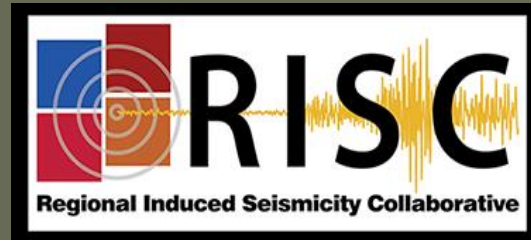


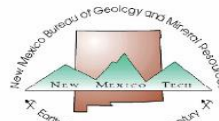
History and Regulatory Response to Induced Seismicity in Arkansas with Examples from Previous Case Studies...

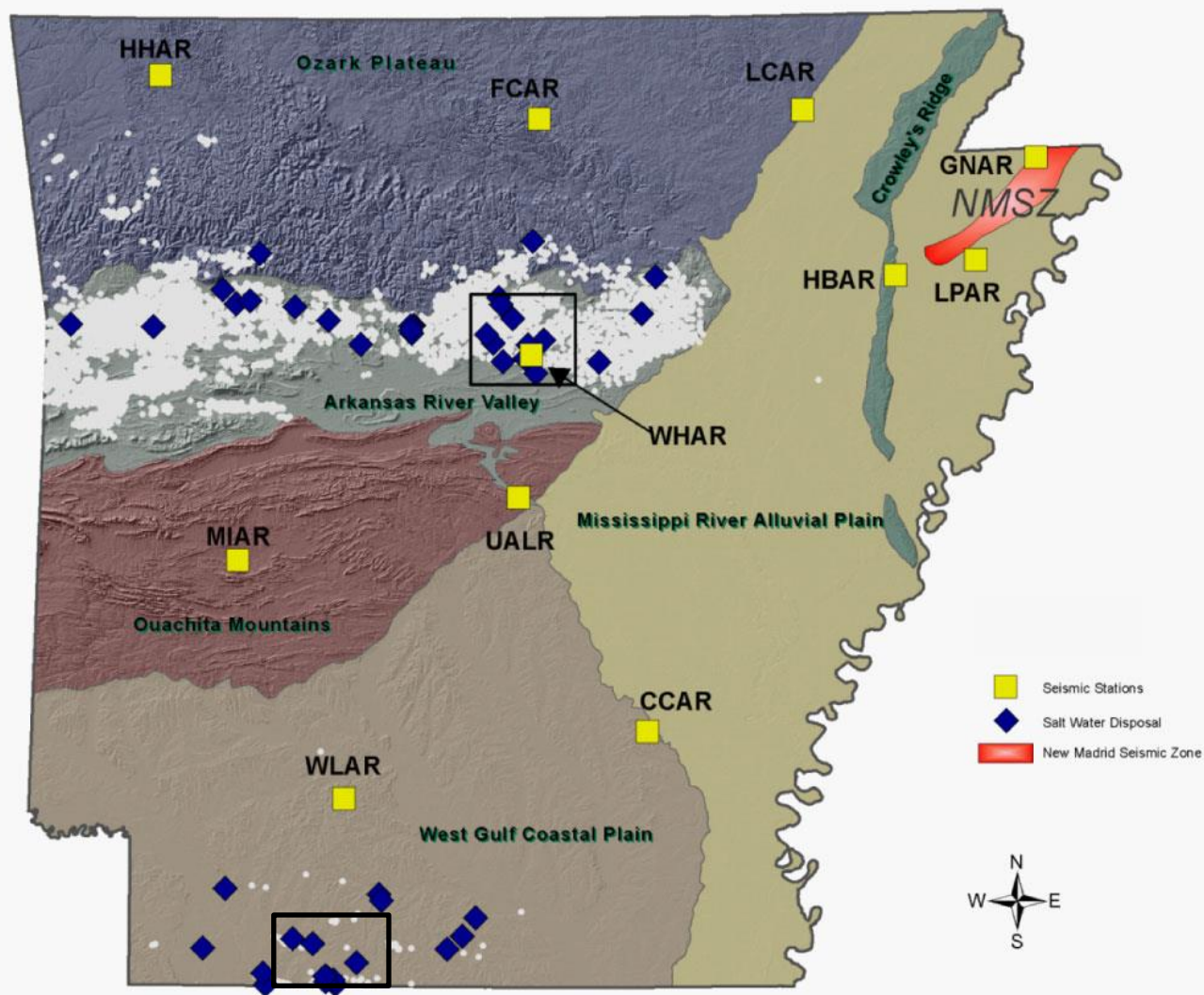
What We Have Learned?



Scott M. Ausbrooks
Martha Kopper
Arkansas Geological Survey

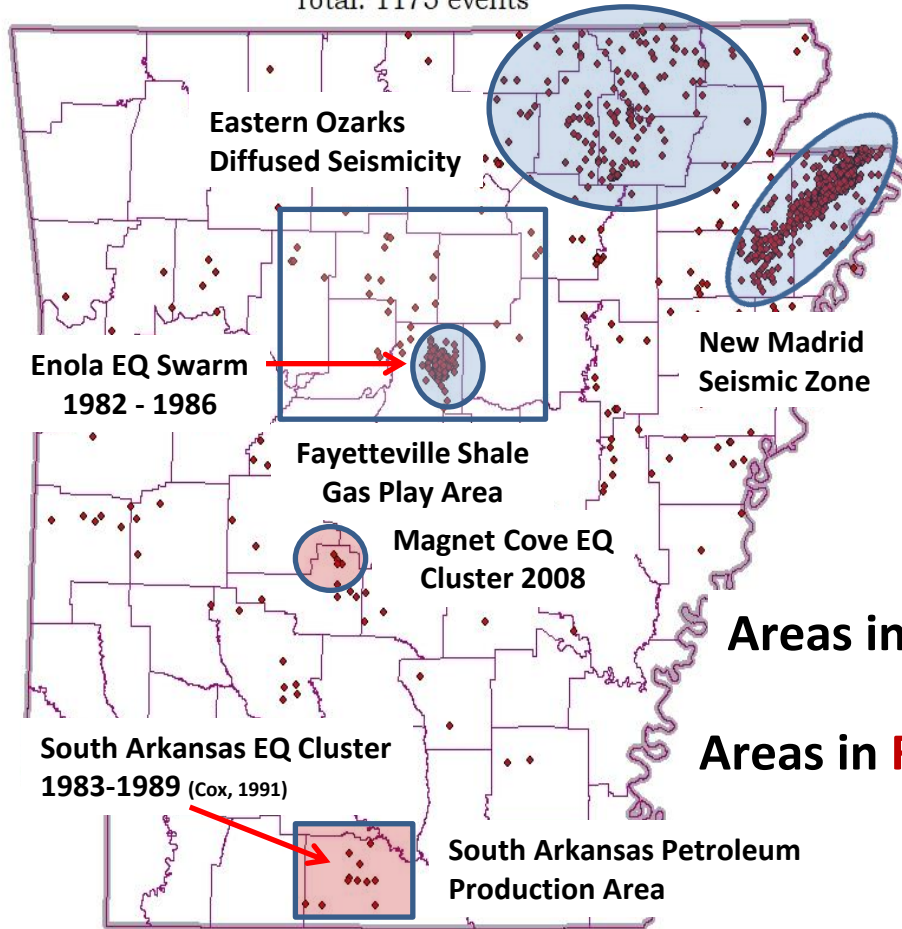
Dr. Stephen Horton
Center for Earthquake Research and Information





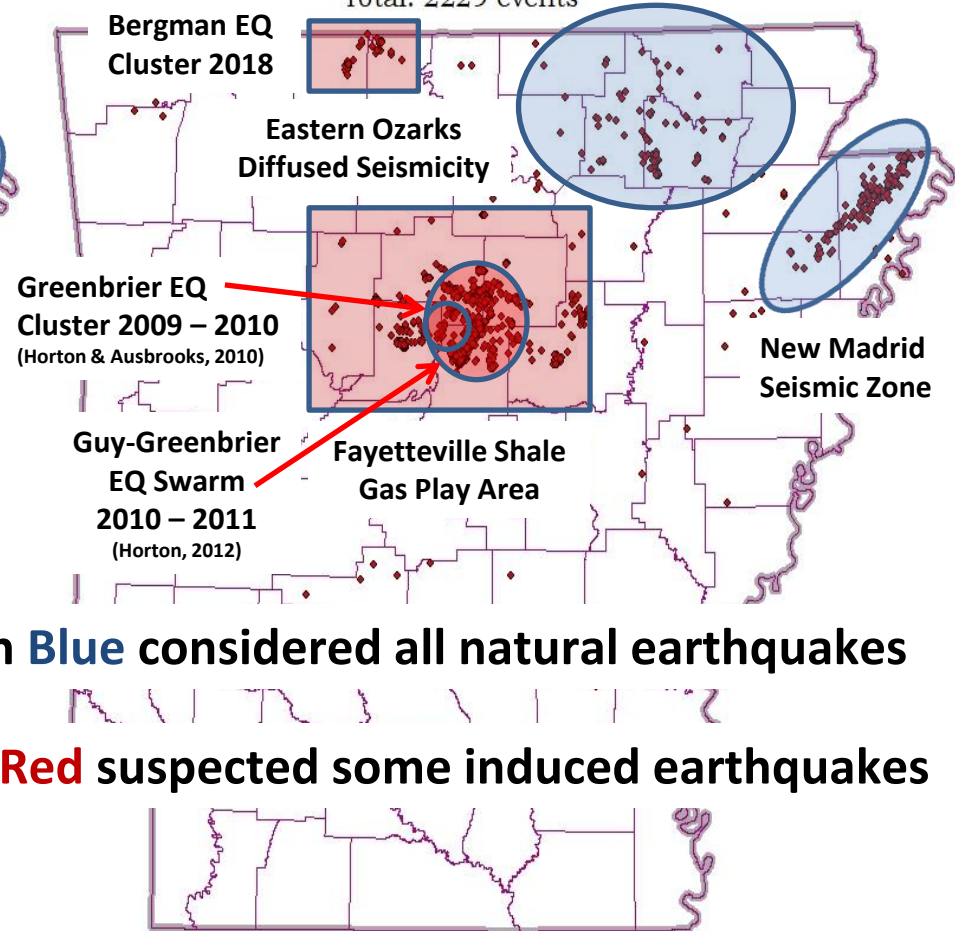
Arkansas Earthquakes from 1811 Thru 2008

Total: 1175 events



Arkansas Earthquakes from 2009 Thru 2018

Total: 2229 events



Areas in **Blue** considered all natural earthquakes

Areas in **Red** suspected some induced earthquakes

Seismicity in Arkansas



Three Published Case Studies of Induced Seismicity in Arkansas... plus one unpublished

- *Possible triggering of earthquakes by underground waste disposal in El Dorado, Arkansas area. (Cox, 1991)*
- *Are recent earthquakes near Greenbrier, Arkansas induced by waste-water injection? (Horton and Ausbrooks, 2010)*
- *Disposal of hydrofracking waste fluid by injection into subsurface aquifers triggers earthquake swarm in Central Arkansas with potential for damaging earthquake. (Horton, 2012)*
- *E. W. Moore Estate “Deep-Six” injection well monitoring program (AGS Open-file report, 2008)*



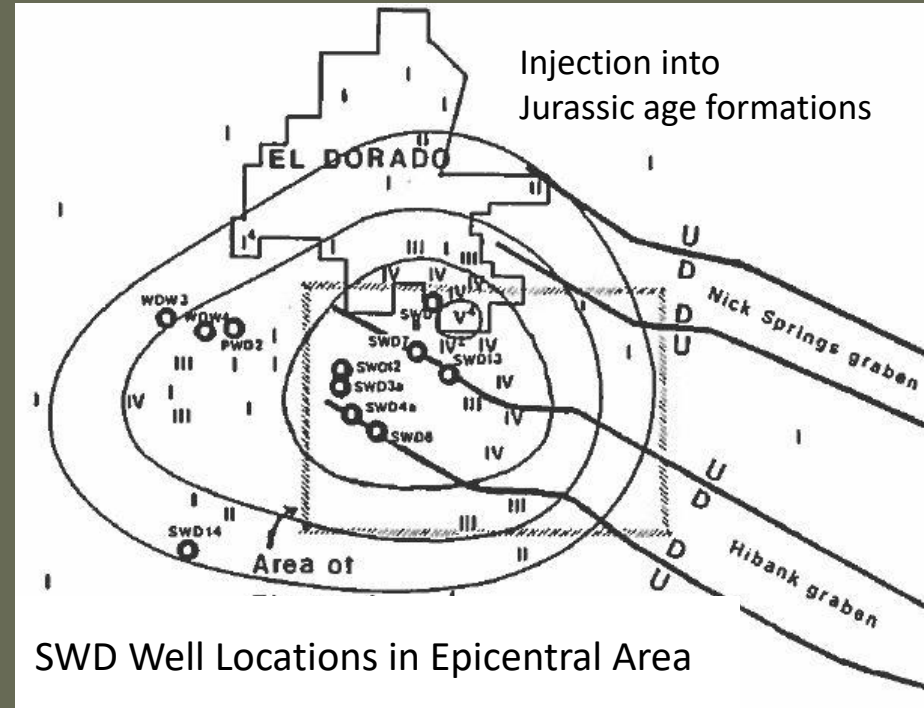
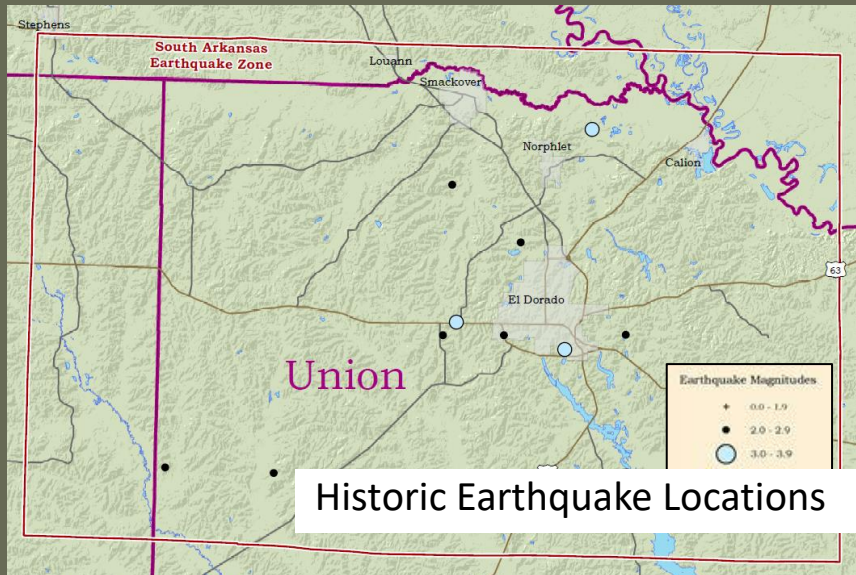
El Dorado EQ Cluster 1983 - 1989

