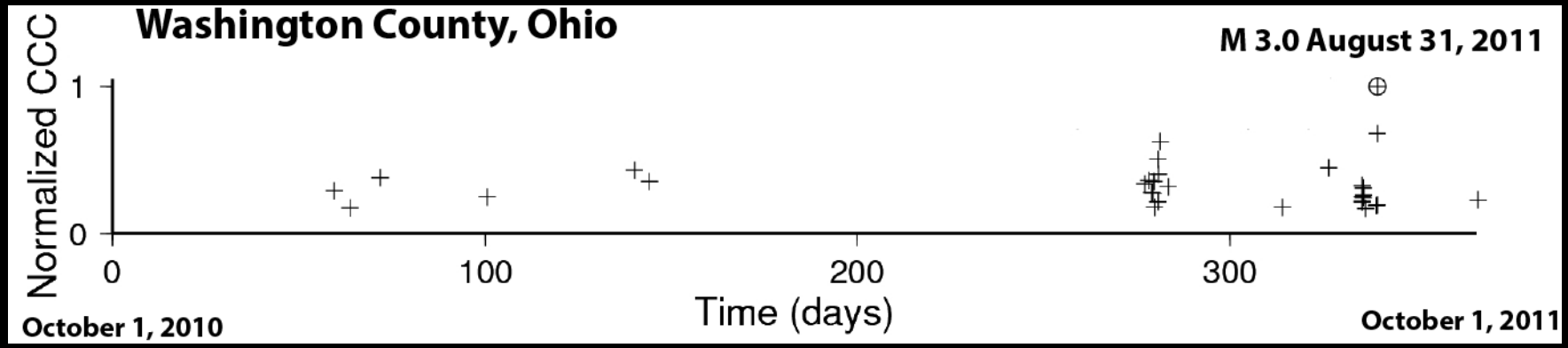
Wells injecting into Silurian strata

Area is near the intersection of 4 regional basement fault zones

Subsurface studies indicate most of these faults cut the injection interval

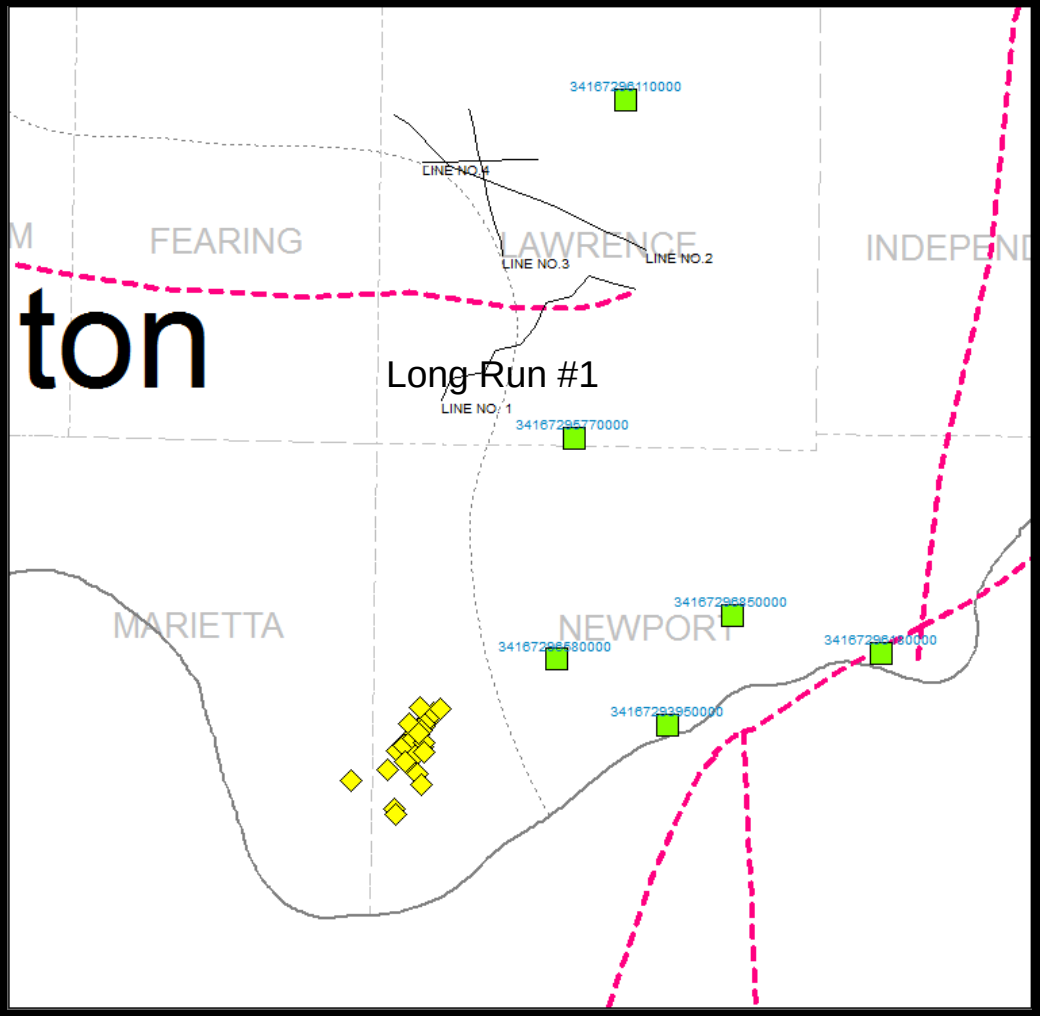
Initial earthquake locations from regional stations show earthquakes spread out.

