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Seismicity During the First Three Months of the Guy-Greenbrier, Arkansas, Earthquake Sequence

Gregory Beroza[1] (beroza@stanford.edu), Yihe Huang[1,2], William Ellsworth[1], Clara Yoon[1] (ceyoon@stanford.edu)
[1]*Department of Geophysics, Stanford University;* [2]*Department of Earth and Environmental Sciences, University of Michigan*

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Most microearthquakes (-1.5 < M_L < 2.9) during first 3 months of the Guy-Greenbrier sequence were induced by hydraulic fracturing at some but not all stimulated production wells

Lower levels of seismicity (M_L < 1) initiated along the Guy-Greenbrier Fault soon after wastewater injection started in July 2010

Earthquake monitoring with low-magnitude detection thresholds and precise locations, even with a sparse 3-station seismic network, provides new insights into previously unknown sources of induced seismicity

Introduction

Background

- This earthquake sequence started propagating along the previously unknown Guy-Greenbrier Fault in July 2010, following wastewater injection at nearby disposal well #1, and lasted until October 2011, several months after injection stopped *(Horton, 2012, SRL; Ogwari et al., 2016, SRL)*
- Largest earthquake in sequence: M 4.7 on 2011-02-27

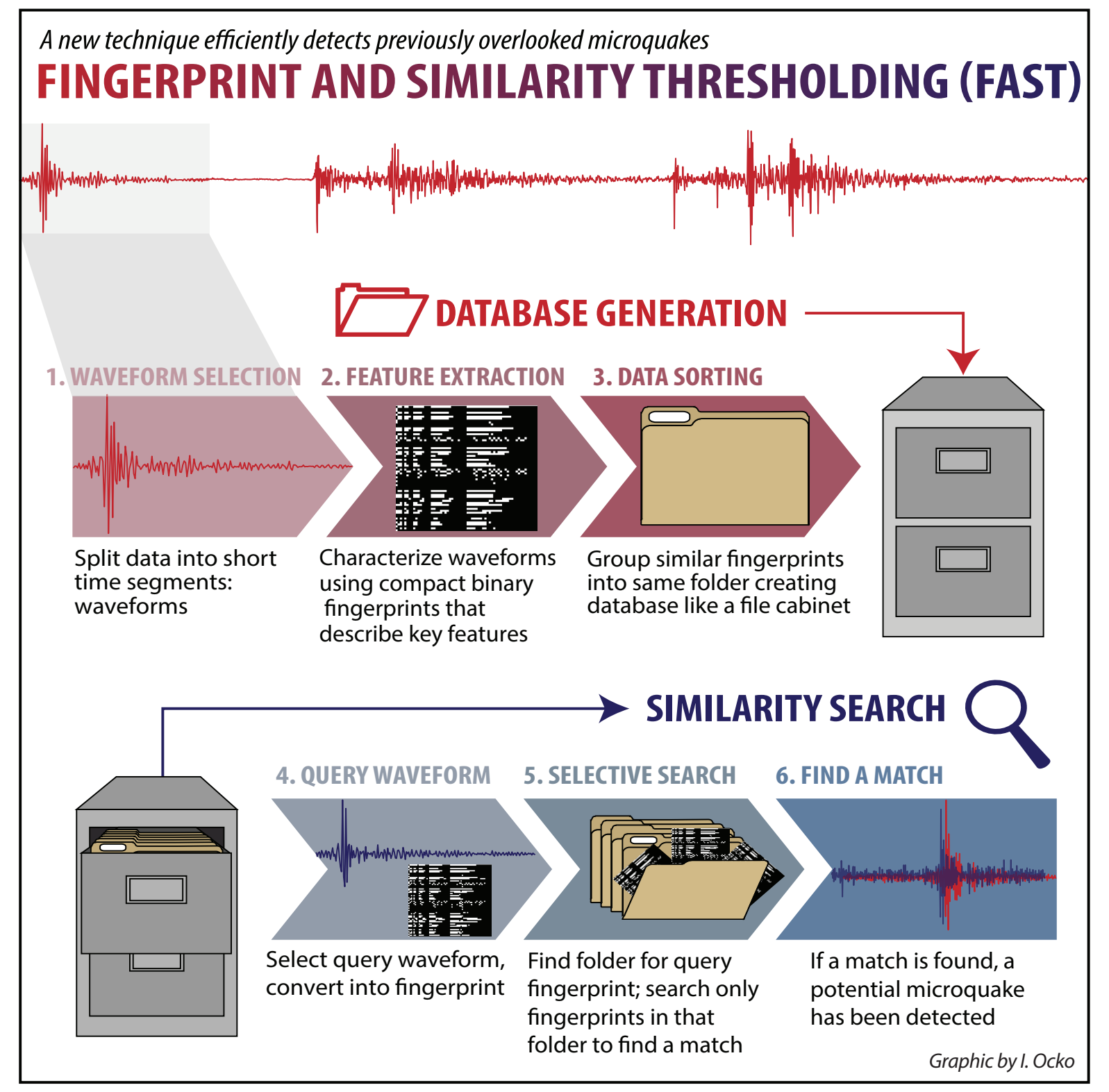
Research Questions

- Were the Guy-Greenbrier earthquakes induced by unconventional hydrocarbon exploitation?
- How does a potentially induced earthquake sequence begin and evolve in its earliest stages?

Approach

- Detect and locate small earthquakes during first 3 months of the swarm (2010-06-01 to 2010-09-01), before and after earthquakes began in July 2010
- Examine spatial and temporal correlations between seismicity, wastewater injection, and hydraulic fracturing stimulation at production wells

Method: Earthquake Detection


A new technique efficiently detects previously overlooked microquakes

FINGERPRINT AND SIMILARITY THRESHOLDING (FAST)

DATABASE GENERATION

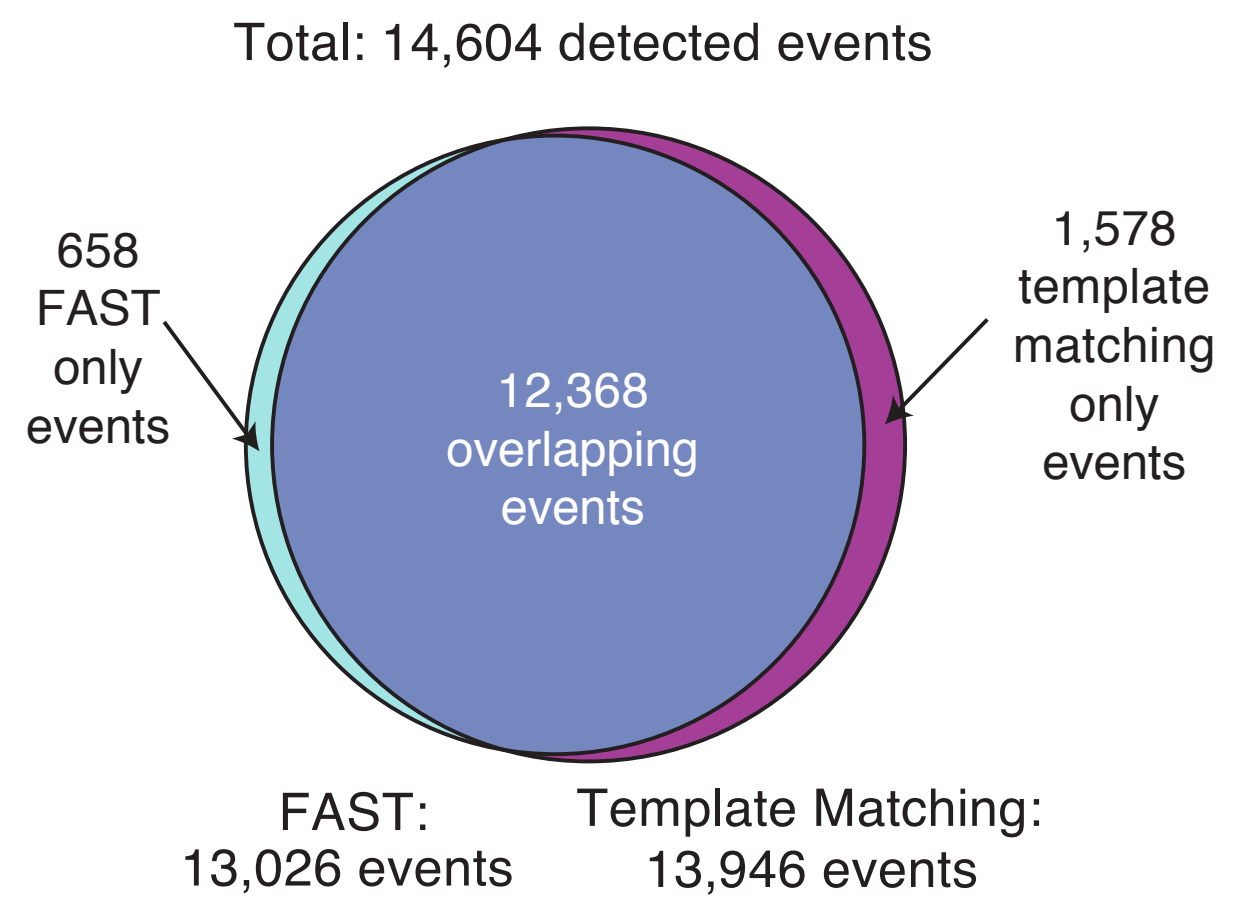
1. WAVEFORM SELECTION: Split data into short time segments: waveforms
2. FEATURE EXTRACTION: Characterize waveforms using compact binary fingerprints that describe key features
3. DATA SORTING: Group similar fingerprints into same folder creating database like a file cabinet