Overview



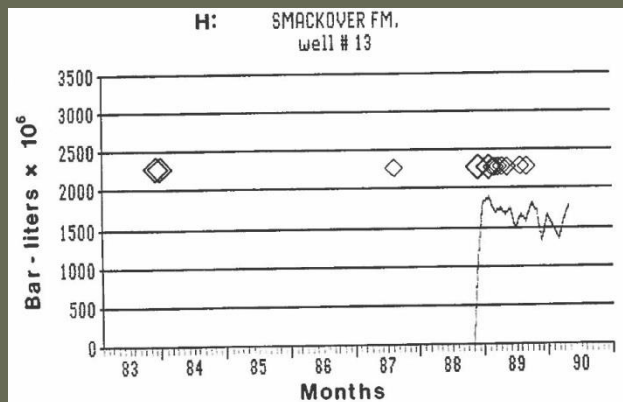
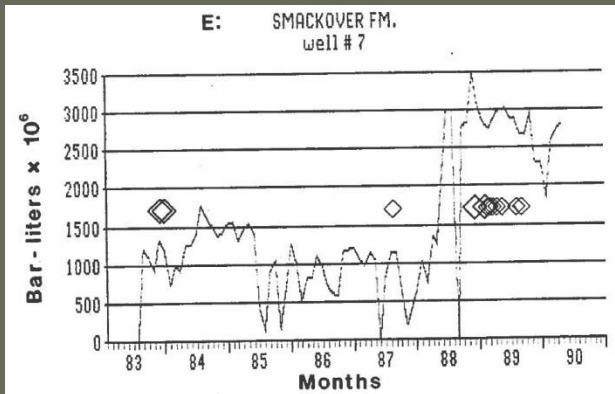
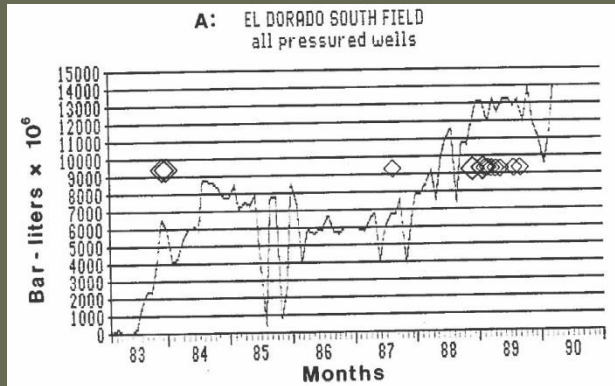
DATE	Hr/Min.	LATITUDE	LONGITUDE	MAGNITUDE
12-09-83	2052	33.209N	92.739W	3.0*
12-10-83	0924	33.264N	92.686W	2.2
08-11-87	2031	33.105N	92.889W	2.0
12-12-88	1310	33.231N	92.884W	2.5*
02-05-89	0838	33.304N	92.742W	2.4*
02-11-89	2322			1.1
03-01-89	2055			1.7
03-03-89	2101			1.0*
04-27-89	1826			1.3
04-30-89	0126			1.3
08-24-89	0427			1.7
09-01-89	0252			1.3

12 Events
(4 Felt)



- The El Dorado area was seismically quiet prior to 1983.
- Large volumes of waste water from the brine industry started being injected under pressure in 1983.

El Dorado EQ Cluster 1983 – 1989 Overview



Twelve (12) SWDs located in a major fault zone (graben).

Increases in disposal rates in SWD #7 and SWD #13 that closely correspond to episodes of seismicity.

Hypo-central depths are occurring within the injection and deeper.

Effective *in situ* stresses in the region may be near several (tens of bars) failure along preexisting fractures, and formation pressures appear to have increased within the fault zone in vicinity of the suspect wells.

Total seismic energy release of detected events in the El Dorado area from **1983 to 1990 was 286×10^7 joules**. Injection energy during the entire interval was only **6×10^7 joules**.

M3.0 in same area occurred in May 2007.

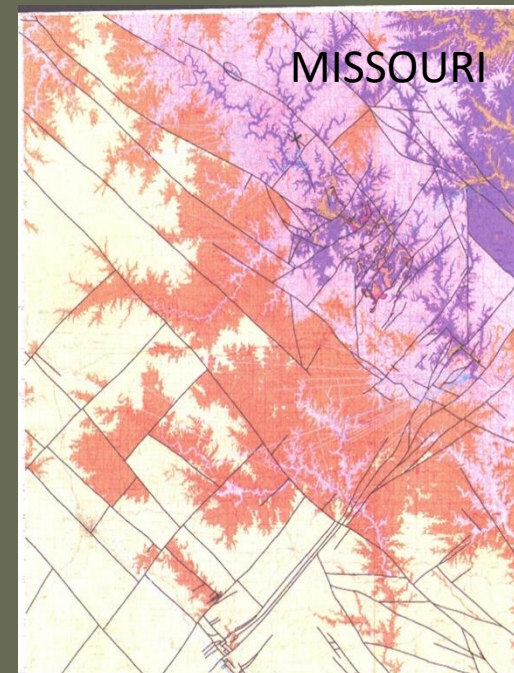
NO REGULATORY RESPONSE.



Enthem System	Geologic unit	Hydrogeologic unit
Paleozoic	Mississippian	Boone Formation St. Joe Limestone Member BOONE Springfield Plateau aquifer
	Devonian	Chattanooga Shale (Sylamore Sandstone Member) Clifty Limestone Peters Chert Ozark confining unit
	Silurian	Latterly Limestone St. Clair Limestone Breenfield Limestone HUNTON
	Ordovician	Green Shale Fernvale Limestone Kimmswick Limestone Pattin Limestone Joachim Dolomite St. Peter Sandstone Everton Formation Smithville Formation Powell Dolomite Cotter Dolomite Ozark aquifer
		Jackson City Dolomite Roubidoux Formation ¹ Greensade Dolomite Van Buren Formation ¹ (Gunter Sandstone Member)
		Emmence Dolomite Potter Dolomite Doe Run Dolomite Derby Dolomite Davie Formation Bonnetate Dolomite Lamotte Sandstone
		St. Francois confining unit
	Cambrian	St. Francois aquifer
		Ozark Plateau aquifer system
		3% - 8% porosity
		ARBuckle

STRATIGRAPHIC SECTION GEOHYDROLOGIC UNITS

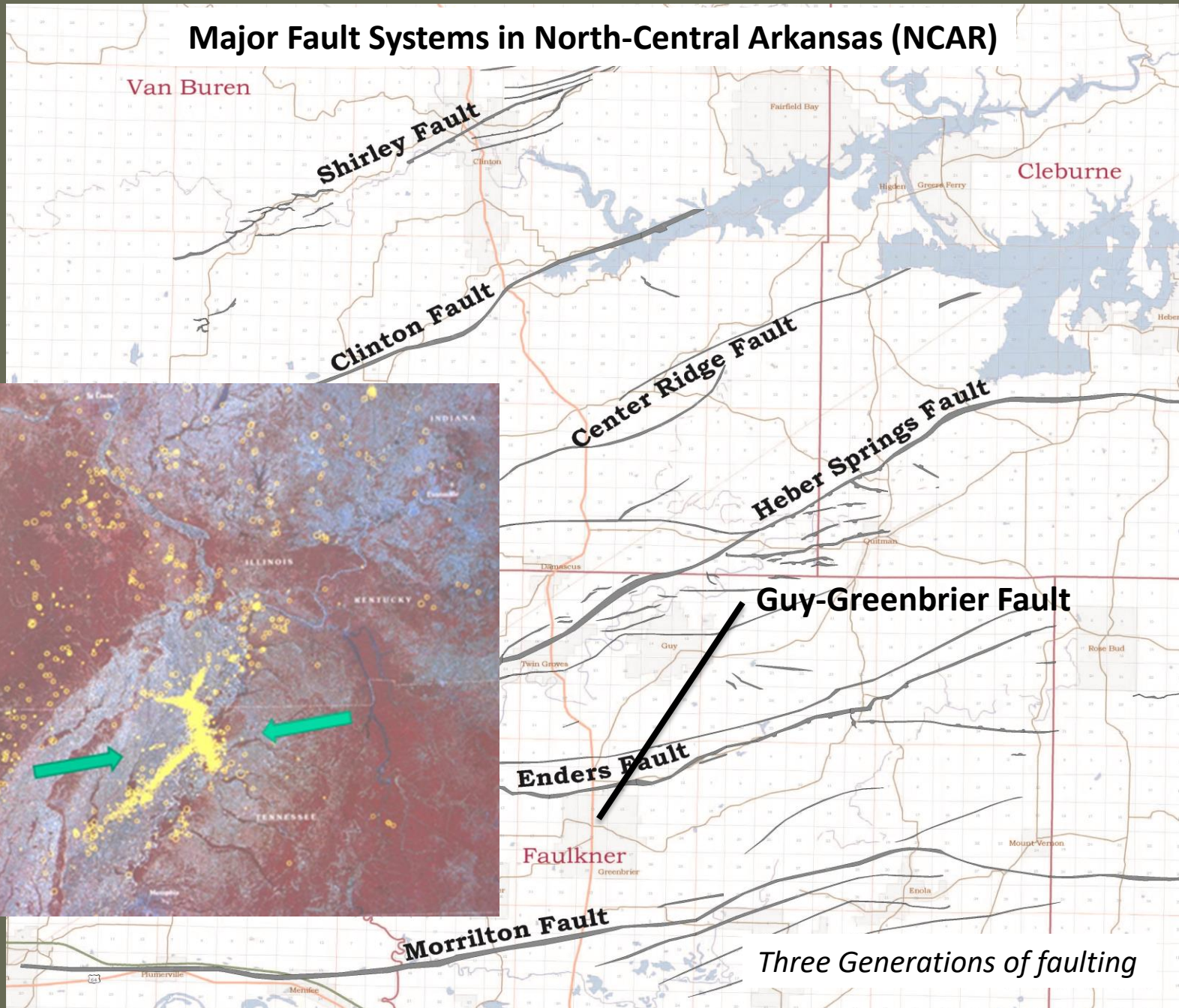
- Ozark Confining Unit is thin and predominately sandstone in the Study Area
- St. Francois Confining Unit is missing in the Study Area (Caplin, 1960)



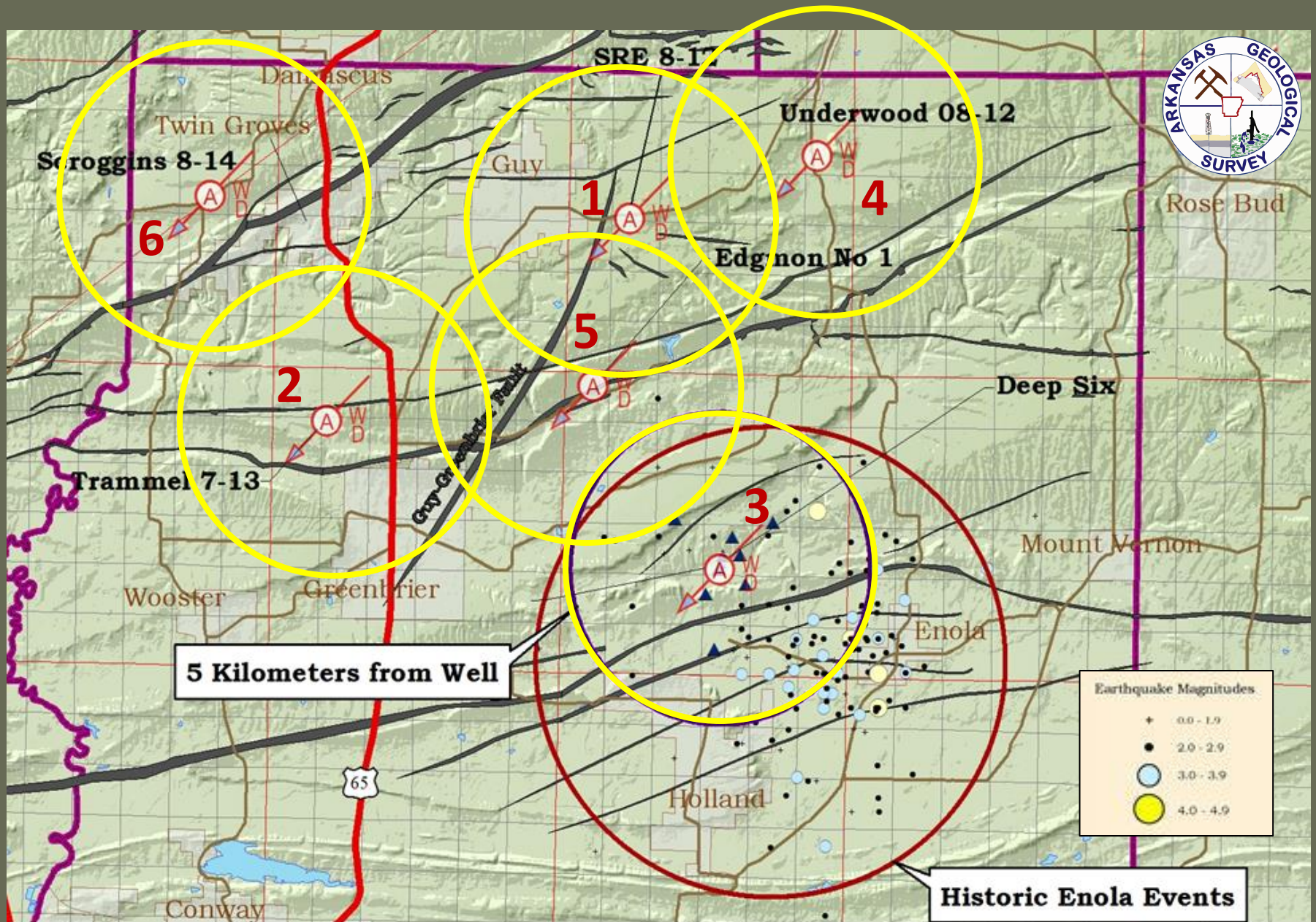
Sets of “favorably oriented” and “orthogonal pair-sets” of fractures, joints and faults formed in basement rocks during Precambrian time. Since then they have been reactivated numerous times creating a “bridging mechanism” into the overlying Paleozoic sedimentary rocks – these sets provide avenues for “groundwater and pressure fronts” to move through impermeable rocks.