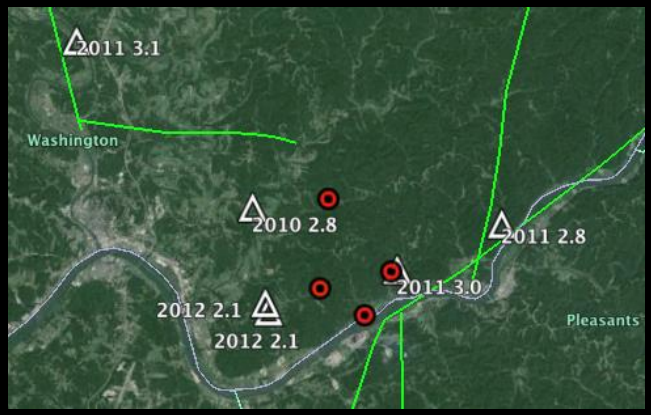
Initial template matching identified 33 <M 2.0 events prior to August 31, 2011 M 3.0 earthquake that occurred in areas close active injection well.



Washington County Events

When using a more detailed velocity model, earthquakes locations were clustered instead of spread out.





Relocated template-matched events indicate earthquakes occurred ~2 km SW of the Long Run # 1 injection well.

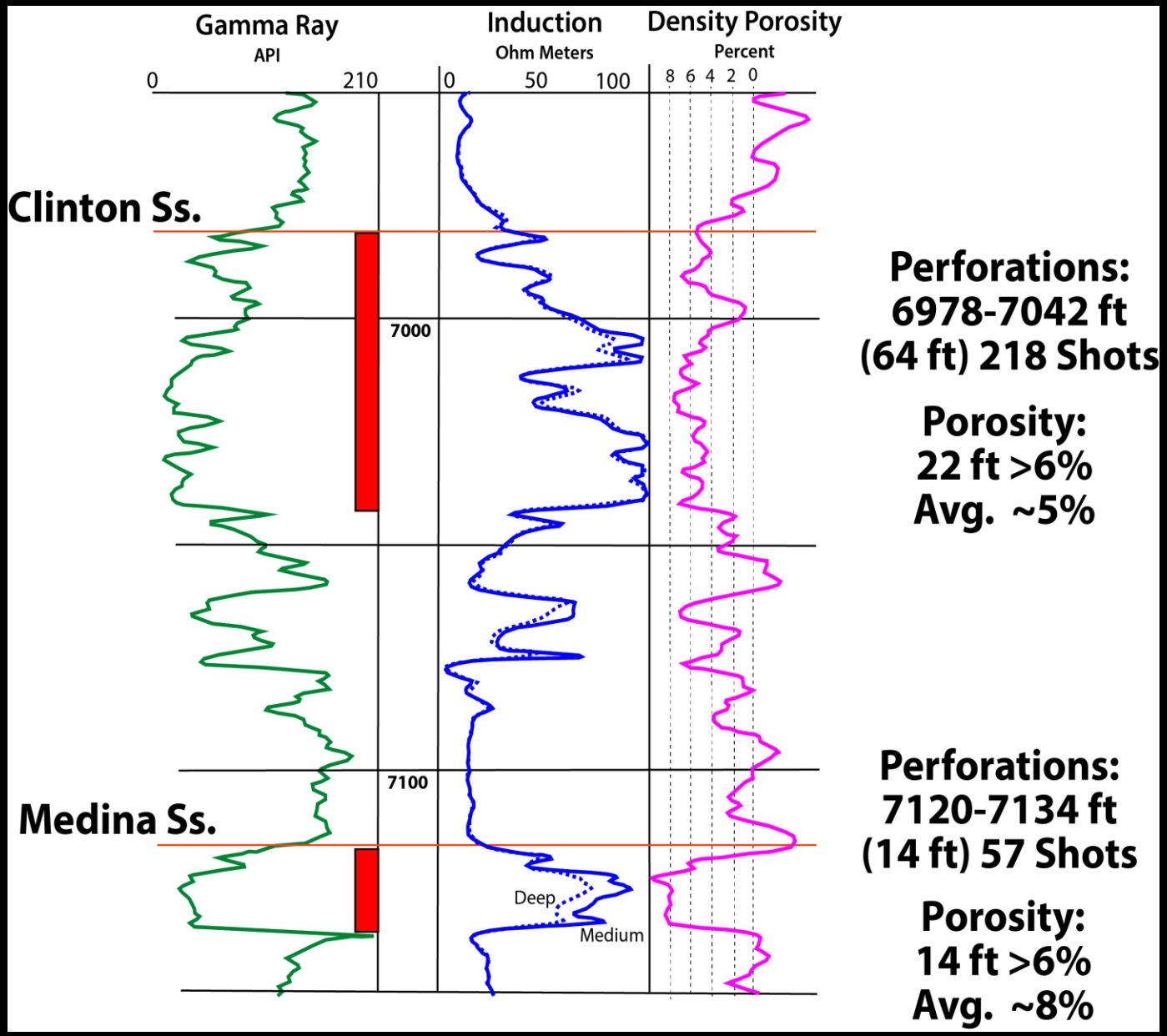
The Long Run # 1 Well began operations in 2008 and injects into the Silurian Clinton and Medina Formations