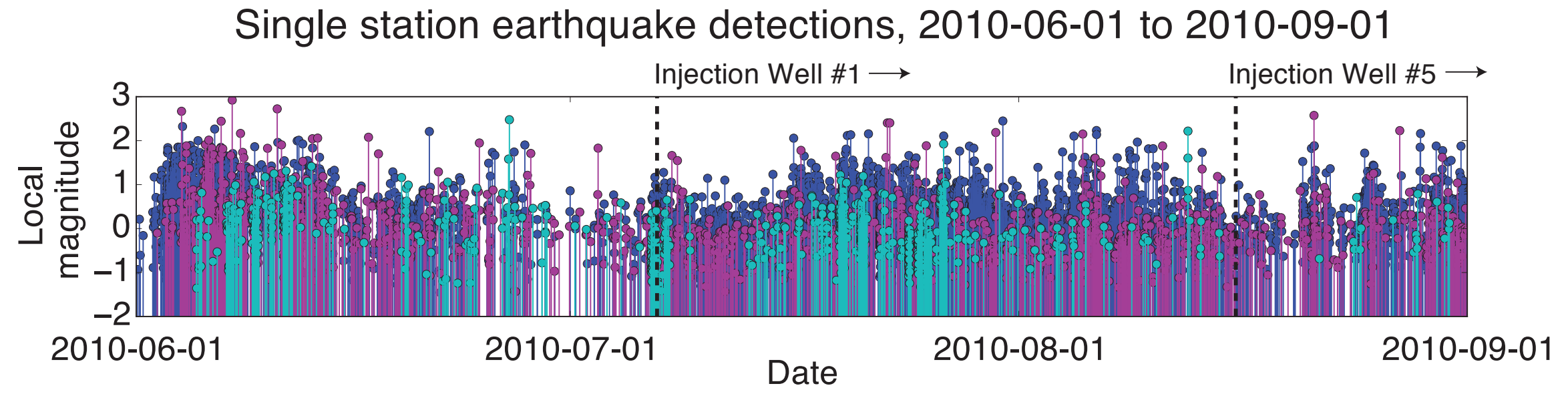
SIMILARITY SEARCH

4. QUERY WAVEFORM: Select query waveform, convert into fingerprint
5. SELECTIVE SEARCH: Find folder for query fingerprint; search only fingerprints in that folder to find a match
6. FIND A MATCH: If a match is found, a potential microquake has been detected

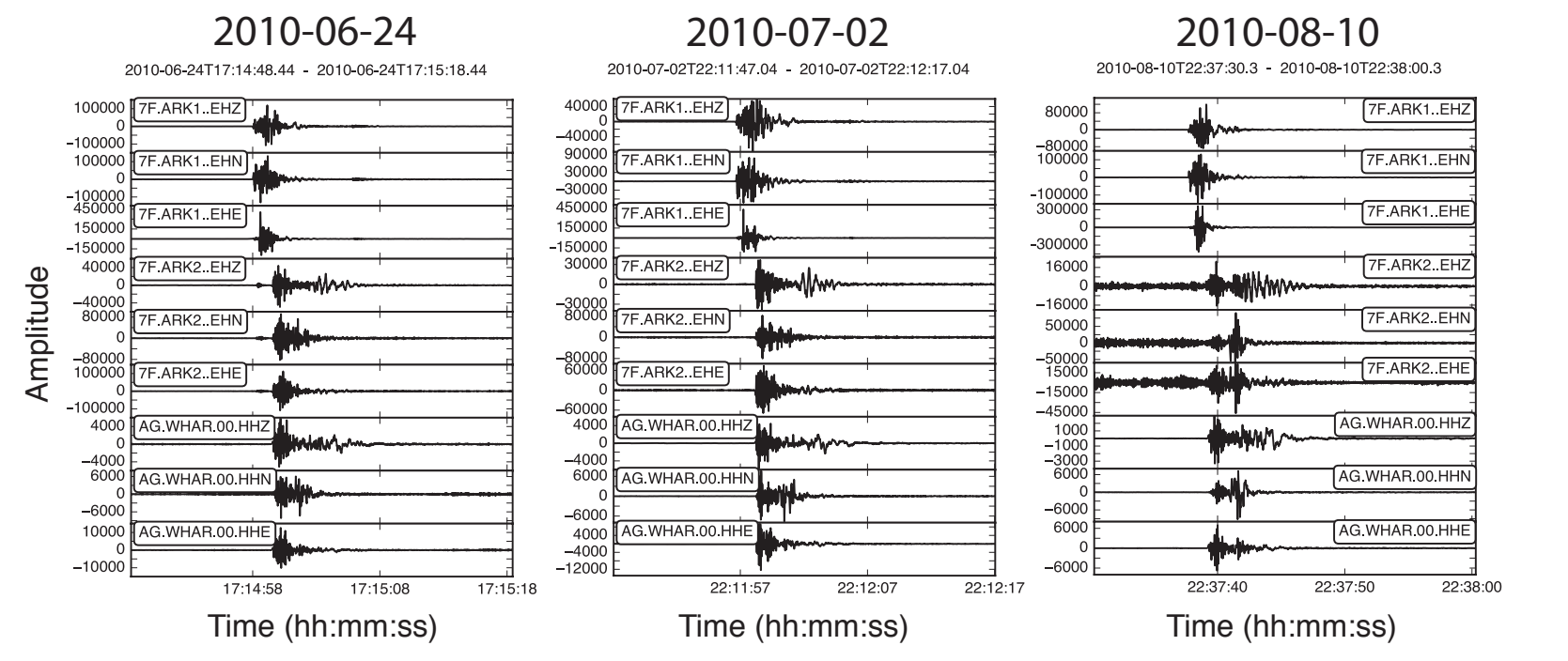
Graphic by I. Ocko

- FAST algorithm (*Yoon et al., 2015, Sci. Adv.*) enables comprehensive, sensitive, efficient detection of low-magnitude earthquakes with similar waveforms, in continuous seismic data at a single 3-component station WHAR
- Compared events detected by FAST to events detected by template matching (*Huang and Beroza, 2015, GRL*)