Major Fault Systems in North-Central Arkansas (NCAR)



Locations of SWDs in North-Central Arkansas



Disposal Well Comparisons

#1 SRE:

Total Depth: 6,460 feet

Sedimentary Rock:

0 to 6,460 feet

Injection Zone:

5,975 to 6,460 feet (Boone and Hunton)

#2 Trammel (TRM):

Total Depth: 7,160 feet

Sedimentary Rock:

0 to 7,160 feet

Injection Zone:

6,503 to 6,590 feet (Boone)

#3 Deep-Six (DP6):

Total Depth: 10,500 feet

Sedimentary Rock:

0 to 10,500 feet

Injection Zone:

7,480 to 7,540 feet (Boone)

Injection Zone:

9,300 to 10,500 feet (Arbuckle)

#5 Edgmon (EDG):

Total Depth: 12,160 feet

Sedimentary Rock:

0 to 12,090 feet

Igneous Rock:

12,090 to 12,160 feet

Injection Zone:

7,806 to 10,970 feet (Arbuckle)

Ranking based on Total
Volume Injected:

TRM: 256,174,800 gal
(WH: 2285psi)

SRE: 103,397,154 gal
(WH: 1717psi)

DP6: 85,658,034 gal
(WH: 2950psi)

EDG: 17,744,832 gal
(WH: 2850psi)

Comparison:

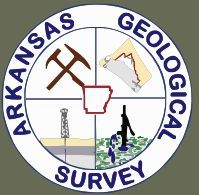
RMA: 165,000,000 gal

RMA=

Rocky Mountain Arsenal

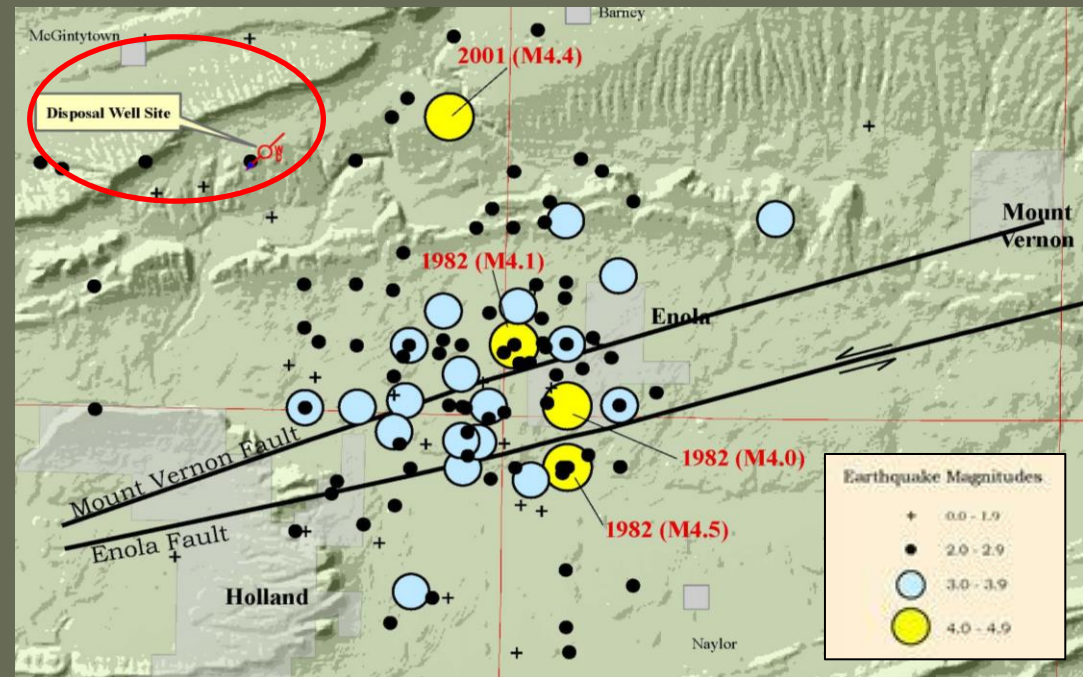


E.W. Moore Estate No. 1 – “Deep-Six” SWD



Originally drilled as a wildcat natural gas well in March of 1974. No commercial gas discovered and the well was plugged and abandoned on April 25, 1974.

Total depth of 10,600 feet and penetrated the Ordovician Arbuckle Formation in the bottom portion of the well bore.



Deep-Six Water Disposal Services, LLC applied for a permit in Spring of 2007 for the reentry and modification of the E.W. Moore Estate No. 1 Well for the commercial disposal of flow-back saltwater into the Ordovician Arbuckle Formation.

The SWD site is located approximately 1.5 miles northwest of the Enola Swarm area. Due to the close proximity of the Deep-Six SWD to the Enola Swarm area, the director of the AOGC ordered a hearing in the Spring of 2008.

Enola EQ Swarm Overview

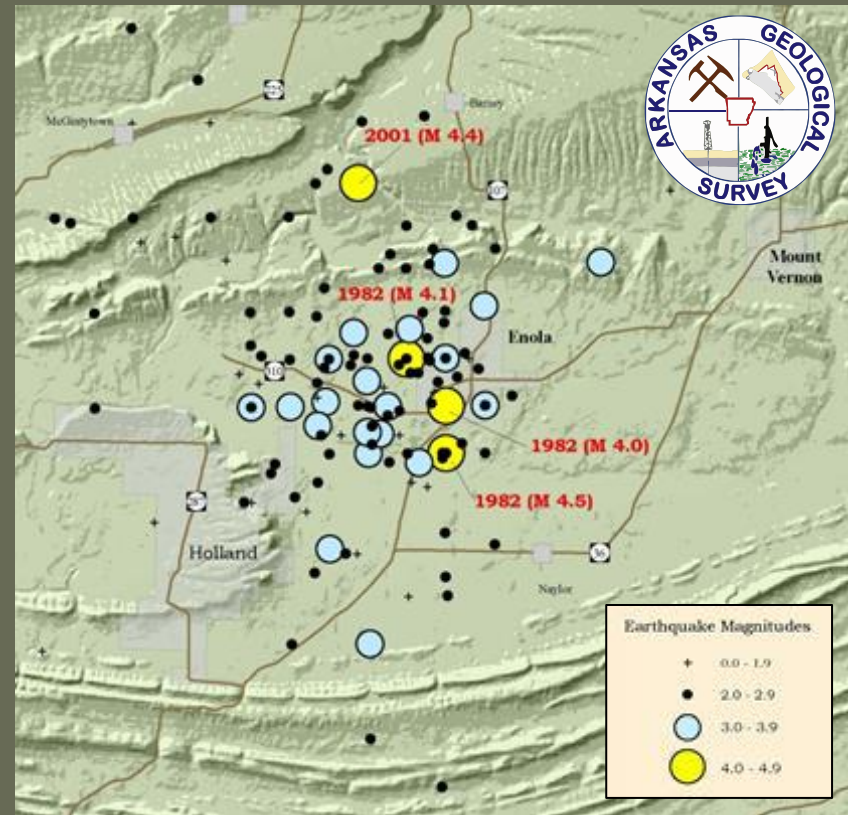
Naturally occurring ... not related to NMSZ

40,000+ earthquakes (largest swarm in EUS)

Hypo-centers in both the igneous basement rock and the overlying sedimentary units

Earthquakes appeared to have occurred in a highly fractured zone associated with a graben

Lower seismic velocities in the swarm area relative to the surrounding area suggests that fluid migration is playing a role.



Date	Magnitude	Comments
1/12/1982	M=1.2	<i>(First detected event)</i>
1/17/1982	M=3.0	<i>(First M3+ with over 93 felt earthquakes the first year)</i>
1/20/1982	M=4.5	
1/23/1982	M=4.3	
2/28/1982	M=4.1	
05/4/2001	M=4.4	<i>(Largest event since 1982 with over 2500 aftershocks)</i>

E. W. Moore Estate “Deep-Six” SWD Monitoring Program

Results from the AOGC hearing in February of 2008:

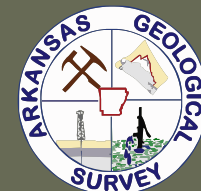
Dr. Barry Raleigh (USGS), Dr. Haydar Al-Shukri (UALR), and Scott Ausbrooks (AGS) testified to the potential for induced seismicity and potential for damages in the Enola Swarm Area.

Deep-Six Water Disposal Services, LLC was require to have the following a permit to inject:

- Obtain \$25,000,000 in liability insurance
- Install, operate and monitor a local seismic array in the vicinity of the the SWD to monitor seismic activity --- Small Aperture Seismic Array

RMA, Nicholson and Wesson, USGS 1990, DWF EQs (Frohlich)





Deep-Six SWD Seismic Array

Deep-Six SWD Seismic Array

Seven elements array

Each element is 3- components short period seismometer

Radio telemetry communication to the central recording station

Solar powered

Central digital recording station (standalone and internet ready for real time data communication)

High capacity computer storage

Capable of high accuracy event location

Flexibility for future modification and expansion

Inexpensive

Injection Well

S2

S4

S5

S1

S7

S3

Deep-Six SWD Seismic Array

Installed: Jul 2008

Testing: Jul - Aug 2008

Background : Sep 2008 – Apr 2009

Injection started: May 2009

Continuous monitoring : May 2009

Start monthly reporting: Sep 2009

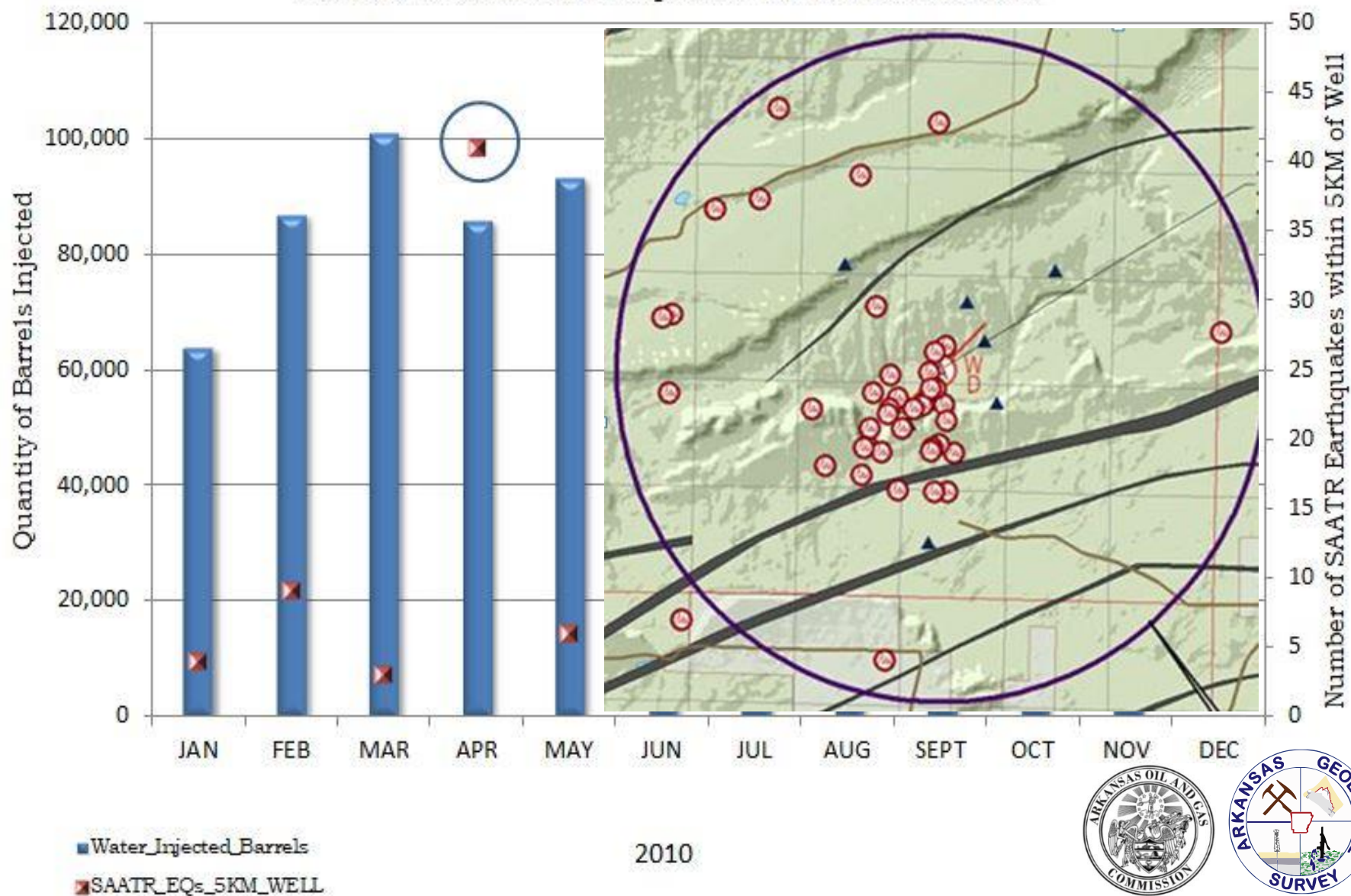
Image © 2008 DigitalGlobe
© 2007 Europa Technology

2693 m

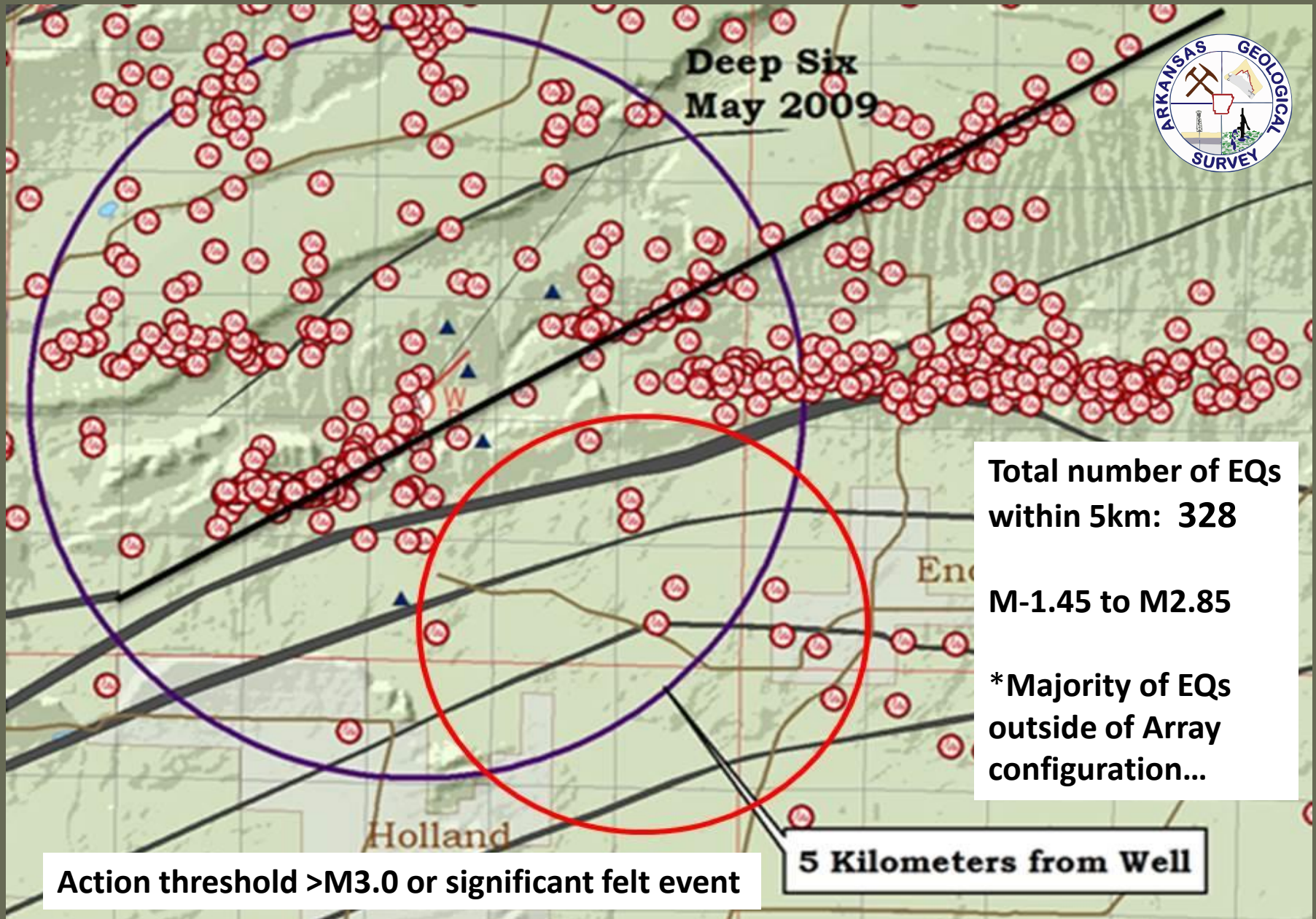
Streaming ||||| 100

Pointer 35°13'00.70" N 92°16'06.13" W elev 100 m

Deep-Six Well - Barrels Injected per Month vs.
Number of SAATR Earthquakes within 5KM of Well