The well has since injected over 4 million barrels

Long Run #1 Well (Injection Interval)

Well was cased, perforated, hydraulically fractured, acid treated

Log porosity values in the injection interval average ~5% in the Clinton and ~8% in the Medina



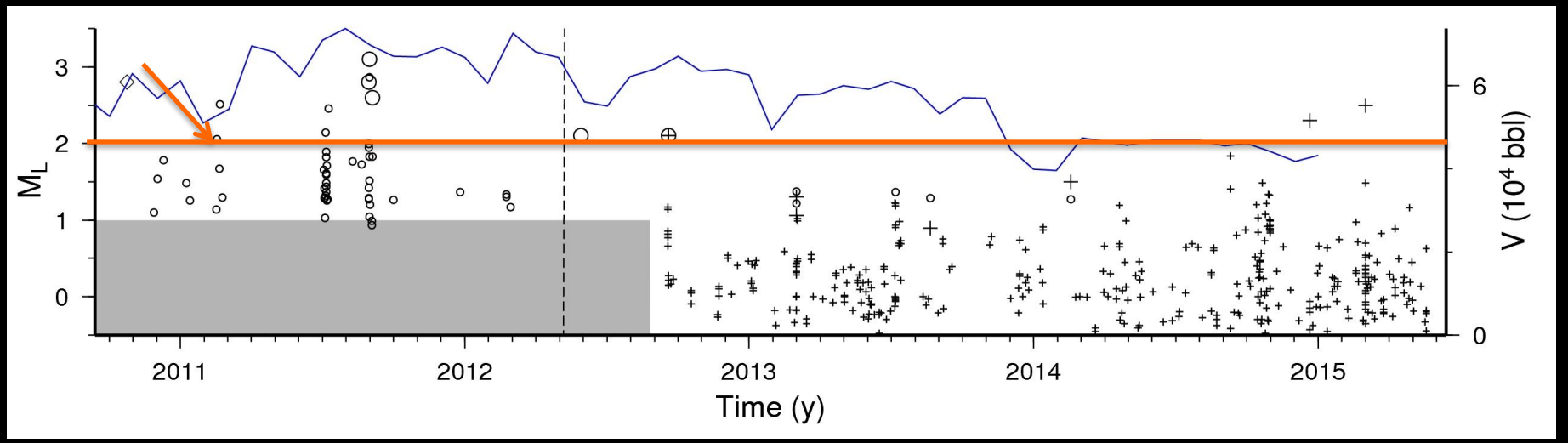
Perforations:
6978-7042 ft
(64 ft) 218 Shots