Total: 14,604 detected events

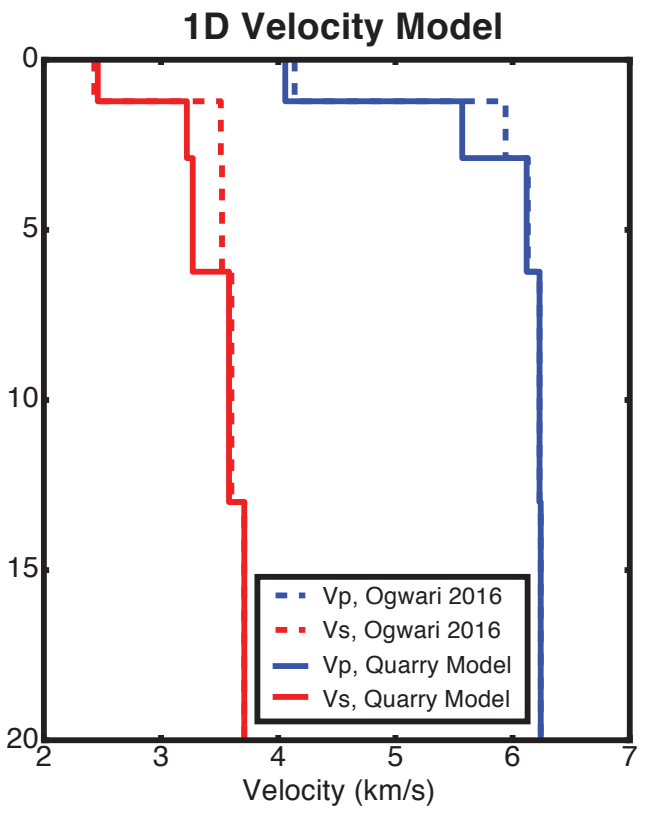

Single station earthquake detections, 2010-06-01 to 2010-09-01

Method: Earthquake Location



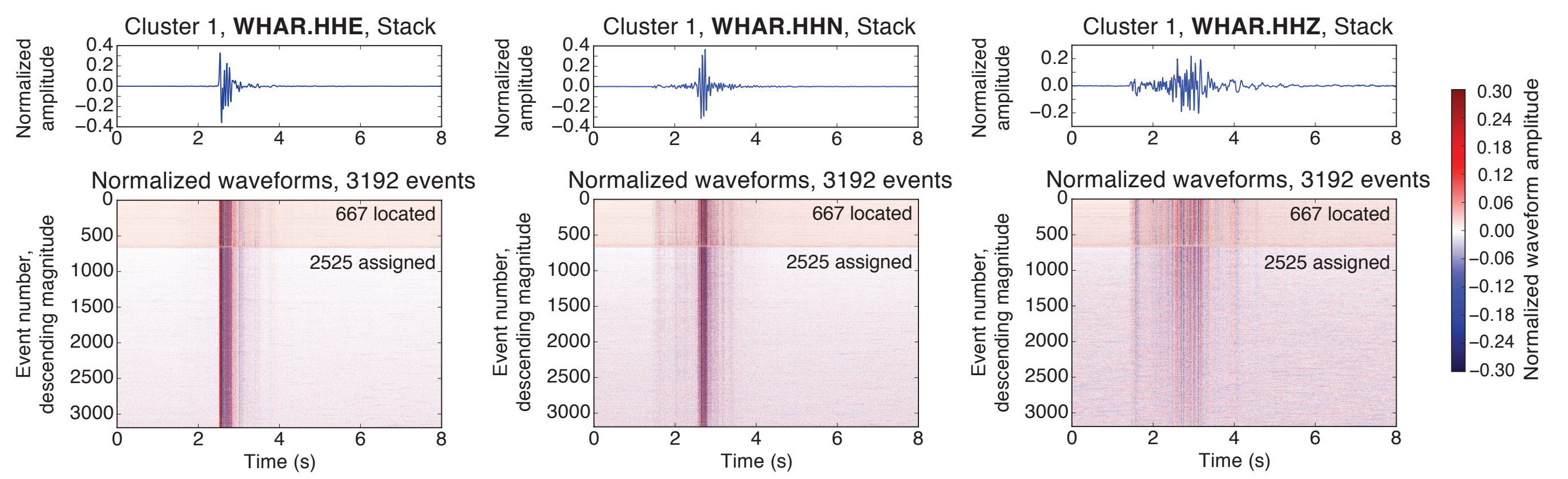

Quarry, 2009-07-23

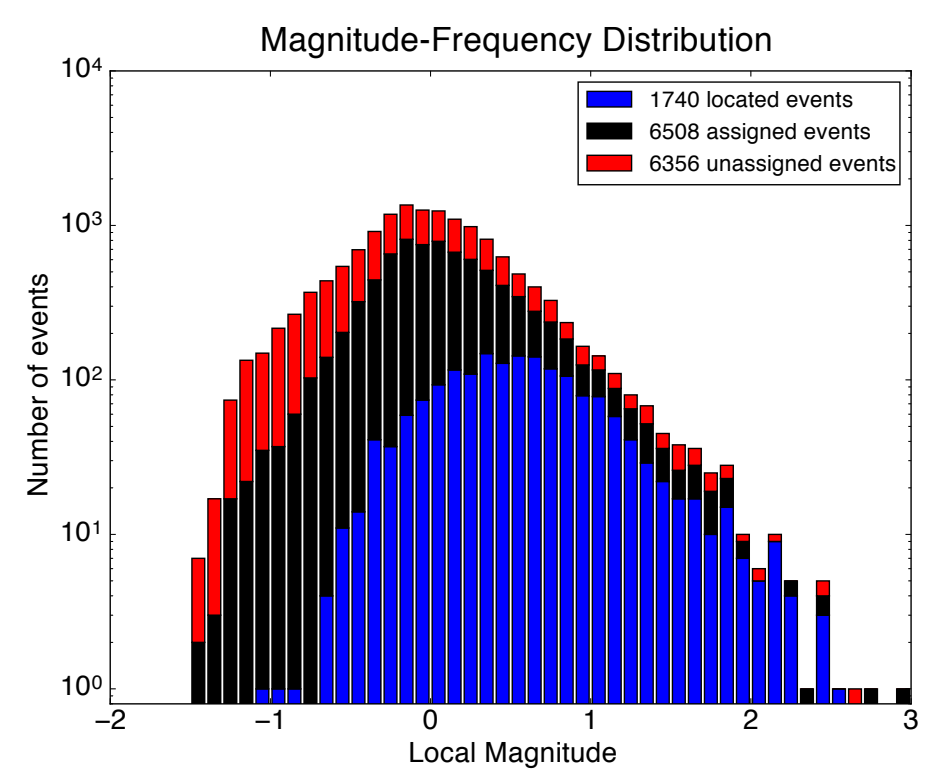

Quarry, 2010-09-15


1D Velocity Model

- Detected 3 quarry blasts with similar waveforms from 2010-06-24, 2010-07-02, 2010-08-10, then identified location on Google Earth satellite images
- Refined existing 1D velocity model (*Ogwari et al., 2016, SRL*) with ground truth from surface quarry blast location
- Picked P, S phase arrivals at 3 stations: WHAR, ARK1, ARK2
- Inverted for initial locations with VELEST (*Kissling et al., 1994, JGR*)
- Refined locations with hypoDD (*Waldhauser and Ellsworth, 2000, BSSA*): differential travel times between event pairs from P, S arrival picks, and cross-correlation
- **Located 1,740 events**: -1.1 < M_L < 2.5