Deep-Six SWD Seismic Array Final Thoughts





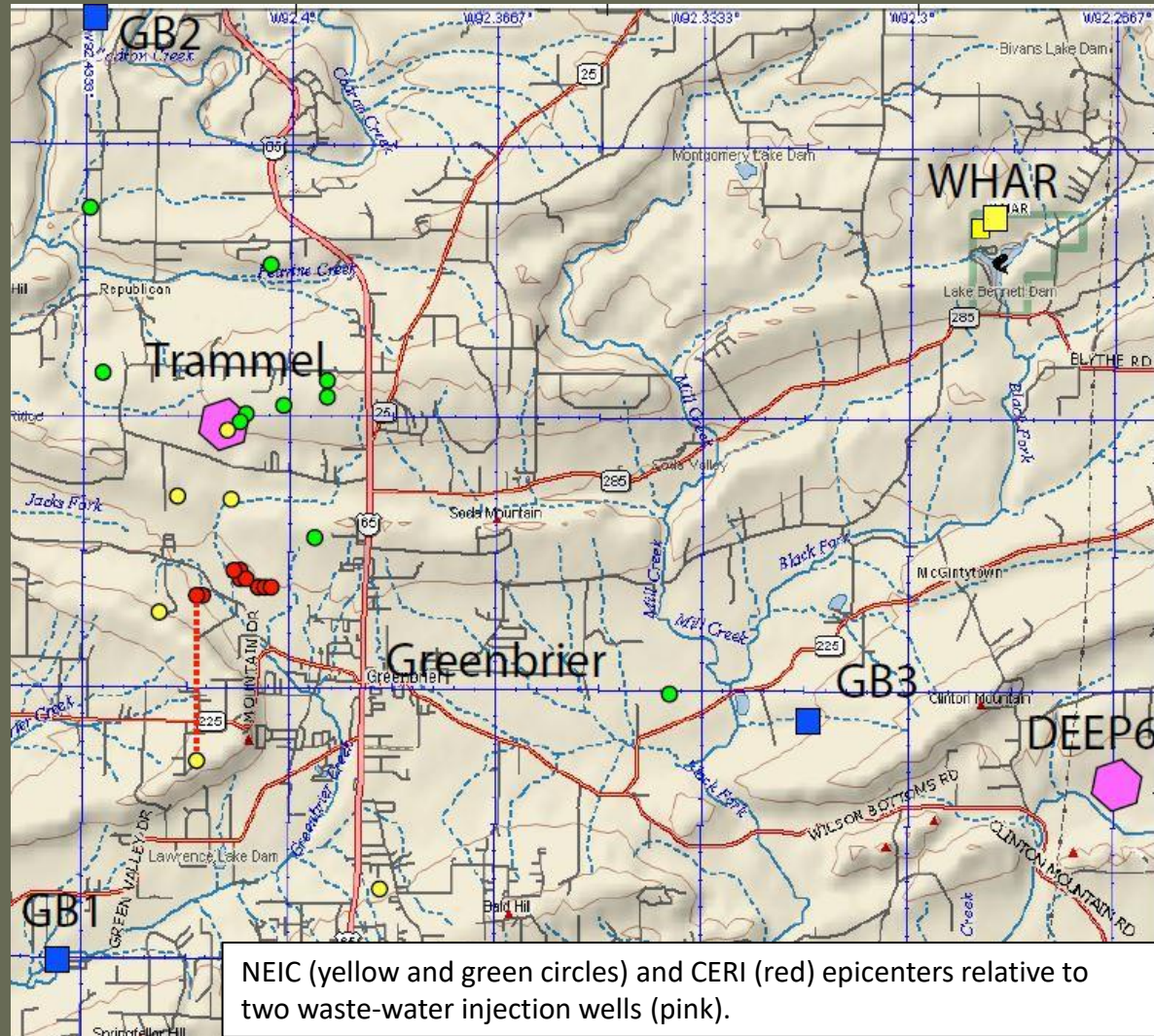
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Greenbrier EQ Cluster 2009 - 2010 Overview

This study was focused on earthquakes near Greenbrier, AR. Between 15th October 2009 and 22nd March 2010, NEIC located **14 regional** earthquakes ($1.7 < m < 3.0$).

The earthquake activity (6 **felt locally**) generated public concern.

A small array (GB) of three seismometers were deployed after the initial events. Cross-correlation (≥ 0.5) resolved **672 micro-earthquakes** close to the Trammel disposal well. **b-value** of 1.4



NEIC (yellow and green circles) and CERI (red) epicenters relative to two waste-water injection wells (pink).

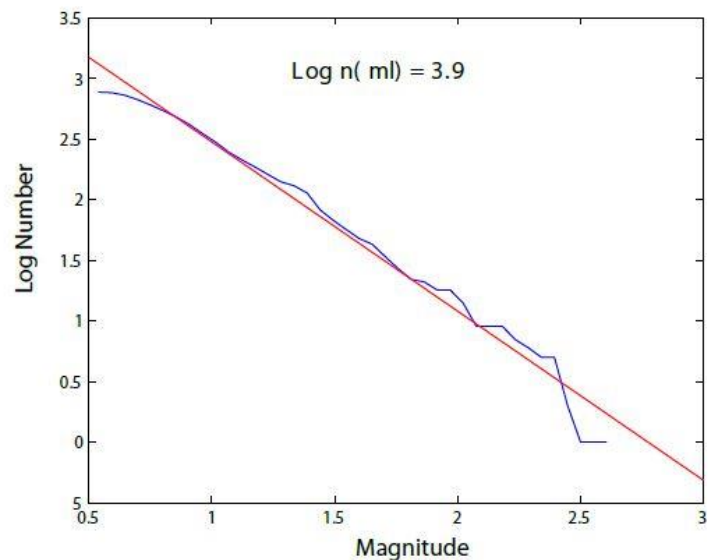
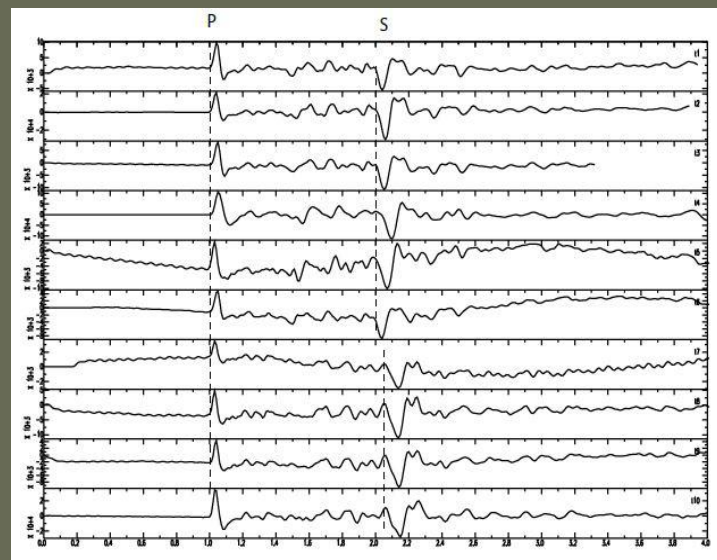
Greenbrier EQ Cluster 2009 – 2010 Overview



Cross correlation of a master event with continuous recordings at site GB1 indicates that the earthquakes have very similar waveforms.

Waveform similarity indicates the events are located in close proximity and consistent focal mechanisms.

672 events were cataloged at a **correlation coefficient of greater than 0.5**.



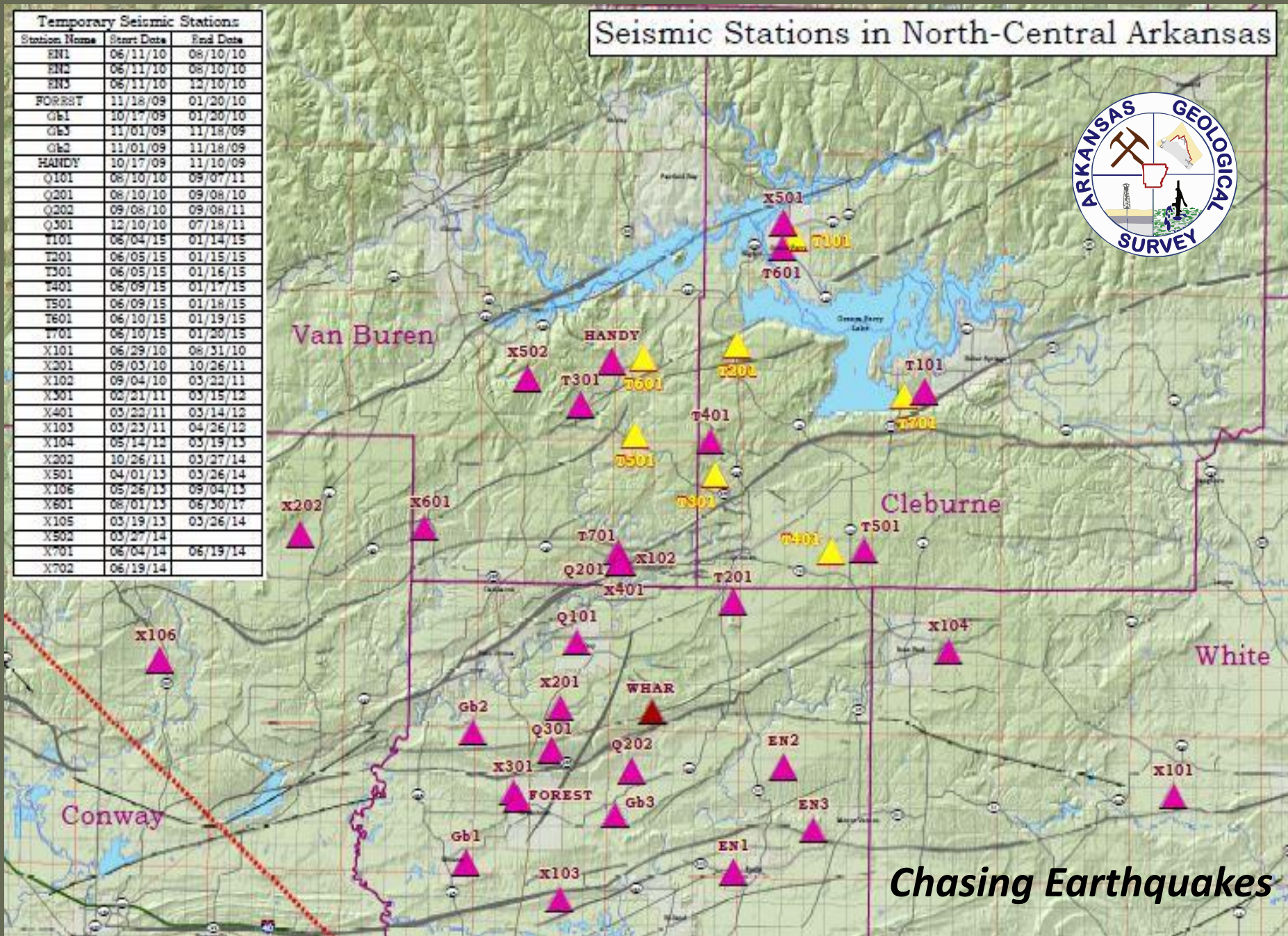
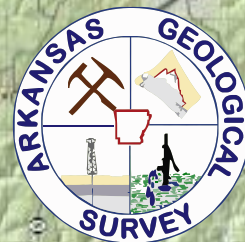
Fitting this distribution to the Gutenberg-Richter relationship gives a **b value of 1.4**.

Sykes (1970) commonly calculated b-values higher than 1.0 for earthquake swarms in volcanic zones and the mid-Atlantic ridge. These tectonic settings share a high degree of influence by fault-zone fluids in earthquake generation.

The high b-value for the Greenbrier earthquakes may thus point to the influence of fault-zone fluids.