Porosity:
22 ft >6%
Avg. ~5%

Perforations:
7120-7134 ft
(14 ft) 57 Shots

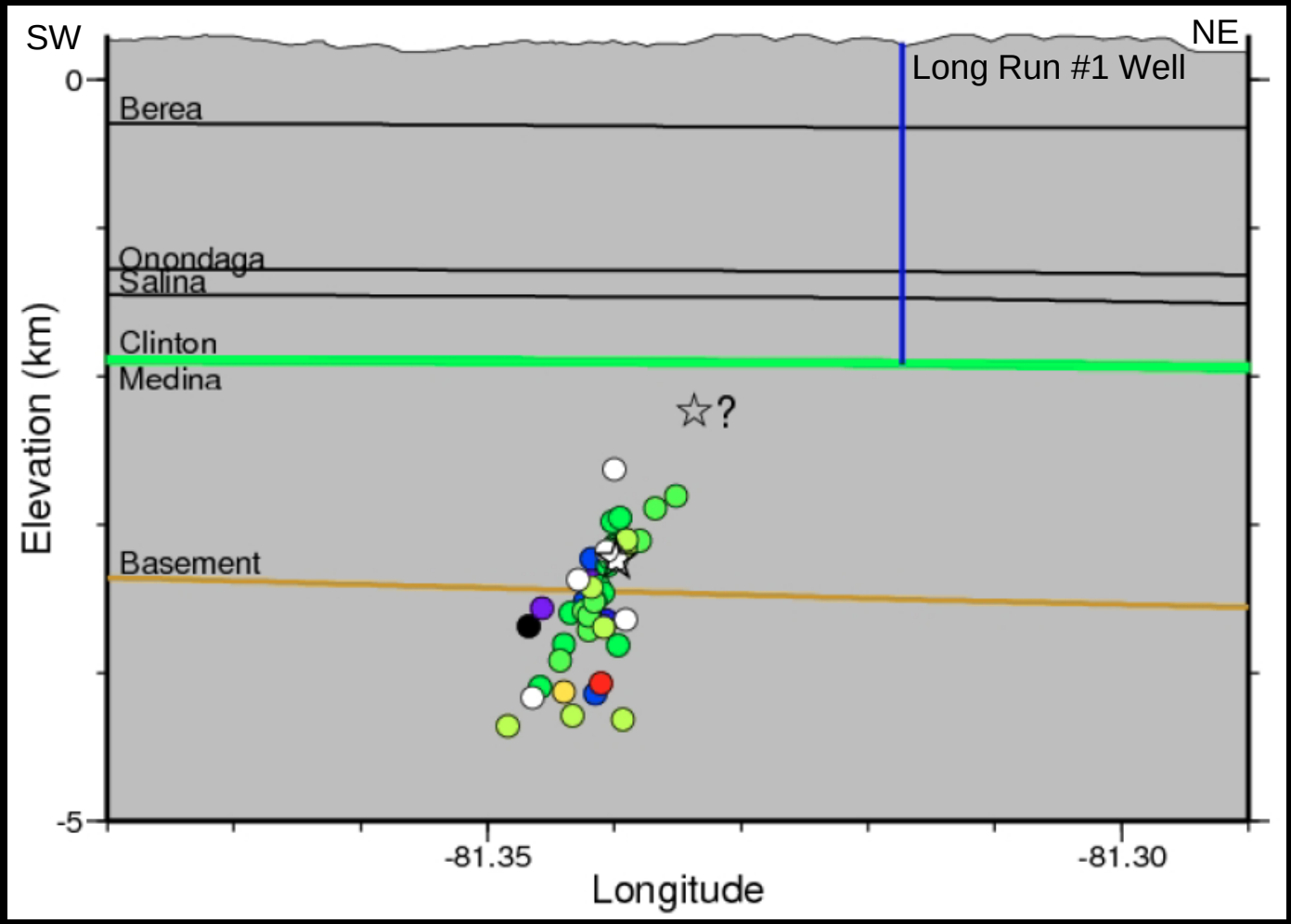
Porosity:
14 ft >6%
Avg. ~8%

Events vs Volume Injected



Subsequent analysis since 2012 yielded >300 template matched events.

Magnitude of recorded events initially decreased following the summer of 2011 >2.0 M events, but has increased in the past year with two events with a magnitude >2.0.



Relocated events are centered close to the contact between the Precambrian crystalline basement and overlying lower Paleozoic sedimentary rocks.

Data from deep wells show little structure, so further investigation was necessary.