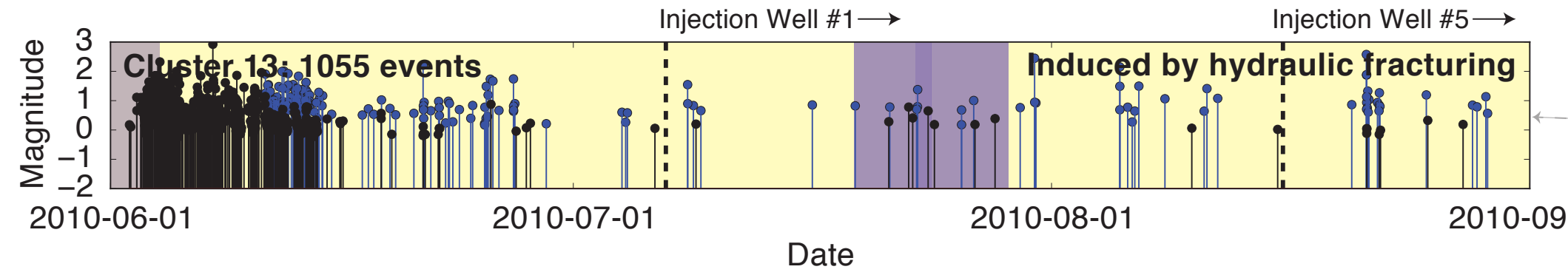
Method: Assign Earthquakes to Clusters

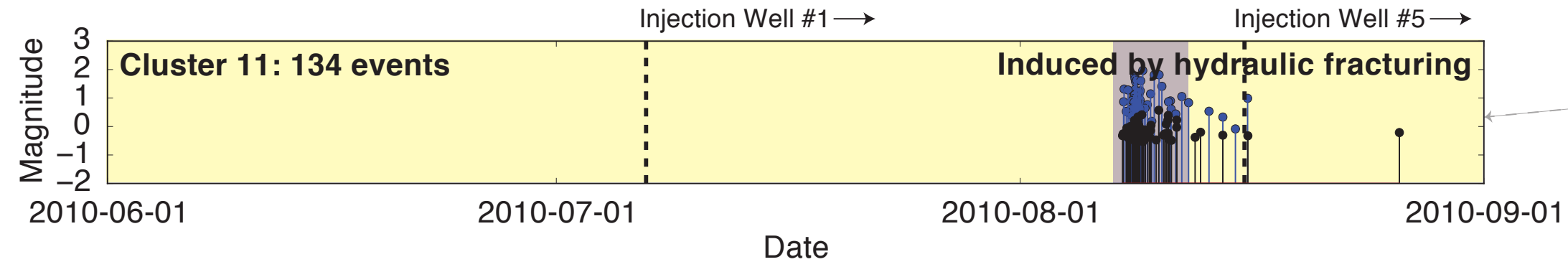


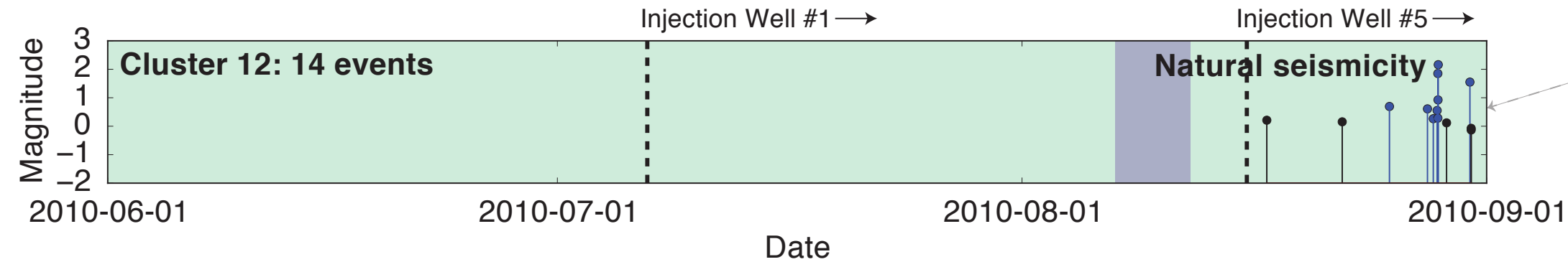

Magnitude-Frequency Distribution

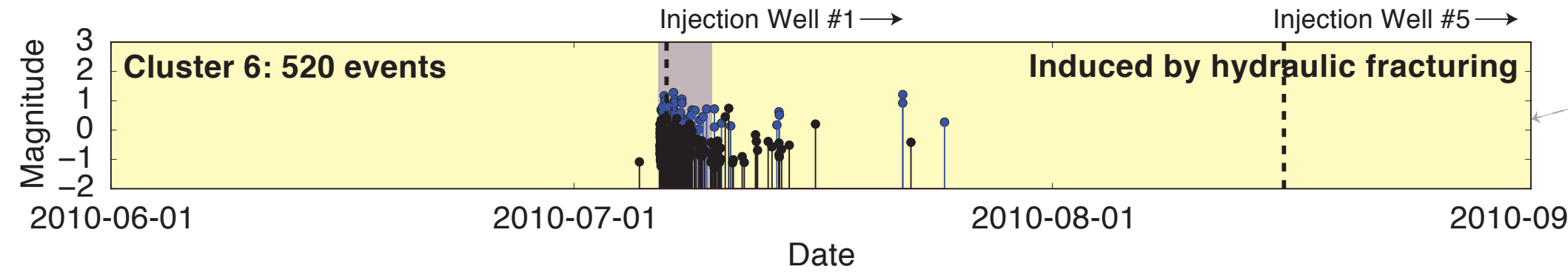
- **Improved temporal resolution of earthquake sequence**: assigned unlocated events to existing earthquake clusters based on waveform similarity at station WHAR
- Stacked all located event waveforms in each cluster to form a representative "stack" waveform
- Cross-correlated each unlocated event waveform with the "stack" waveform from each cluster, then assigned unlocated event to cluster with highest correlation above an empirical threshold
- **Assigned 6,508 events**: -1.5 < M_L < 2.9

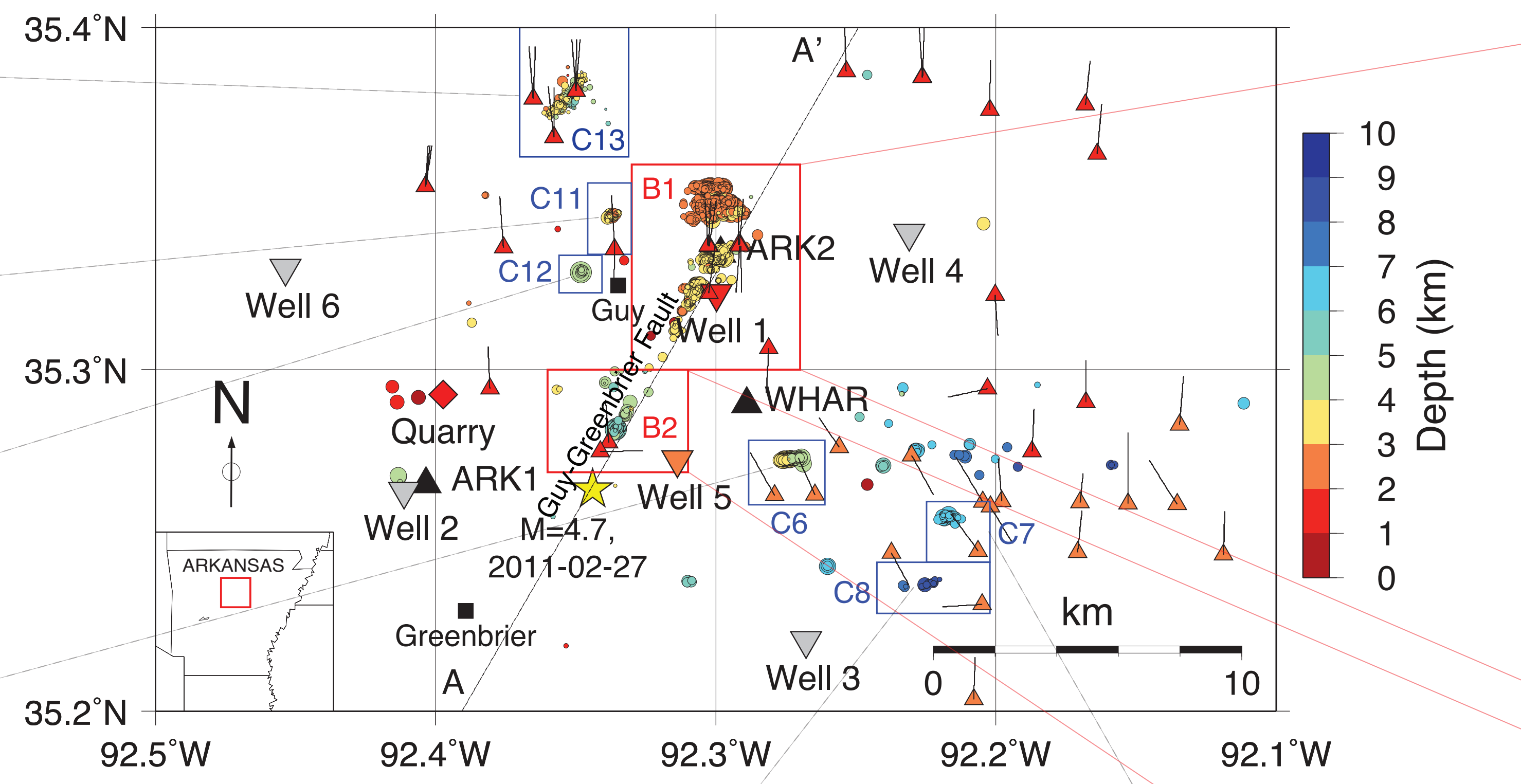
Results: Most microearthquakes (-1.5 < M_L < 2.9) during first 3 months of the Guy-Greenbrier sequence were induced by hydraulic fracturing; we also identified initial seismicity on the Guy-Greenbrier Fault induced by wastewater injection starting in July 2010