Temporary Seismic Stations			
Station Name	Start Date	End Date	
EN1	06/11/10	08/10/10	
EN2	06/11/10	08/10/10	
EN3	06/11/10	12/10/10	
FOREST	11/18/09	01/20/10	
Gb1	10/17/09	01/20/10	
Gb2	11/01/09	11/18/09	
Gb3	11/01/09	11/18/09	
HANDY	10/17/09	11/10/09	
Q101	08/10/10	09/07/11	
Q201	08/10/10	09/08/10	
Q202	09/08/10	09/08/11	
Q301	12/10/10	07/18/11	
T101	06/04/15	01/14/15	
T201	06/05/15	01/15/15	
T301	06/05/15	01/16/15	
T401	06/09/15	01/17/15	
T501	06/09/15	01/18/15	
T601	06/10/15	01/19/15	
T701	06/10/15	01/20/15	
X101	06/29/10	08/31/10	
X201	09/03/10	10/26/11	
X102	09/04/10	03/22/11	
X301	02/21/11	03/15/12	
X401	03/22/11	03/14/12	
X103	03/23/11	04/26/12	
X104	05/14/12	03/19/13	
X202	10/26/11	03/27/14	
X501	04/01/13	03/26/14	
X106	05/26/13	09/04/13	
X601	08/01/13	06/30/17	
X105	03/19/13	03/26/14	
X502	03/27/14		
X701	06/04/14	06/19/14	
X702	06/19/14		

Seismic Stations in North-Central Arkansas

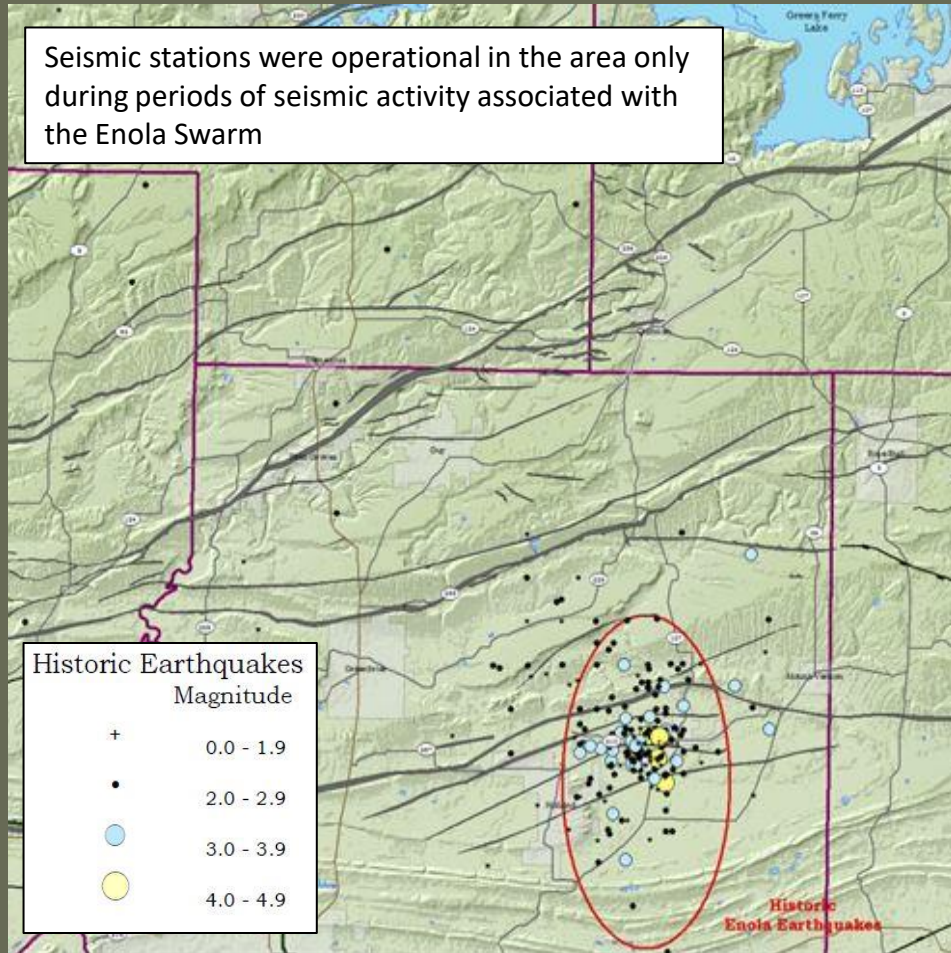
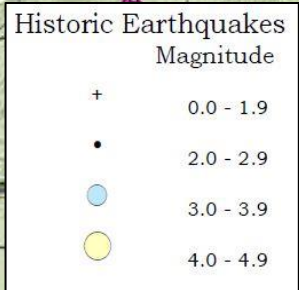


Chasing Earthquakes

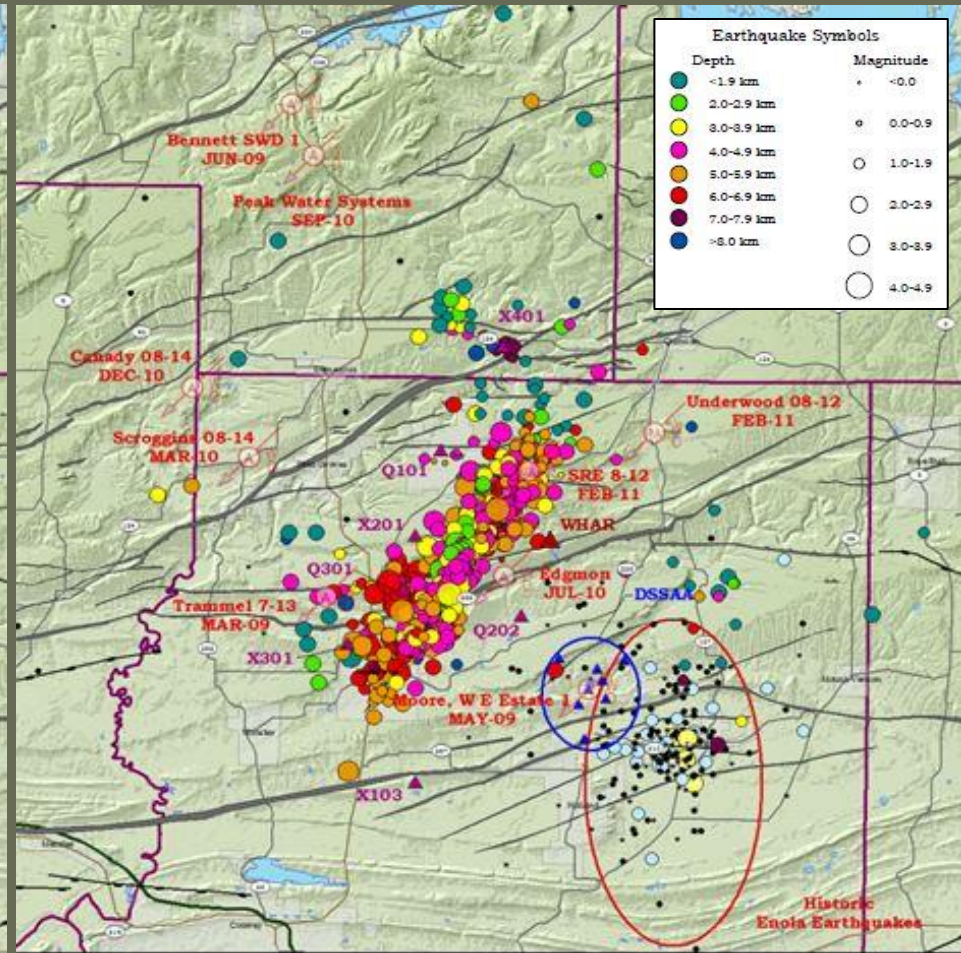
Guy-Greenbrier EQ Swarm 2010 – 2011



Seismic stations were operational in the area only during periods of seismic activity associated with the Enola Swarm



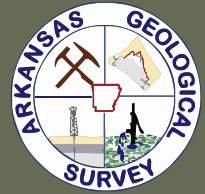
Historic Seismicity 1960 - 2008



G-G EQ Swarm 2010 - 2011

Guy-Greenbrier EQ Swarm 2010 - 2011

Summary

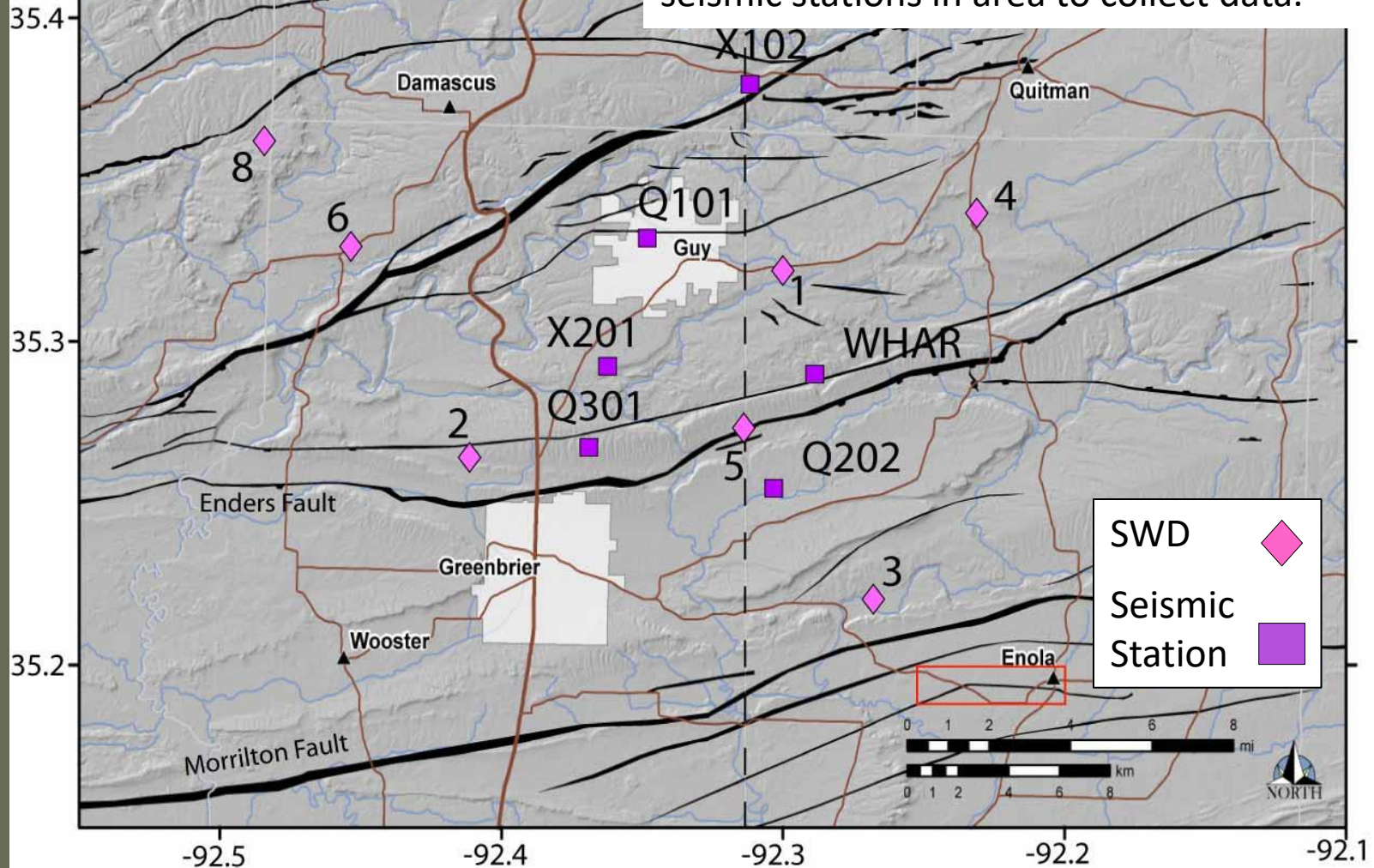


- The Guy-Greenbrier fault, was a previously unknown fault, illuminated by over **1,300 earthquakes ($M \leq 4.7$)** that occurred from the Fall of 2010 to Spring of 2011.
- A plausible hydraulic connection exists between the injection depths at a waste-disposal wells and the nearby Guy-Greenbrier Fault.
- One of the primary concerns at the height of the seismicity was that the fault was theoretically capable of producing a potentially damaging --- $M5.6 - 6.0$ earthquake.
- Given the spatial and temporal correlation between the UIC wells and activity on the fault, it would be an extraordinary coincidence if the earthquakes were not triggered by fluid injection.

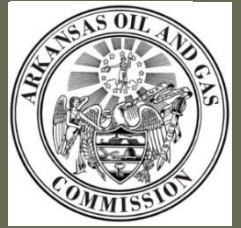
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The AGS and CERI became aware in the Summer of 2010 on the plan to permit the installation and operation of two new SWDs (#1 and #5) in the Guy and Greenbrier area. Based on a working hypothesis, the AGS and CERI deployed seismic stations in area to collect data.

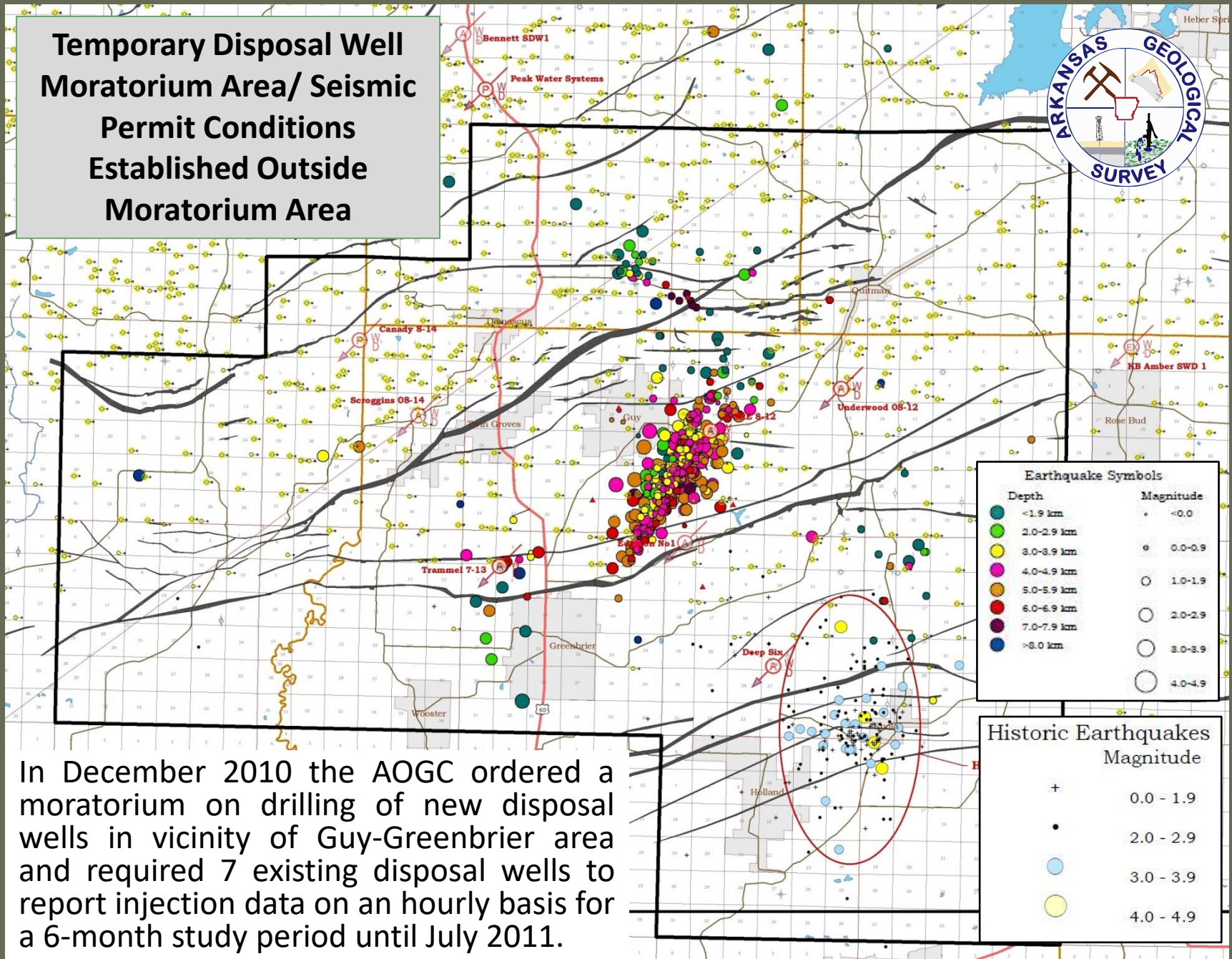
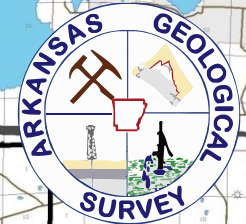


G-G EQ Swarm Regulatory Timeline



- In late summer of 2010, seismic activity began to occur in the Guy area of north-central Arkansas. Due to this increase in seismic activity, formal consultation between the AOGC, AGS and CERL began in early Fall of 2010. The seismic activity ramped up significantly in October and November of 2010.
- After an initial drop-off in seismic activity during January of 2010, a significant increase of seismicity was observed in the last two weeks of February culminating in a M4.7 earthquake on Sunday night February 28, 2011.

