The broken traffic light: the troubles with a stale yellow light

Austin Holland and Amberlee Darold, Oklahoma Geological Survey

austin.holland@ou.edu, www.ogs.ou.edu

Introduction

- On September 17, 2013, a swarm of earthquakes began in Love County, Oklahoma, north of Marietta.
- These earthquakes began occurring about two weeks after injection began at a nearby disposal well (LCD #1).
  - Injection well was placed in "yellow light" rate and injection pressure limited
- The largest earthquake was a magnitude 3.4.
- Local residents consistently feel magnitude 1.8 earthquakes
  - Barely detectable by regional monitoring
- The earthquakes are occurring at shallow depths (~2 km) consistent with injection depths of the nearby disposal well.

Damage summary from the magnitude 3.4 Sep. 23, 2013
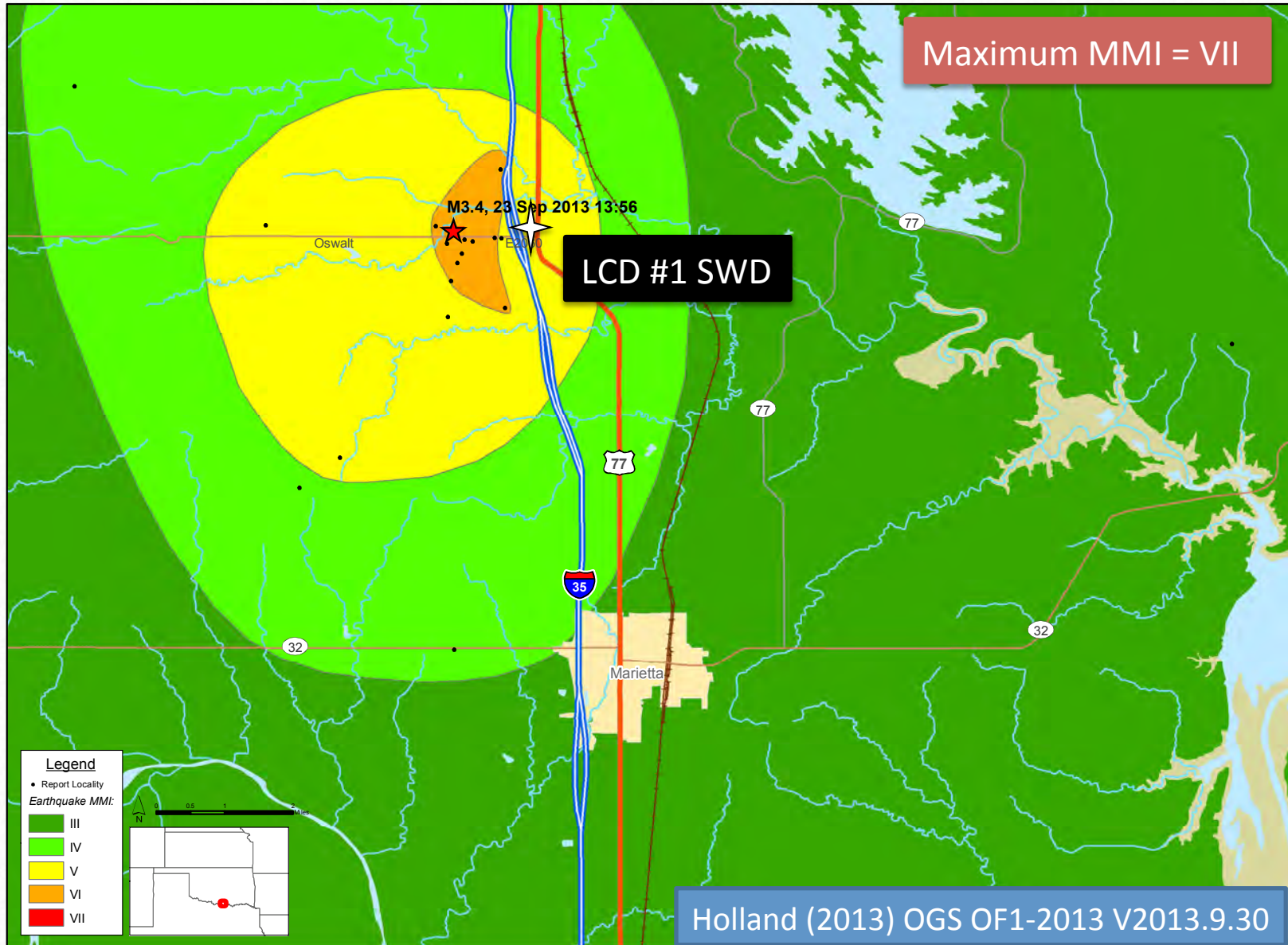
Damage to Homes