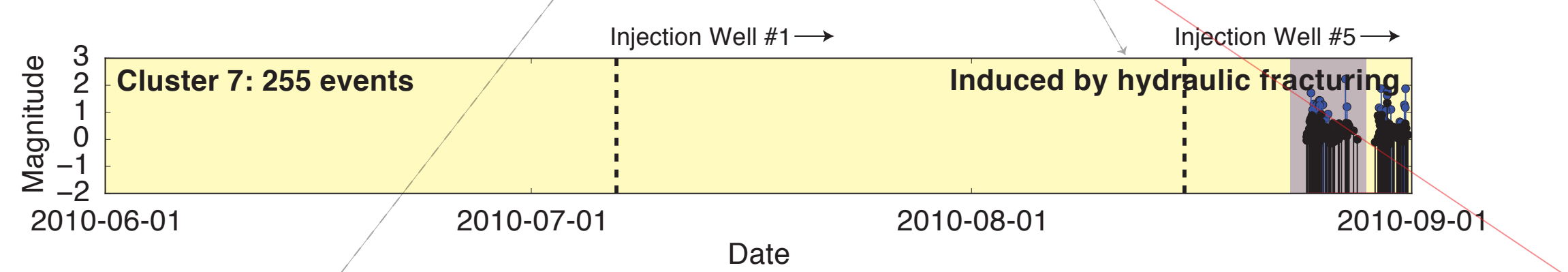


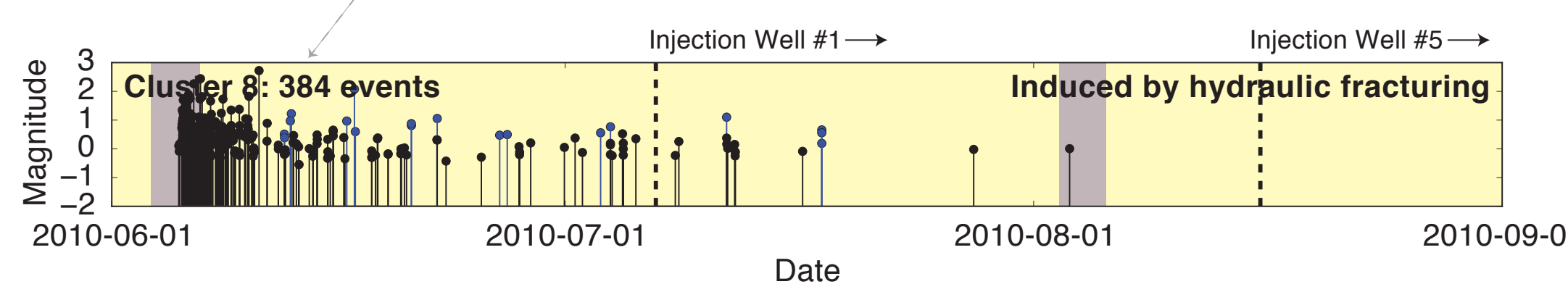
Natural background seismicity may be scattered throughout region, which is known to have natural earthquakes: 1982 and 2001 Enola swarms (*Chiu et al., 1984, BSSA; Rabak et al., 2010, SRL*)

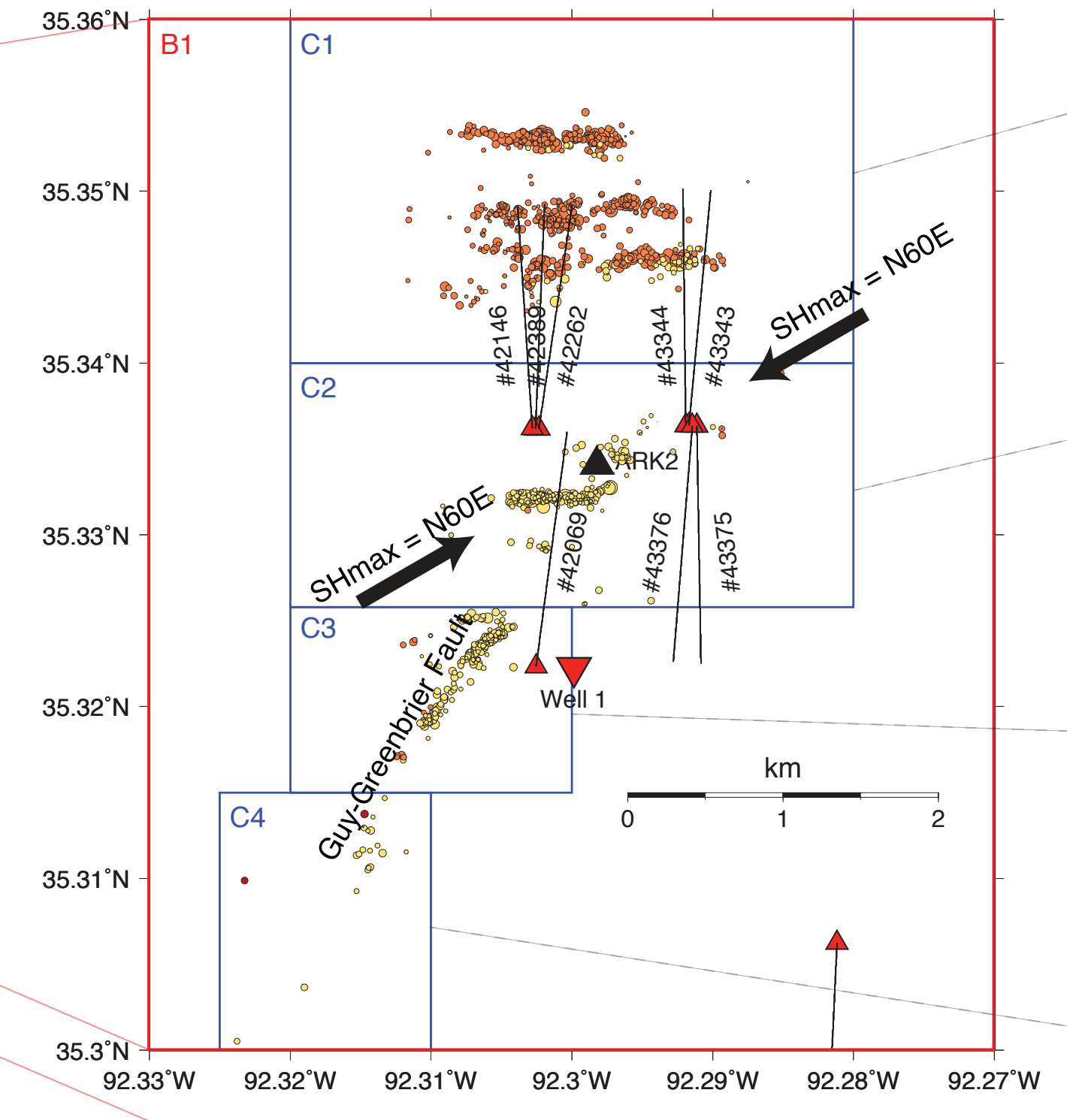
Earthquake depths are poorly constrained due to sparse seismic network with only 3 stations, and strongly depend on choice of velocity model