Temporary Disposal Well Moratorium Area/ Seismic Permit Conditions Established Outside Moratorium Area



In December 2010 the AOGC ordered a moratorium on drilling of new disposal wells in vicinity of Guy-Greenbrier area and required 7 existing disposal wells to report injection data on an hourly basis for a 6-month study period until July 2011.

Sep 2010 to Mar 2011

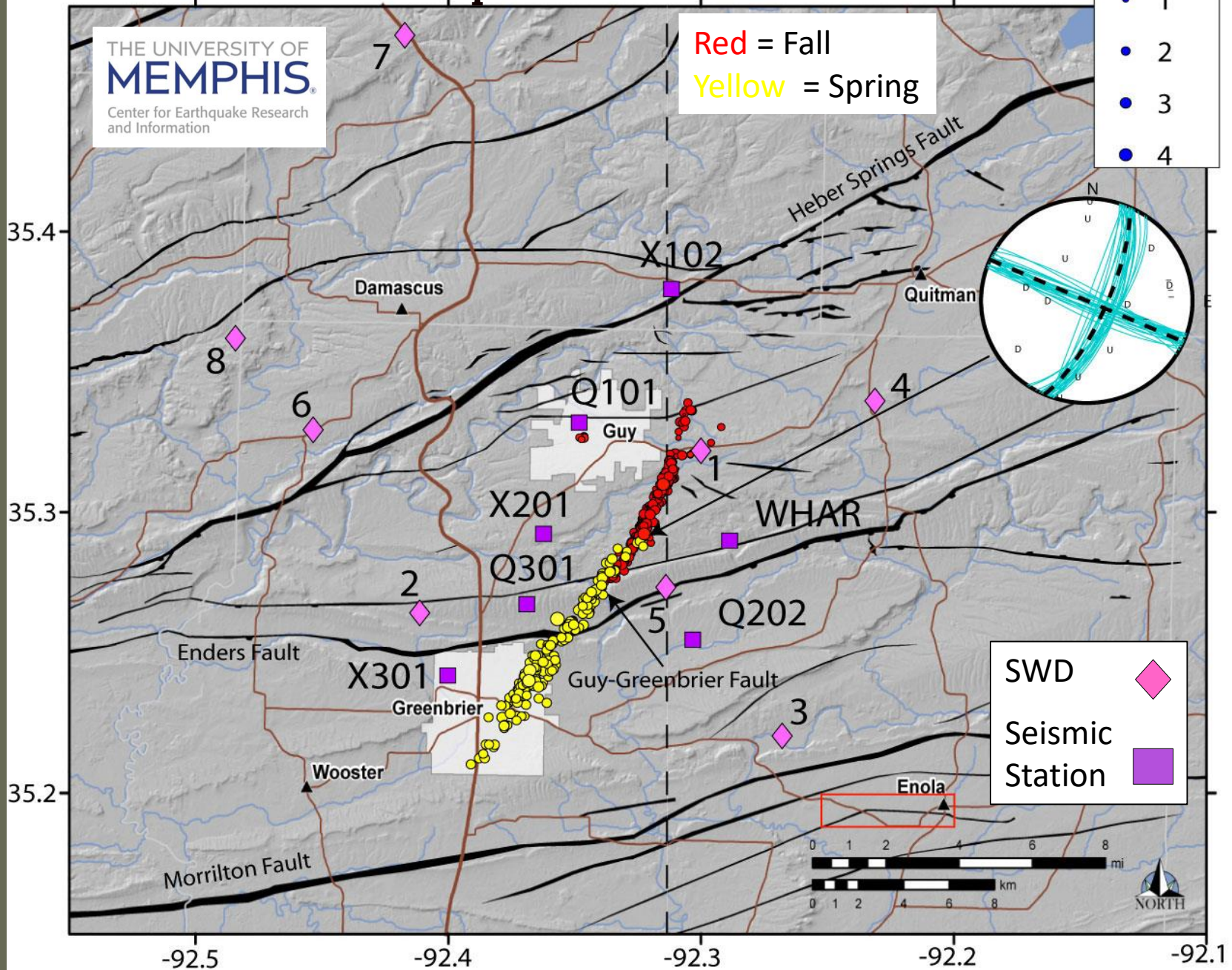
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Red = Fall

Yellow = Spring

- 1
- 2
- 3
- 4



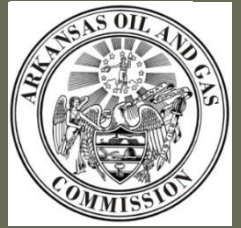
SWD

Seismic

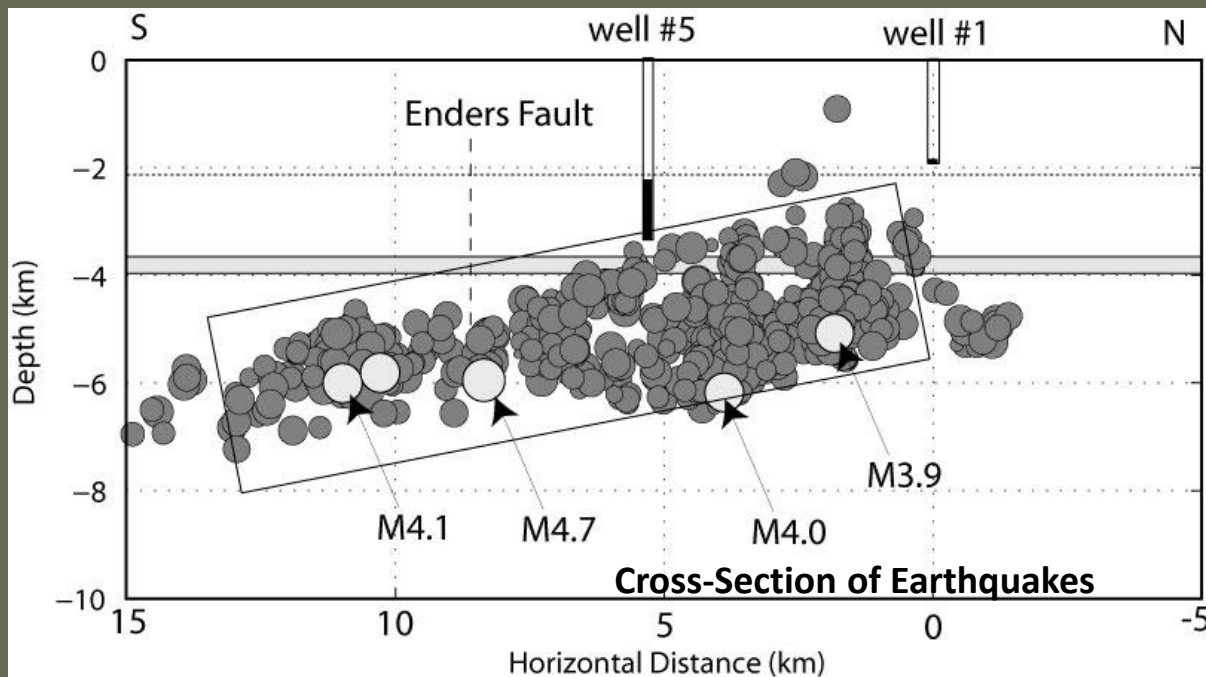
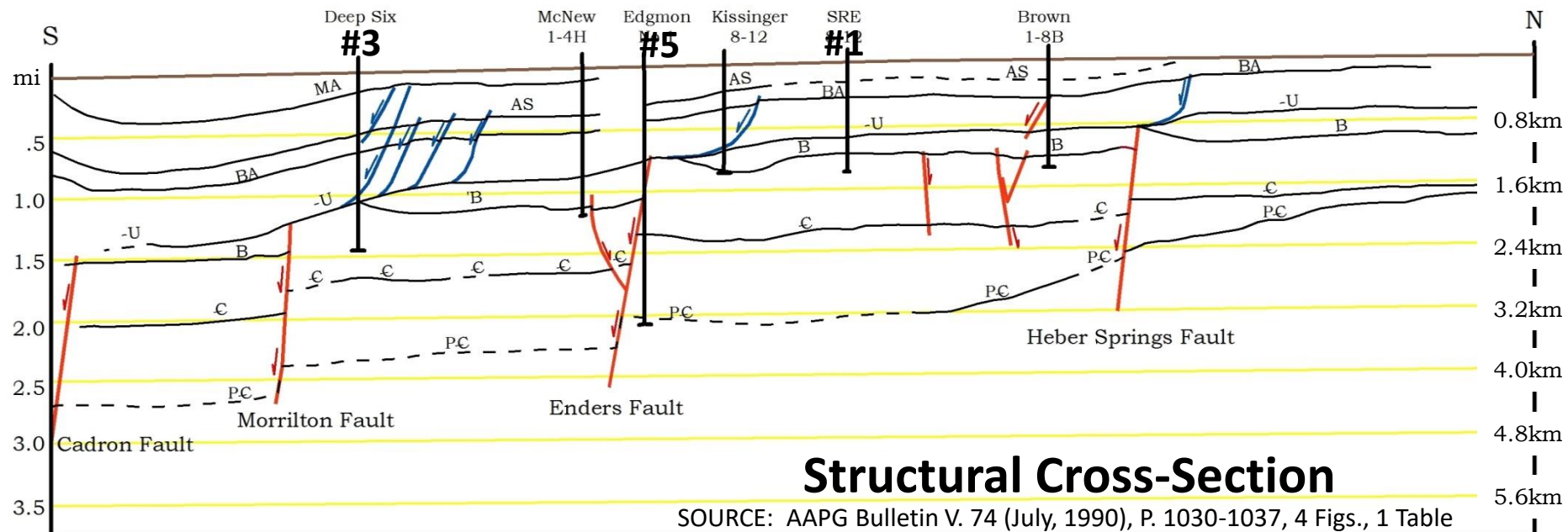
Station



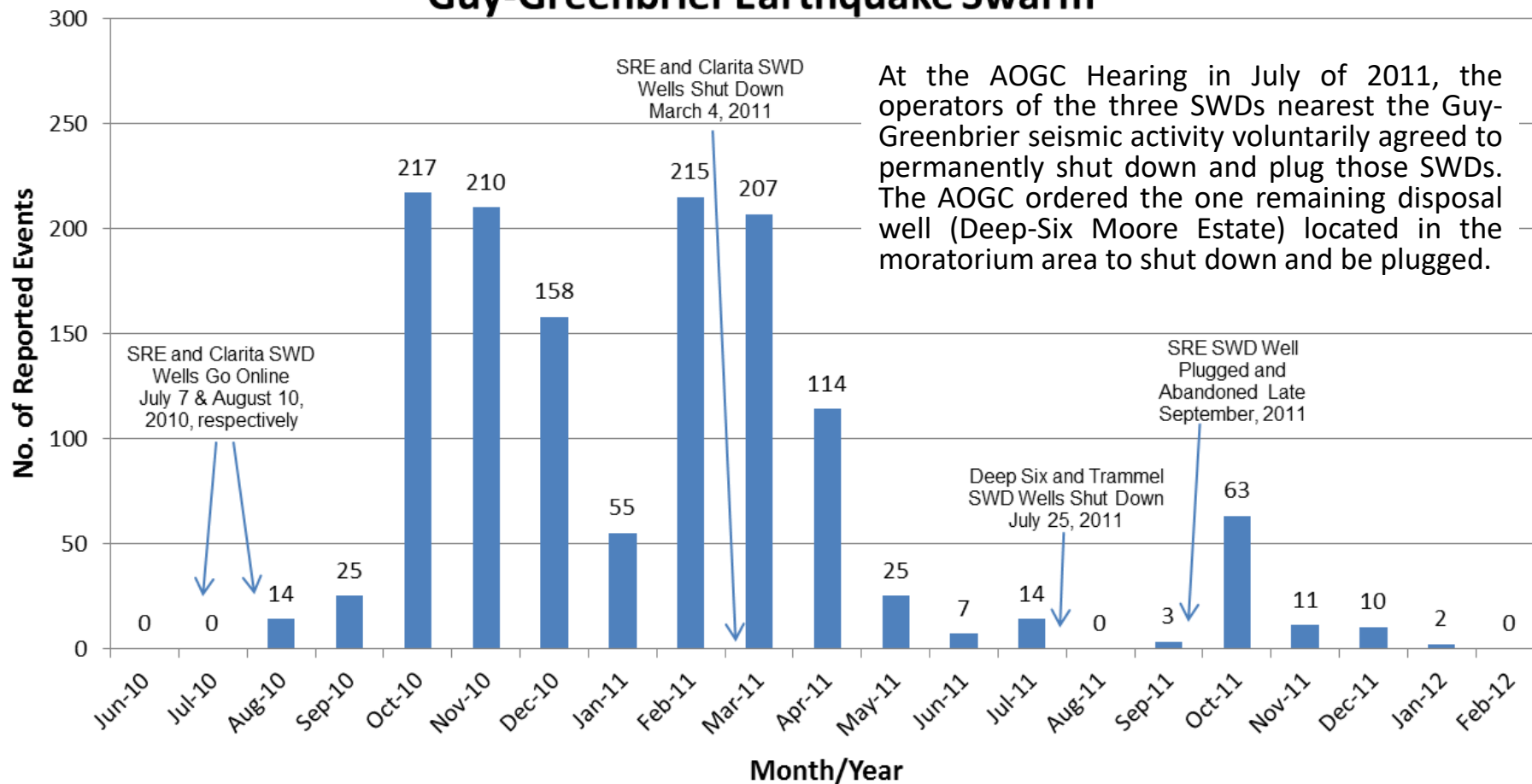
G-G EQ Swarm Regulatory Timeline



- During the week after the M4.7 event, disposal well operators of three of the SWDs closest to the Guy-Greenbrier seismic activity agreed to voluntarily shut down.
- By Friday afternoon on March 04, 2011, the AOGC formally ordered the temporary cessation of the three disposal operations in the Guy-Greenbrier area while the fourth well (Deep-Six Moore Estate) was allowed to continued to operate until the six-month study was completed in June of 2011.