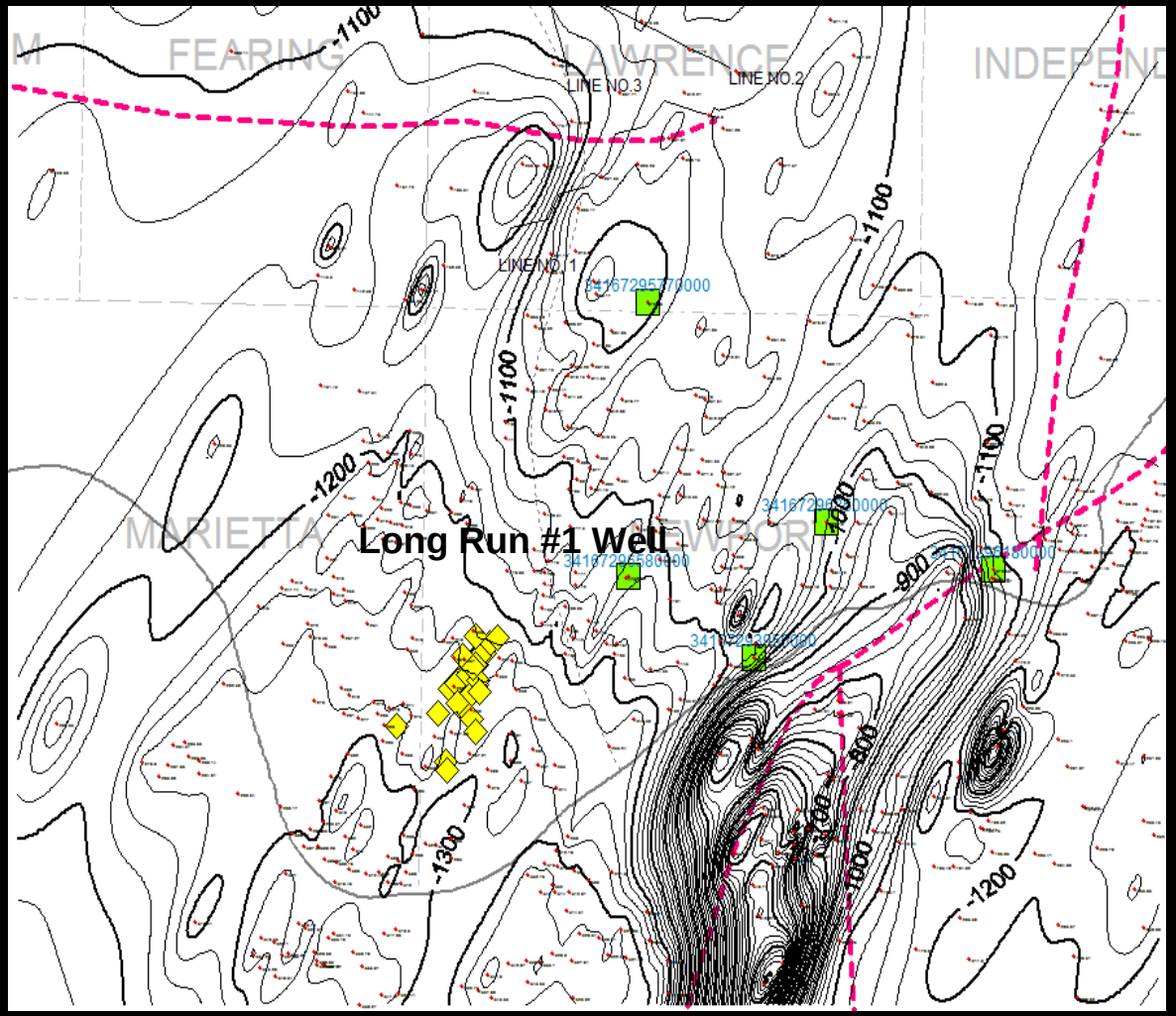
Relationships between seismicity and existing structure

Structure contour maps of stratigraphic horizons in Paleozoic strata were constructed to identify existing structures in the area of recorded seismicity.

Maps were generated from identified and reported formation tops from > 600 nearby oil and gas wells in Ohio and West Virginia.

Relationships between seismicity and existing structure

Upper Devonian Berea Sandstone Structure Map



Contour mapping has identified numerous NE-SW trending, low-amplitude folds.