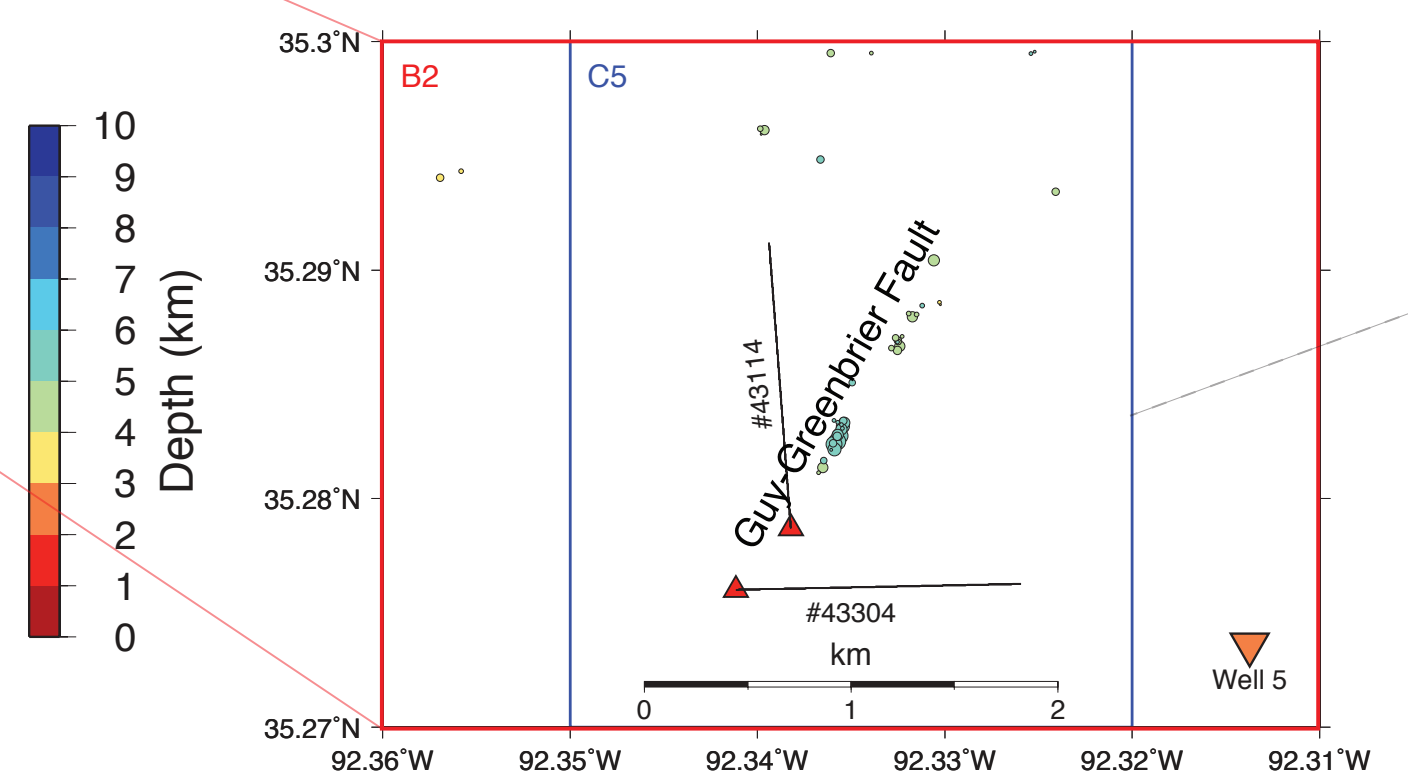
Legend

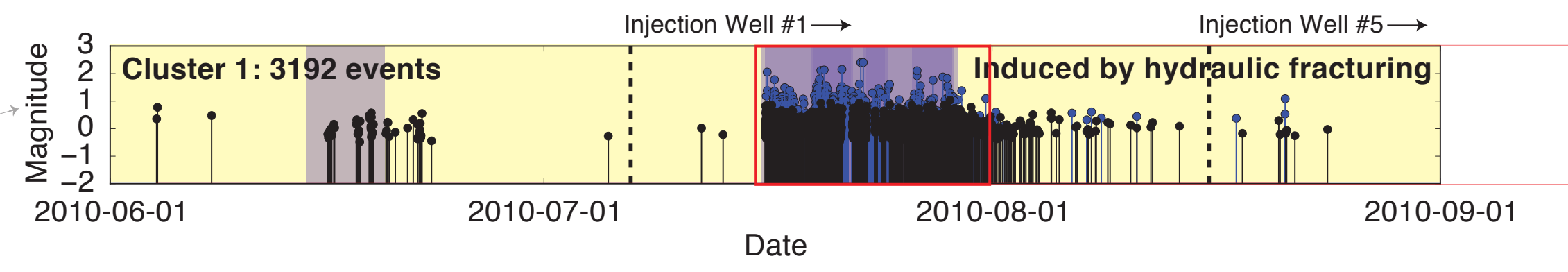
- ● New detected and located earthquakes, 2010-06-01 to 2010-09-01; Sized by magnitude (-1.5 < M < 2.9), colored by depth
- ☐ Earthquake clusters
- ▲ Seismic stations
- ■ Cities
- ◆ Quarry
- ☐ Zoom-in areas
- ☆ Largest earthquake in sequence, Mw 4.7, 2011-02-27
- ▼ Wastewater injection wells (colored by depth: started injecting 2010-06-01 to 2010-09-01)
- Production wells with hydraulic fracture stimulation, 2010-06-01 to 2010-09-01 (triangle: surface location and heel, colored by depth; line: horizontal extent to toe)
- ▨ Duration of hydraulic fracture stimulation at nearby well (within 2 km radius), start of first stage to end of last stage; Well data source: Arkansas Oil & Gas Commission Database (http://www.aogc.state.ar.us)
- ⋮ Start date of wastewater injection
- Located earthquakes
- Assigned earthquakes