Guy-Greenbrier Earthquake Swarm



At the AOGC Hearing in July of 2011, the operators of the three SWDs nearest the Guy-Greenbrier seismic activity voluntarily agreed to permanently shut down and plug those SWDs. The AOGC ordered the one remaining disposal well (Deep-Six Moore Estate) located in the moratorium area to shut down and be plugged.

Number of events per year:

2010 = 624

2011 = 724

2012 = 8

2013 = 2

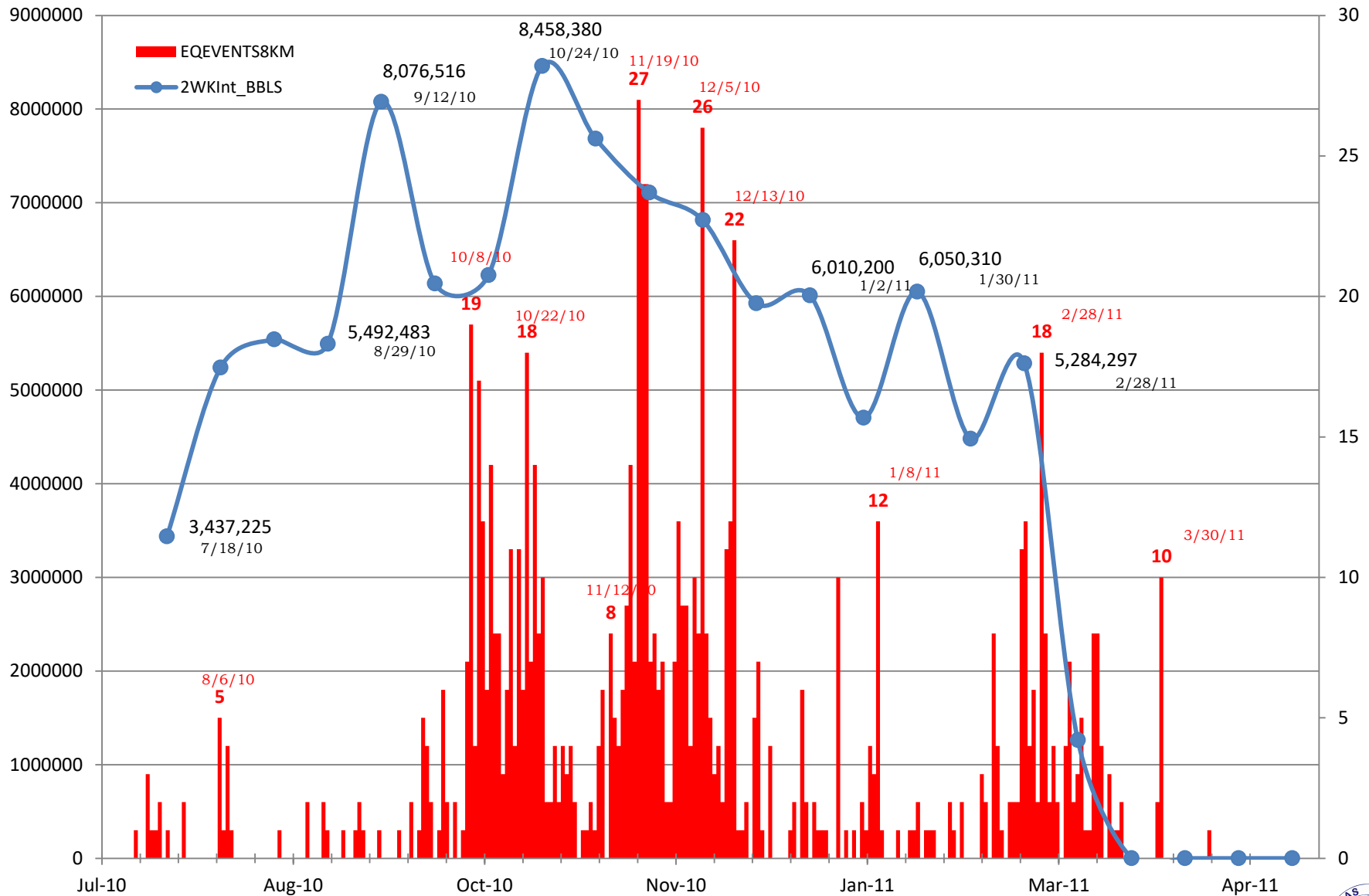
~ 200 = $M_{\geq 2.5}$

~ 40 = $M_{\geq 3.0}$

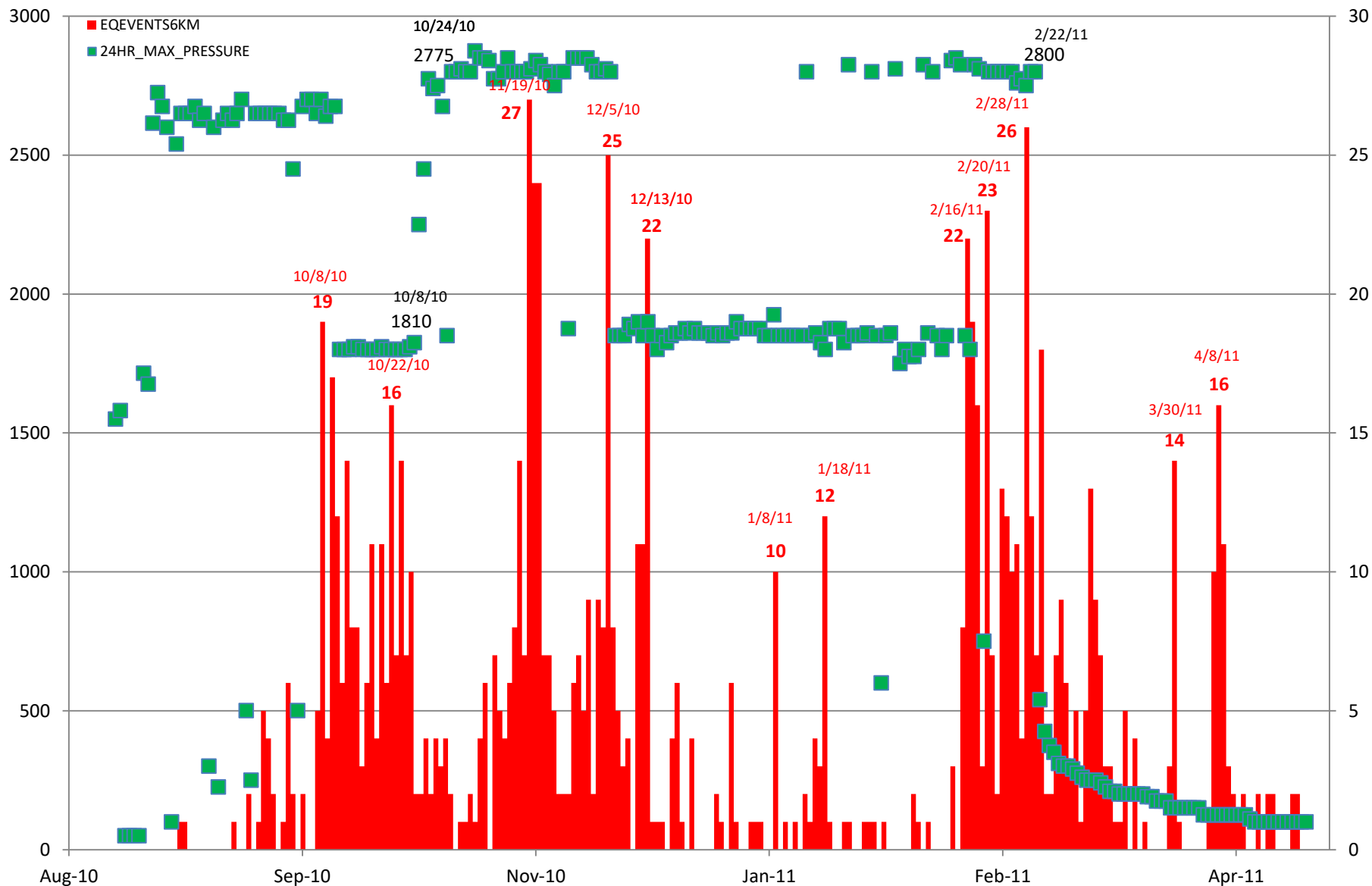
4 = $M_{\geq 4.0}$

Total: 1,358 (>M1.0)

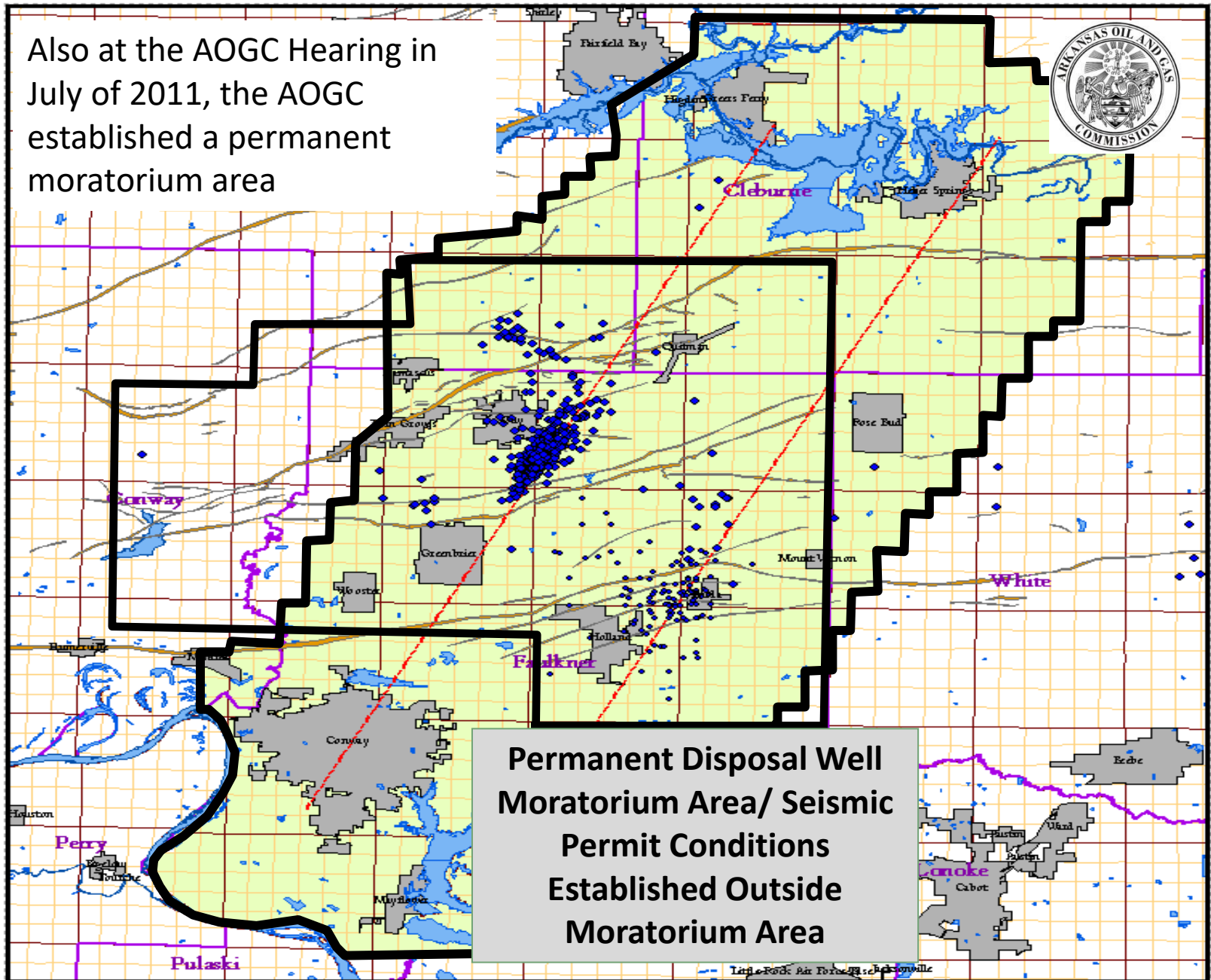
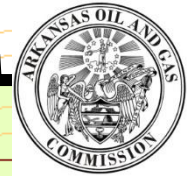
7/8/2010 – 5/8/2011 – SWD #1 Injection Volumes in Gallons



8/18/2010 – 4/30/2011 – SWD #5 Daily Maximum Pressures



Also at the AOGC Hearing in July of 2011, the AOGC established a permanent moratorium area



**Permanent Disposal Well
Moratorium Area/ Seismic
Permit Conditions
Established Outside
Moratorium Area**

General Rule H-1 Disposal Well Permit Seismic Requirements Outside Moratorium Area in Fayetteville Shale Production Area

- Disposal wells not permitted within 1 mile of regional fault (defined) and within 5 miles of deep fault (defined).
- Disposal well spacing established based on stratigraphic depth of disposal zone (1/2 to 5 mile spacing).
- Information on faults required to be submitted with permit application. Director may request additional information if necessary.
- Permitted wells required to submit daily injection rate and pressure information.

Future Items:

- Modification of the Permanent Moratorium Area
- Proposed *Traffic Light Monitoring System...*



What We Have Learned?... Ten years later...

- The **El Dorado EQ Cluster study** suggested that the injection of fluids increases the pore pressure within the reservoir/aquifer of injection.
- The **El Dorado EQ Cluster study** suggested that injection energy contributes little to the magnitude of the earthquakes, and that tectonic strain must already be present in a region in order to induce earthquakes.
- The **Deep-Six EQ study** suggested that injection in previously seismically active areas may not necessarily induce more earthquakes --- the Enola EQ Swarm may have already released the area stress.
- The **Greenbrier EQ Cluster study** indicated that Cross-correlation (template matching) was going to be an important tool for future induced seismicity studies. Also the high b-value for this EQ cluster suggested that fluid-filled faults may be a consideration.