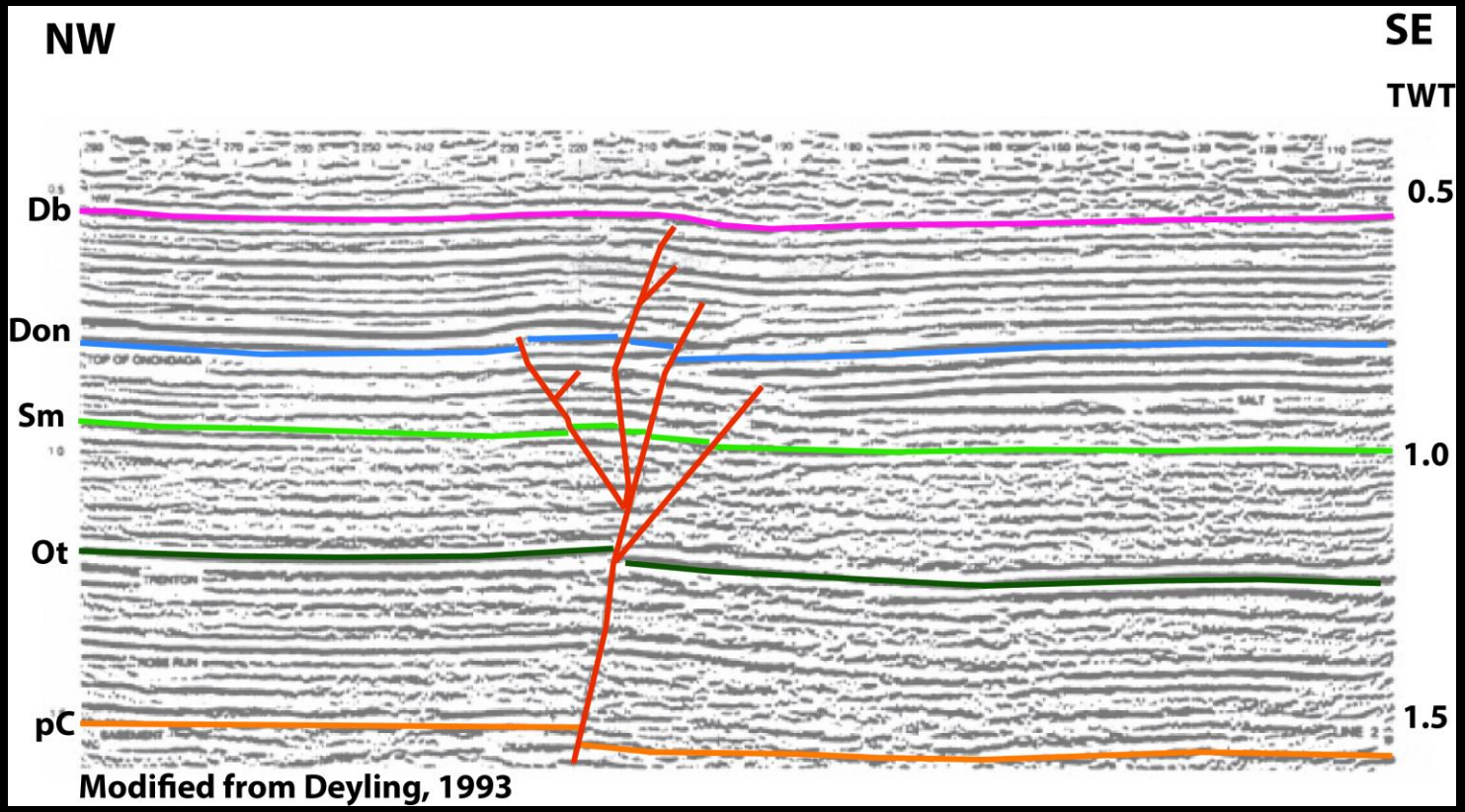
Structures persist down strata.

25 foot contour interval.

◆ Template Matches 2011-2012

■ Local Wastewater Injection Wells

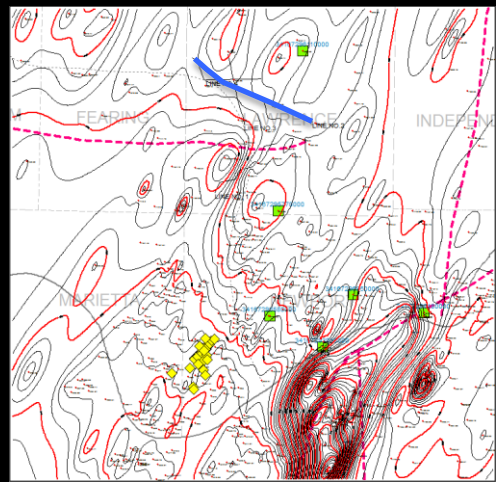
Relationships between seismicity and existing structure