- Collapsed Chimney (1)

- Shattered Window (1)

- Damaged brick façade (~5)

- Doors and frames crooked (~5)

- Cracked foundations
  - Difficult to distinguish from normal OK soil effects

- Cracked drywall and cosmetic damage (~15-20)

- Fallen objects and strong shaking (>20)

Photo courtesy of Rhonda Lumry
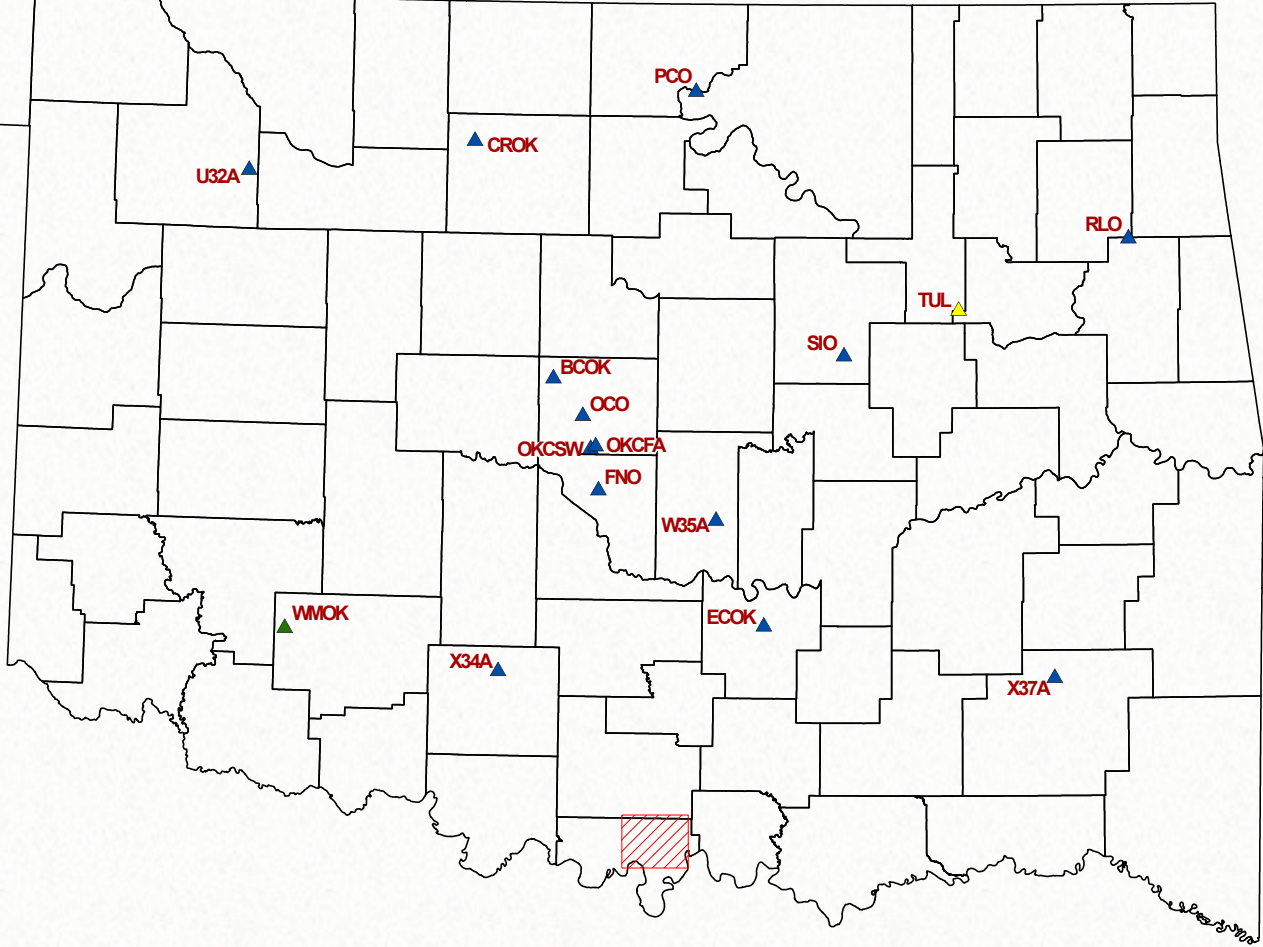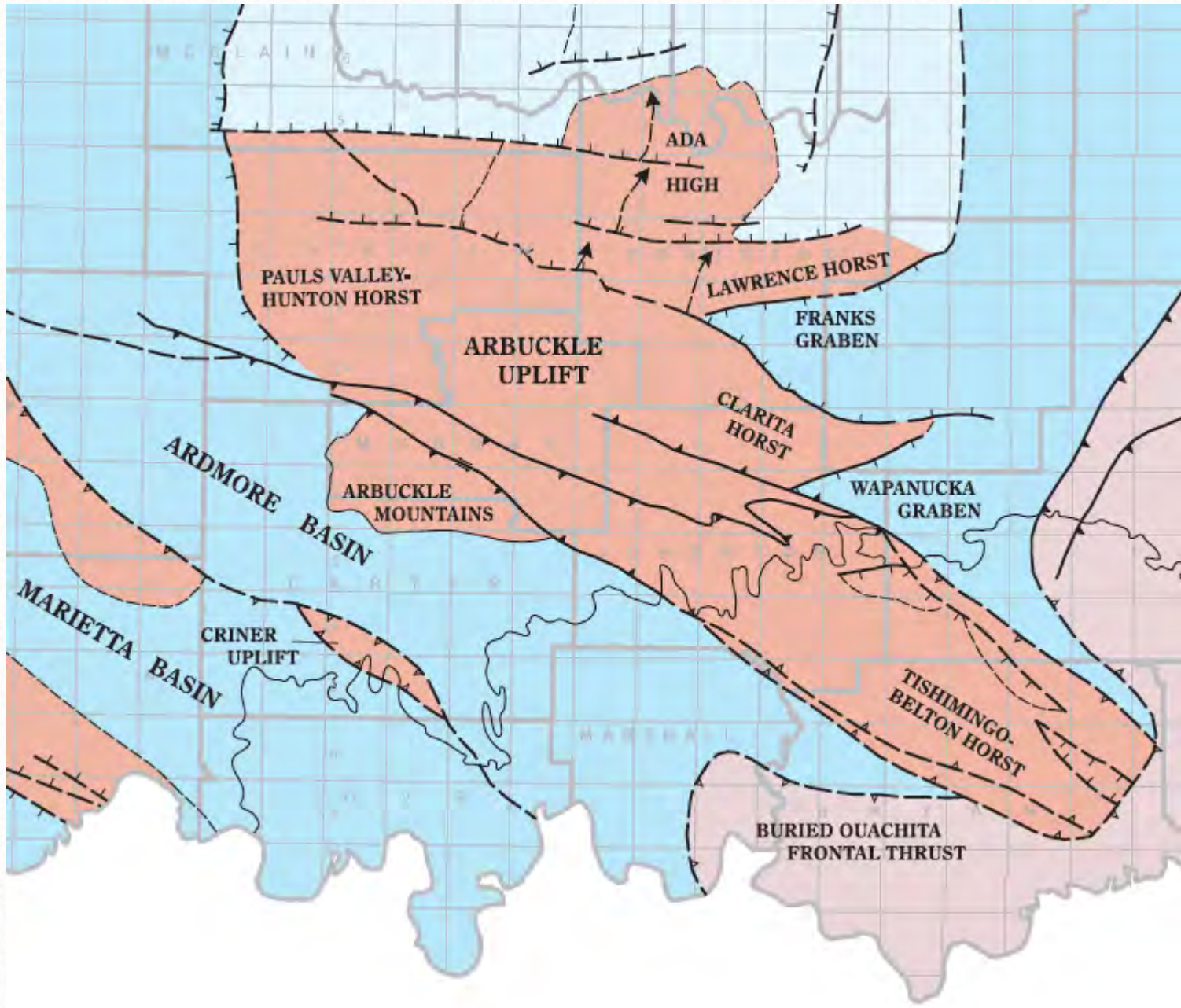
Felt Reports to Modified Mercalli Intensity

Maximum MMI = VII

M3.4, 23 Sep 2013 13:56

LCD #1 SWD

Oswalt

Edno

Marietta

Legend

- Report Locality

Earthquake MMI:

- III
- IV
- V
- VI
- VII

Holland (2013) OGS OF1-2013 V2013.9.30

Created 4:00 PM (CST) 09/26/2013

Regional Seismic Stations

Oklahoma Seismic Stations

Network

△ Leonard Observatory

▲ OGS

▲ USGS

Map labels: PCO, CROK, U32A, RLO, TUL, SIO, BCOK, OCO, OKCSW, OKCFA, FNO, W35A, WMOK, ECOK, X34A, X37A

Arbuckle Uplift

SOUTHERN OKLAHOMA AULACOGEN → ← CRATON

ARBUCKLE ANTICLINE

WASHITA VALLEY SYNCLINE

MILL CREEK SYNCLINE

Cattle Pens

East Timbered Hills

Turner Falls

Seven Sisters Overlook

Dolese Quarry

SOUTH

ARDMORE BASIN
clastics   carbonates

NORTH

Sea Level

Missourian $\mathbb{P}_3$

Desmoinesian (Deese Group)

Morrowan and Atokan (Dornick Hills)

Caney Shale

Sycamore Ls.

Woodford Sh.

Devonian - Silurian Hunton Group

Ordovician-Sylvan-Viola

Ordovician-Simpson Group

Early Ordovician: Arbuckle Group

Late Cambrian

Middle $\mathbb{C}$ Volcanics 525 my

Colbert Rhyolite

Colbert Rhyolite

Mc

Ms

DMw

DS

Osv

Os

Oa

$\mathbb{C}$v

$\mathbb{C}$

$\mathbb{P}_4$

Os

Osv

DS

DMw

Mc

Ms

DMw

Hunton Group

Ordovician Sylvan-Viola

Ordovician - Simpson Group

Os

Oa

Oa

$\mathbb{P}_3$

Virgilian $\mathbb{P}_4$

$\mathbb{P}_2$

DMw

DS

Osv

Os

Early Ordovician Arbuckle Group

Oa

p$\mathbb{C}$

Precambrian granites 1350 my

$\mathbb{C}$

$\mathbb{C}$v

-5,000

-10,000

-15,000

-20,000

0   1   2   3   4   5 Miles

HORIZONTAL AND VERTICAL SCALE
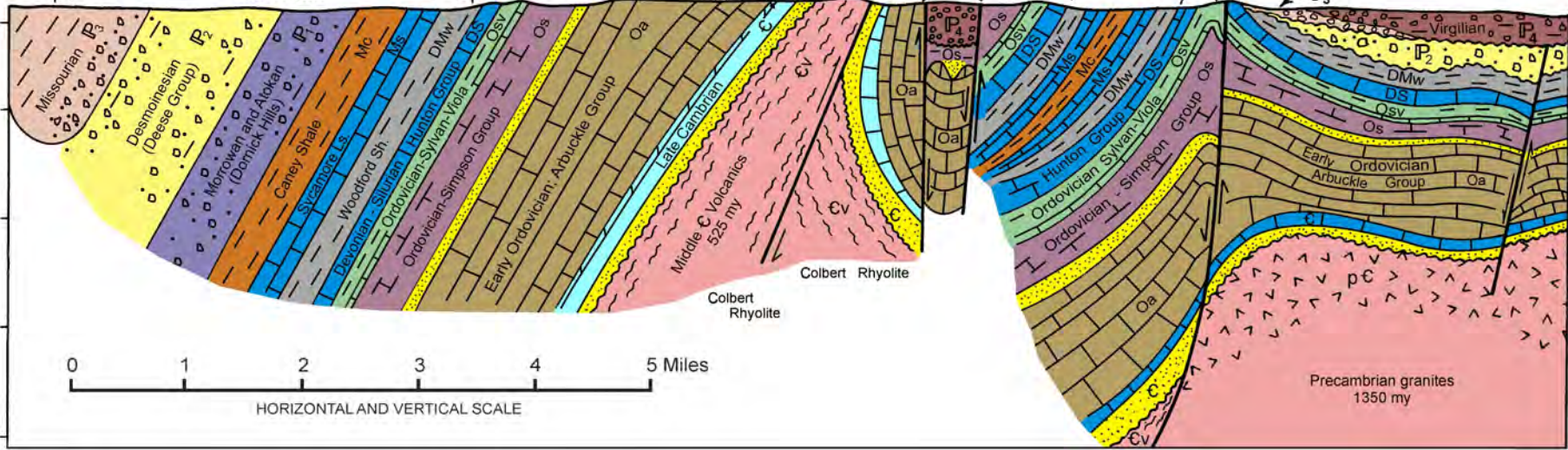
Earthquakes 1882 - 08/29/2013