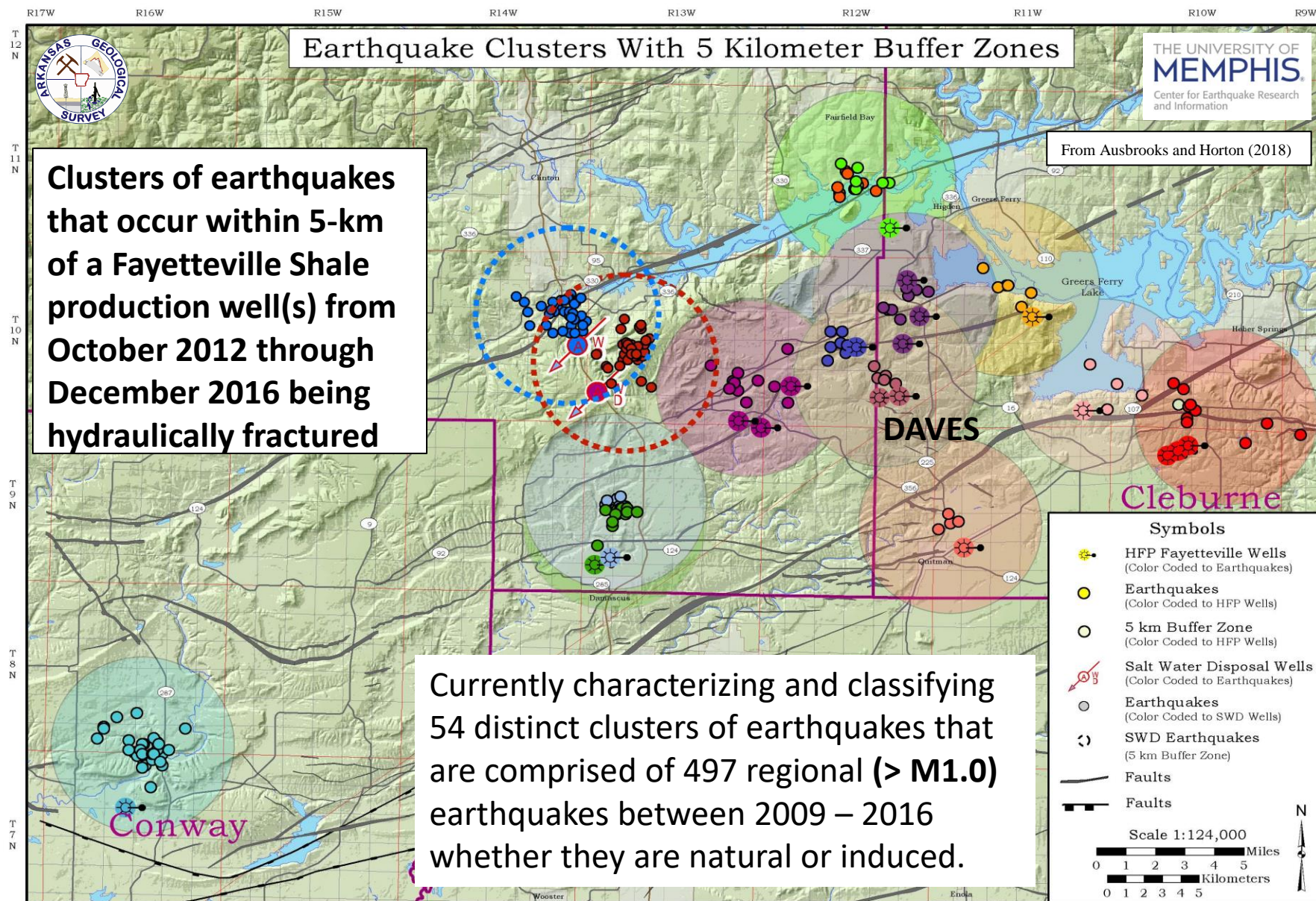


What we have learned?... Ten years later...

- The **Guy-Greenbrier EQ Swarm study** suggested a plausible hydraulic pressure connectivity between the well(s) and the fault(s) via missing confining units and the orthogonal joint sets and fractures thus increasing the pore pressure in the fault zone. This results in a change in the Mohr-Coulomb criterion --- resulting in movement.
- The **Guy-Greenbrier EQ Swarm study** suggested that earthquakes are more likely to occur on faults that are critically stressed (near failure) and are favorably oriented to the regional stress.
- The **Guy-Greenbrier EQ Swarm study** suggested that multiple SWDs in close proximity and injecting into the same interval(s) may have a multiplier effect.
- All the **North-Central Arkansas (NCAR) studies** suggested that tight injection zone rocks with low primary porosity/permeability between the grains. This pressures up the injection reservoir/aquifer quickly. Most likely the pressure front will take the path of least resistance via the joints and fractures (secondary porosity/permeability).



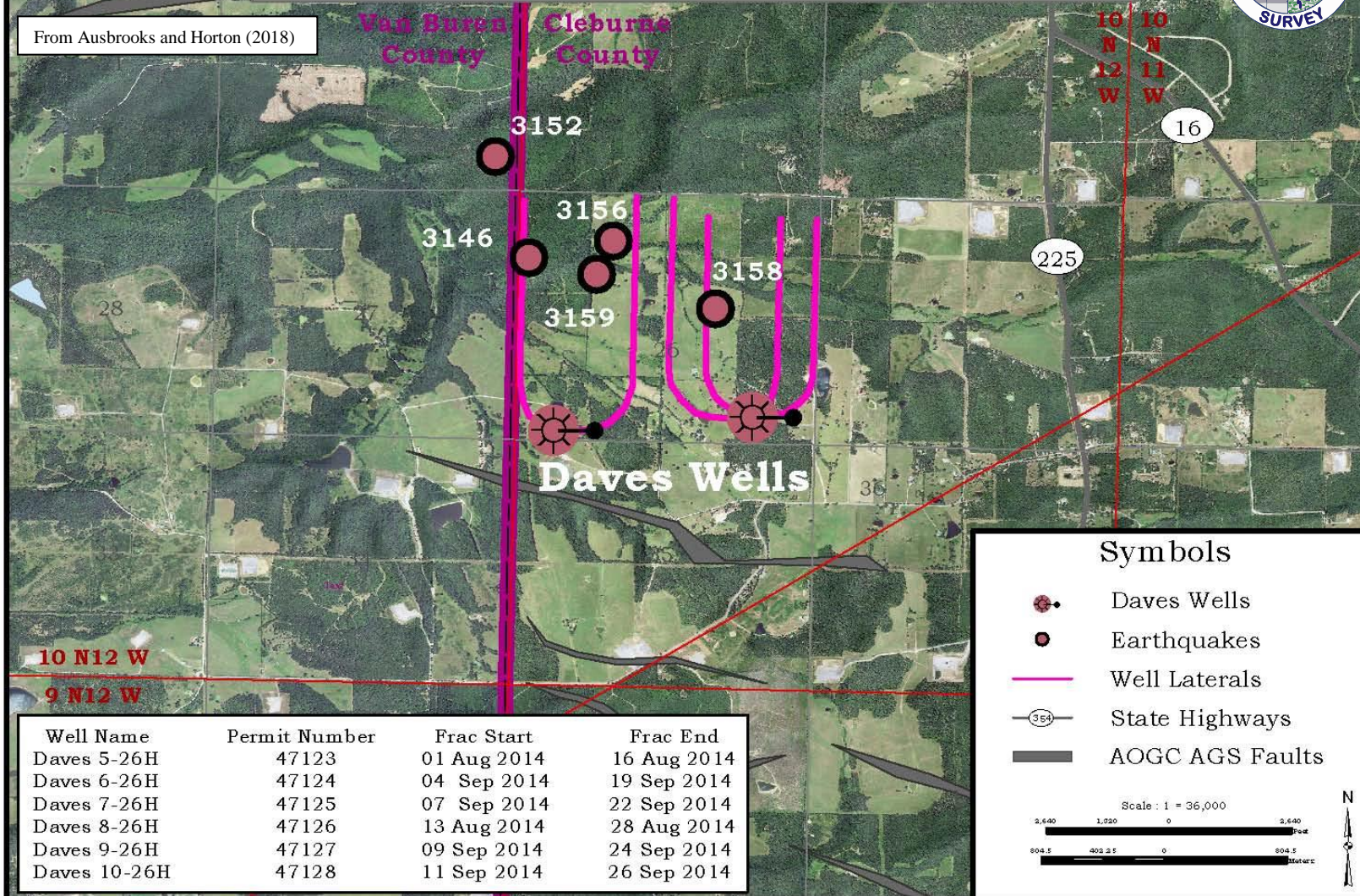
AGS/CERI Current Research Activities Related to Induced Seismicity



Daves Wells Undergoing Hydraulic Fracturing During Earthquake Activity Near Crossroads, AR



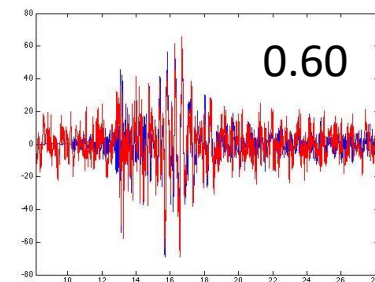
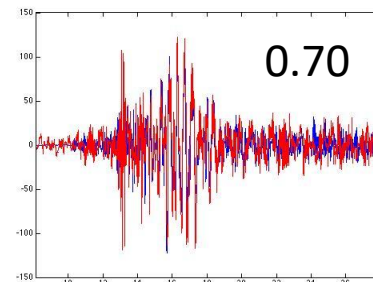
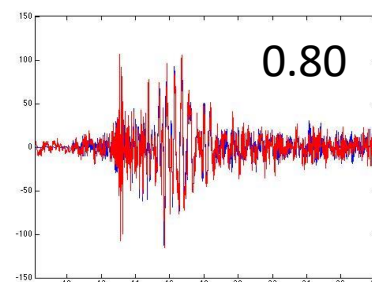
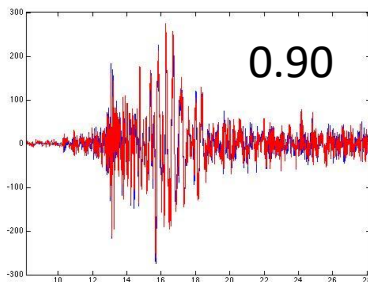
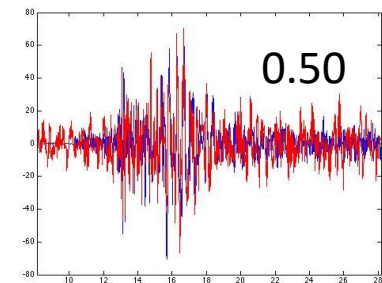
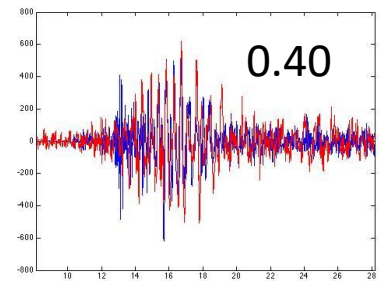
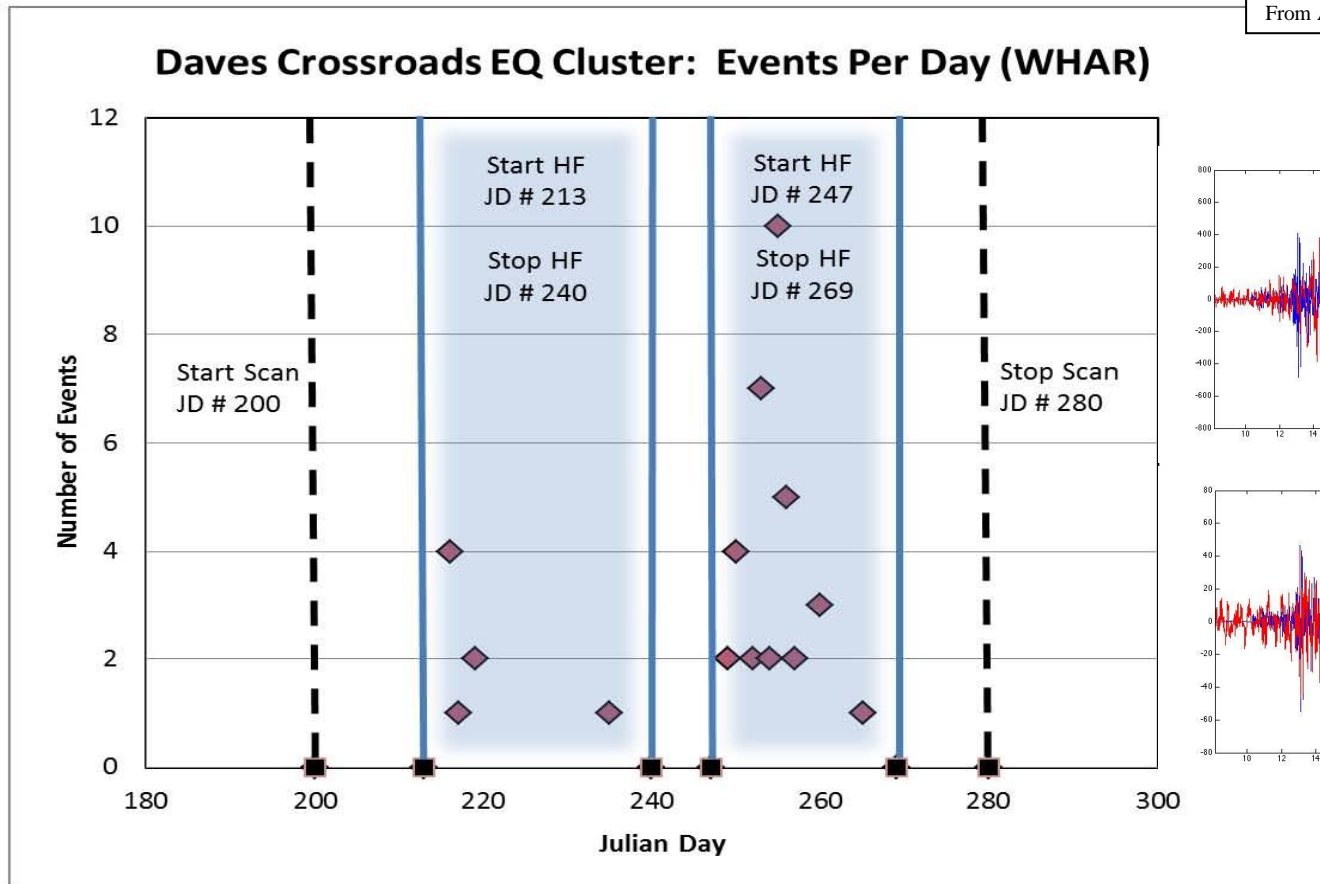
From Ausbrooks and Horton (2018)



Template Matching Earthquake Clusters



From Ausbrooks and Horton (2018)



Sources, Contributors & References



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