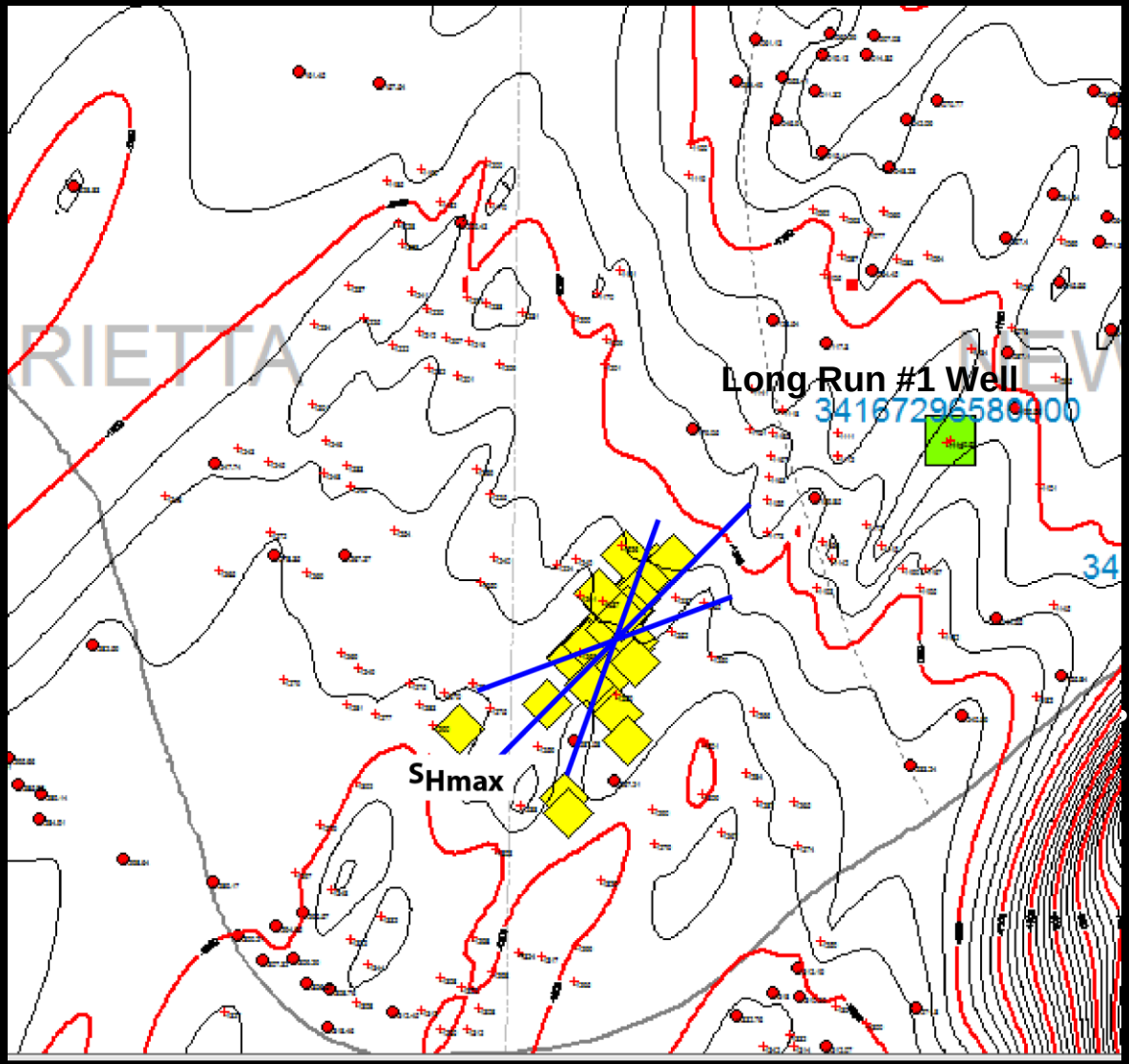
Mapped folds are similar to those interpreted from nearby reflection-seismic lines.

Folds are related to possible wrench faults originating in the basement and tipping out in Upper Paleozoic strata.

These faults likely have similar trends to the mapped folds and cut the injection interval which could provide a permeability pathway.



Regional Stress Regime



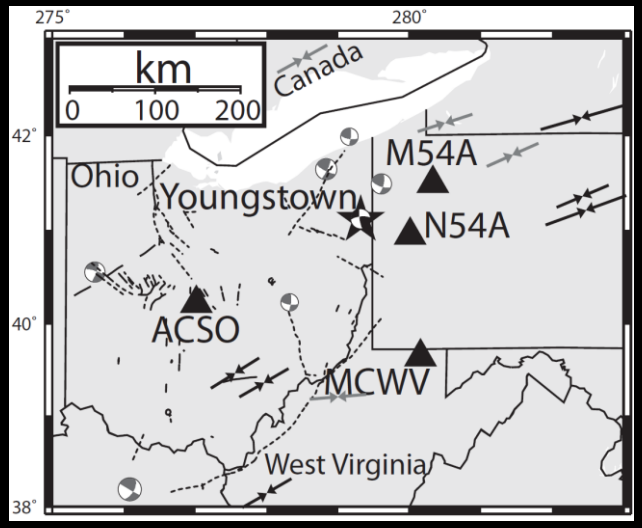
The regional stress regime of Washington County has its greatest horizontal stress direction (σ_1) oriented at roughly N55°E.

Due to the orientation of the σ_1, there is a preferential orientation within 20-30° on either side of σ_1 that is optimal for fault/fracture reactivation.