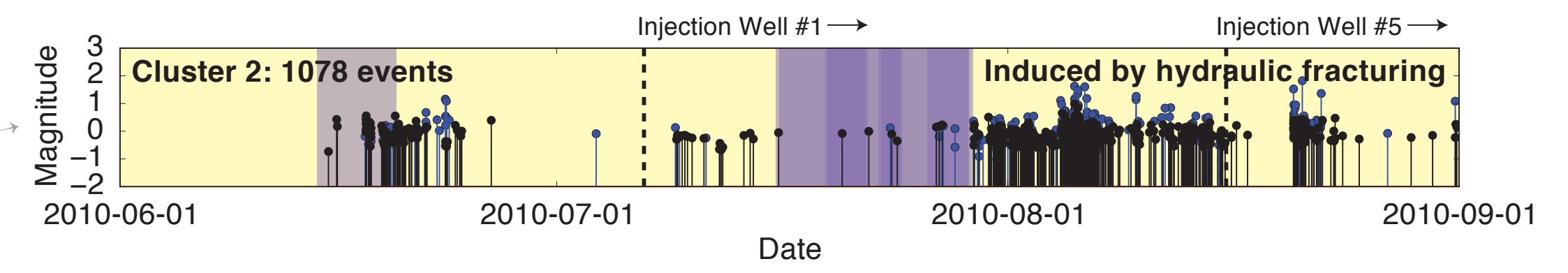


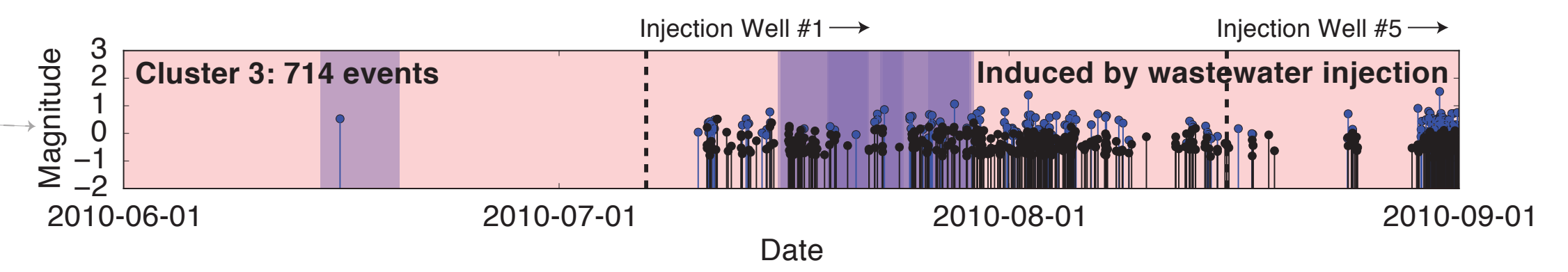


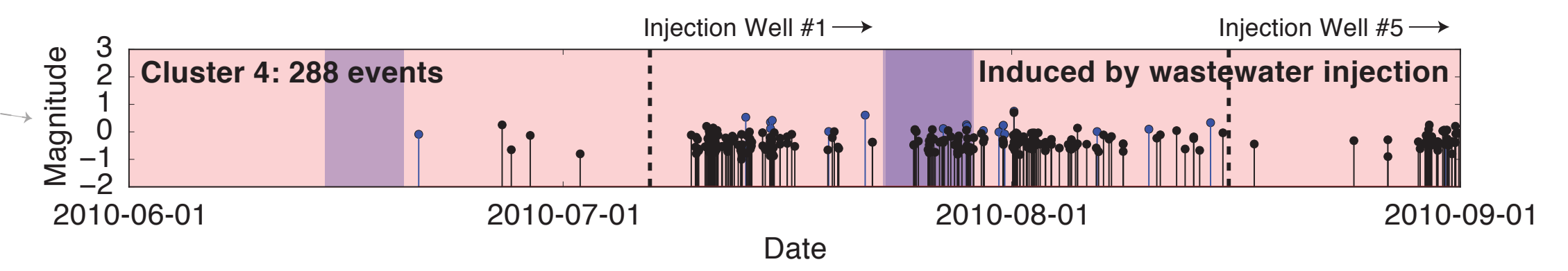


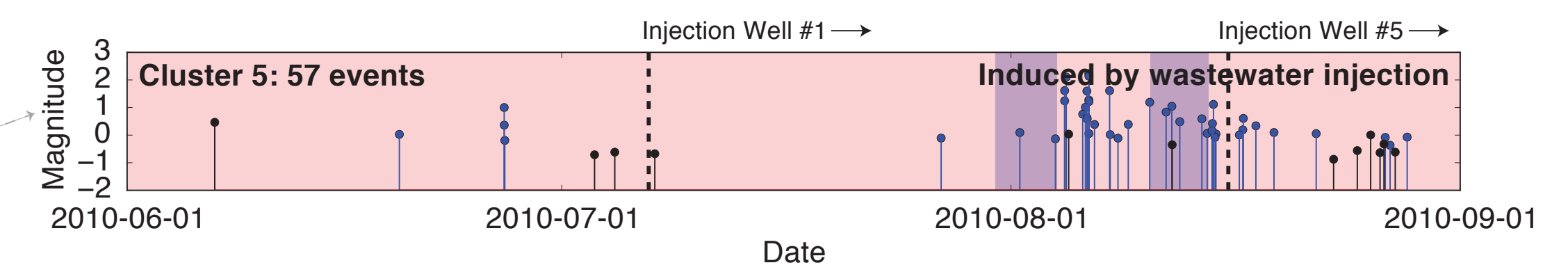




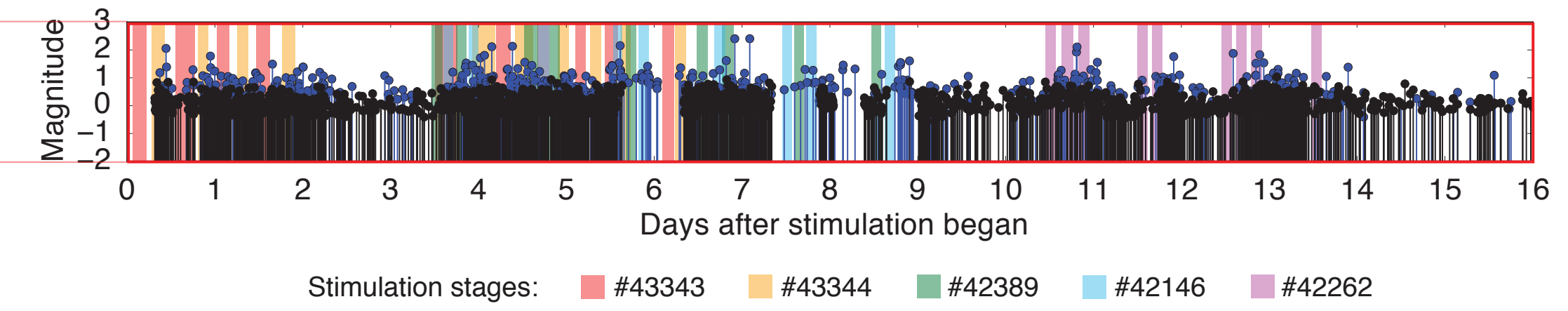






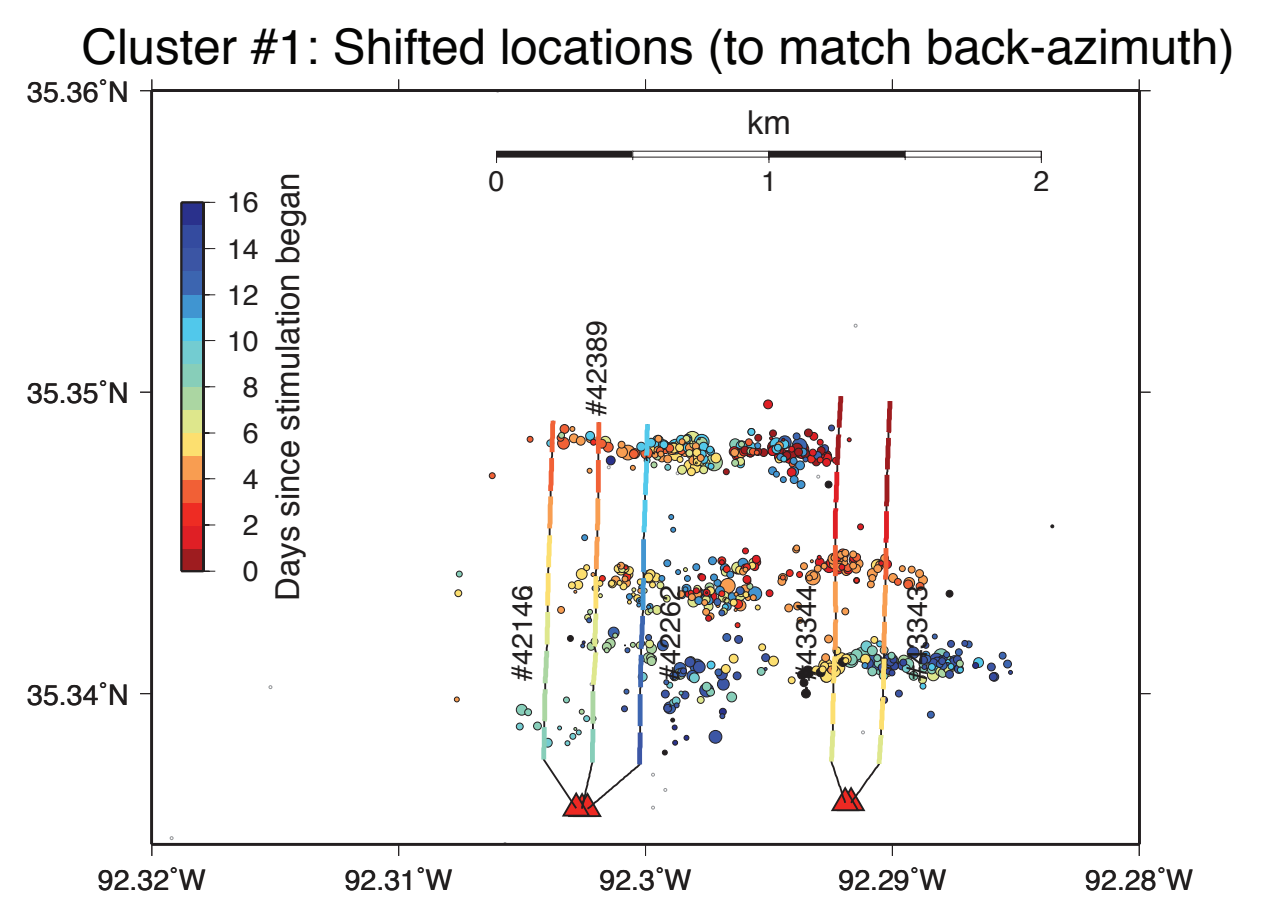


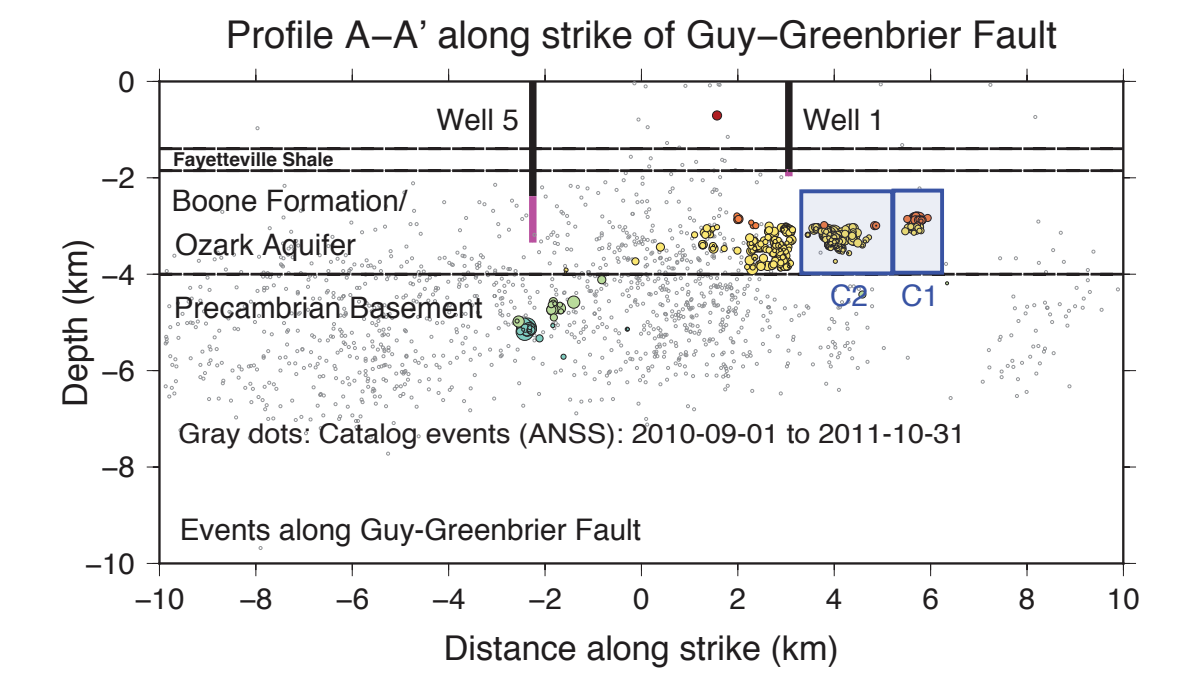
Precision seismology and a high-quality public well database allow us to separate earthquakes induced by hydraulic fracturing from earthquakes induced by wastewater injection

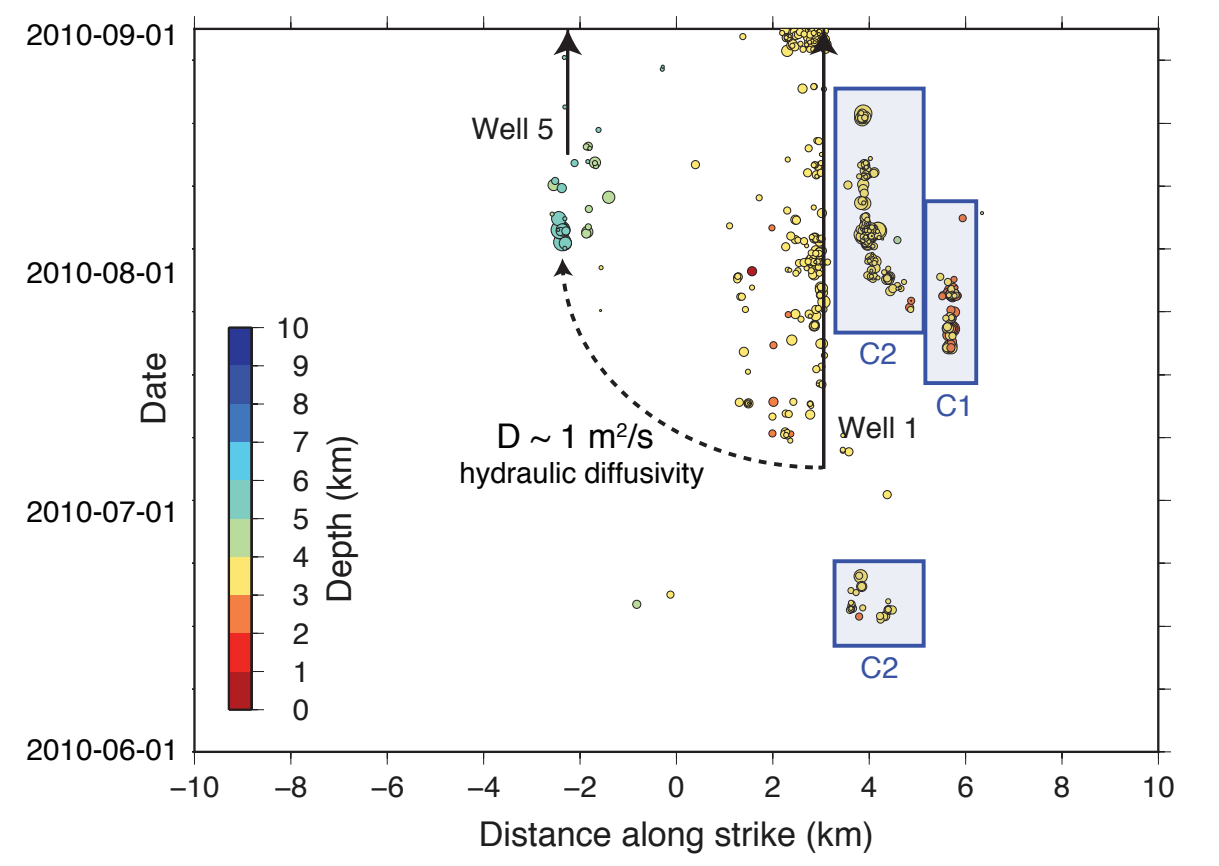


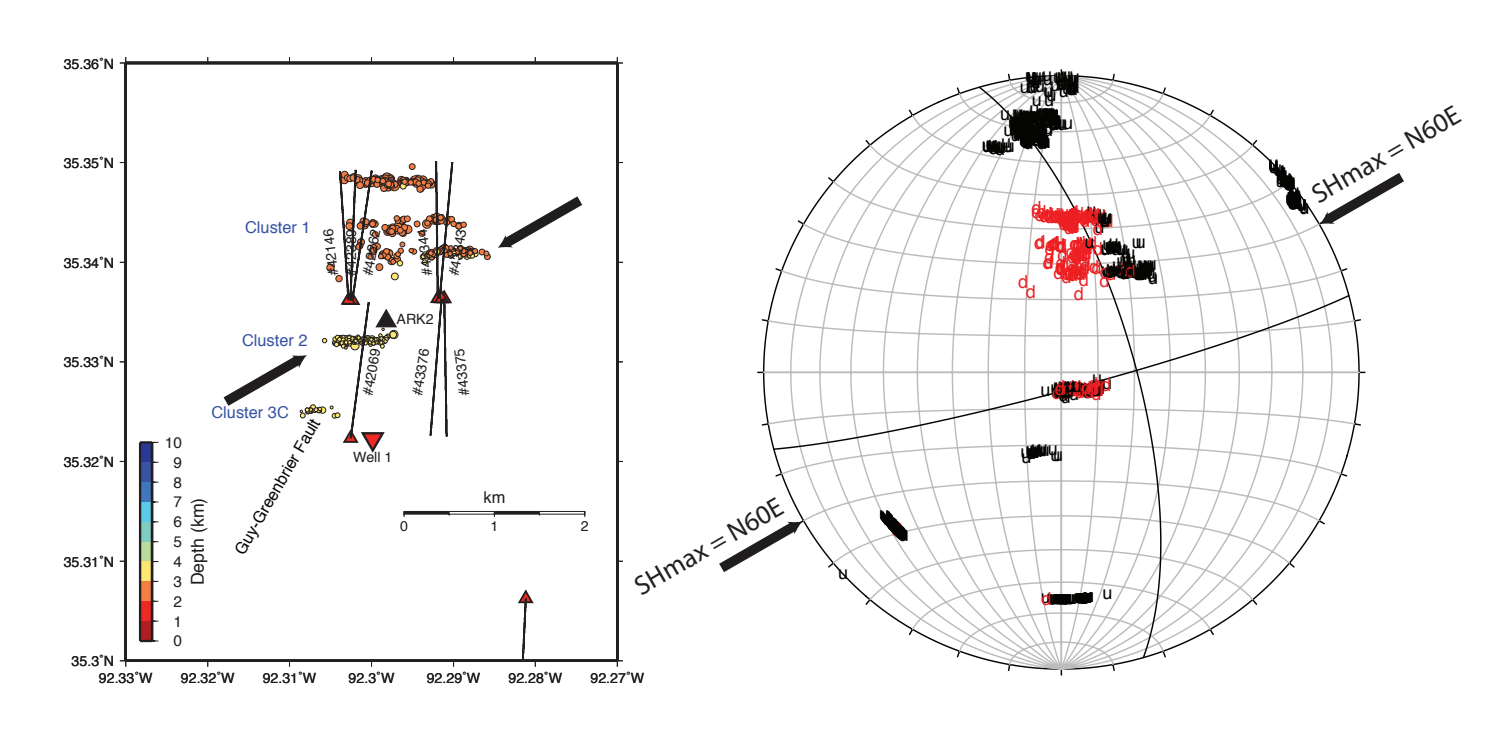
Cluster 1 seismicity: spatially and temporally correlated with individual stages of hydraulic fracturing stimulation at 5 adjacent production wells

Higher seismicity rate during or immediately after stimulation stages


Cluster #1: Shifted locations (to match back-azimuth)


Profile A–A' along strike of Guy–Greenbrier Fault





Composite focal mechanism: Clusters 1, 2, 3C (oriented east-west)

- Assuming double-couple: fit two nodal planes to first motions; choose ~N75E fault plane, consistent with east-west trending seismicity
- Contradiction: first motions indicate right-lateral slip, but SHmax ~ N60E predicts left-lateral slip on a preexisting fault
- Instead, a possible combination of shear and tensile faulting, consistent with hydraulic fracturing mechanism? (*Sileny et al., 2009, JGR; Fischer and Guest, 2011, GRL; Vavrycuk, 2011, JGR*)
- Interpretation limited by lack of first motion data at enough stations