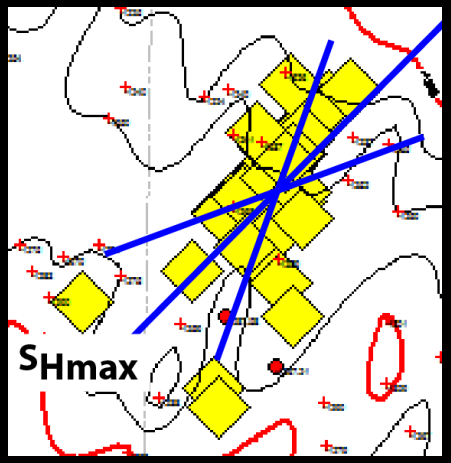
Located events cluster along a mean orientation of 025° that is the window of orientations optimal for fault-fracture reactivation

Estimated in-situ stress orientations at depth in the Appalachian basin indicate a horizontal σ_1 and σ_3, and a vertical σ_2.

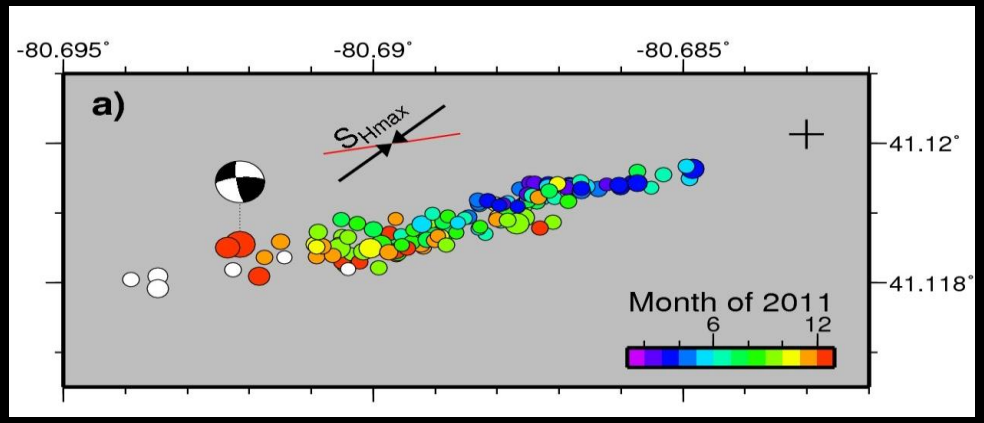
The fault mechanics of a system with these characteristics would be strike slip, consistent with calculated earthquake focal mechanisms from other induced events in Ohio.



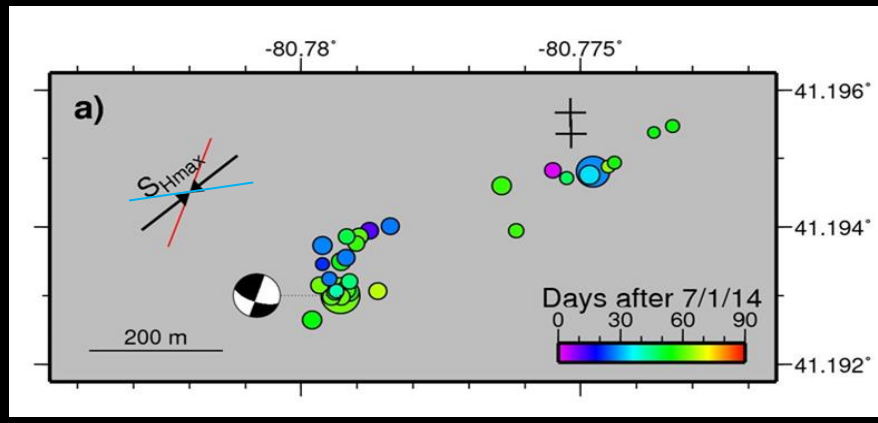
Washington Co.



We haven't been able to determine the focal mechanisms in Washington Co., but the seismicity is similar to Trumbull Co. and Youngstown where the focal mechanisms were strike slip.



Youngstown, 2010-12



Trumbull Co. 2014

Conclusions

Template matching has identified >300 events in close proximity to the Long Run #1 injection well in Washington County, Ohio

Recorded seismicity is associated with the NE trending Late Paleozoic Structures.

The presence of the faults cutting the injection interval could provide a mechanism for increasing pore-fluid pressures in pre-existing fault/fracture zones.

The alignment of the structures with the regional stress field is optimal for fault-fracture reactivation and similar to other injection-induced events in Ohio.

Acknowledgements

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Ohio Environmental Protection Agency

American Water Management Services
LMKR