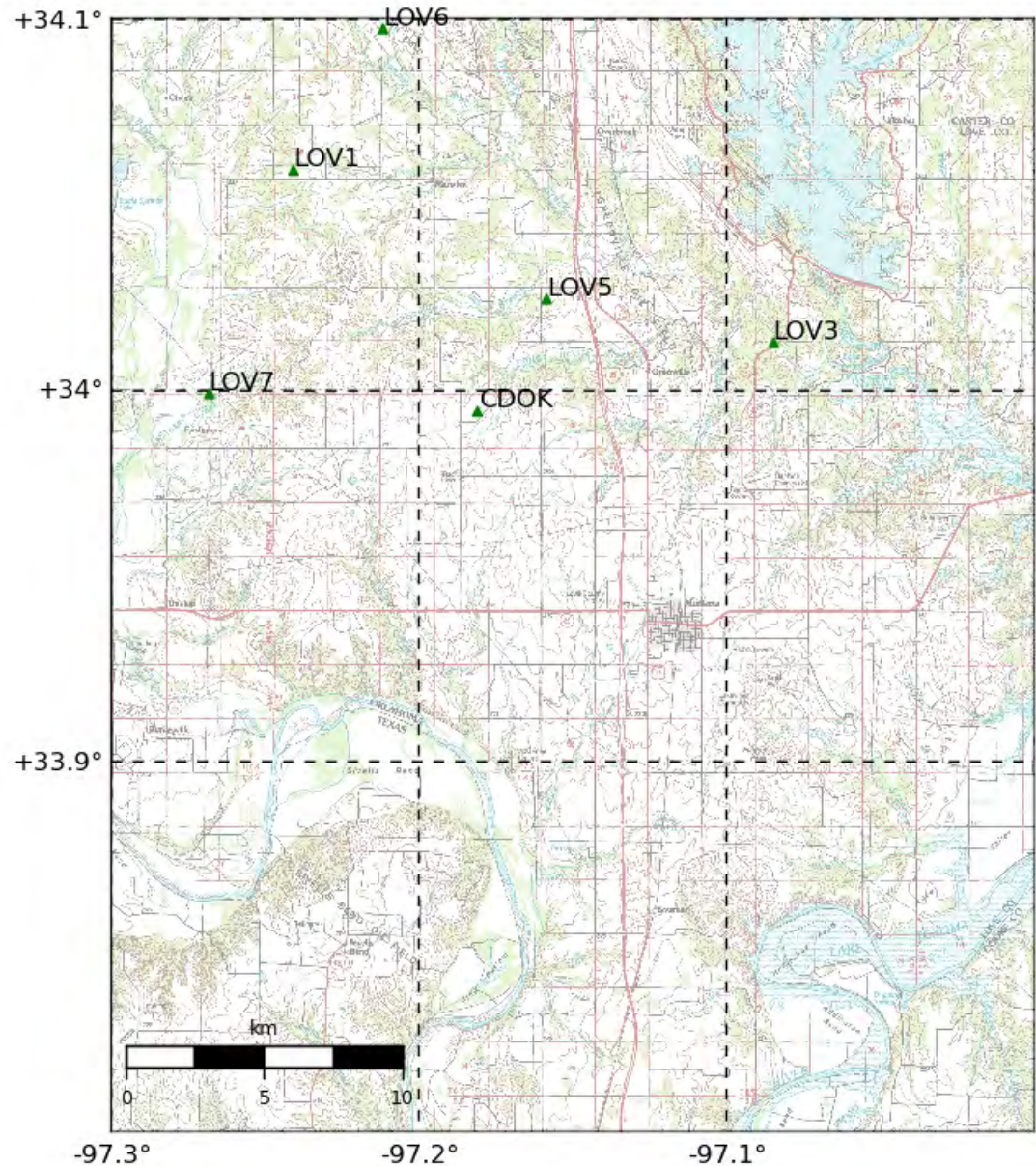**Legend**

Earthquake MM:

- + <1.5
- + 1.5–2.0
- + 2.0–2.5
- + 2.5–3.0
- + >3.0
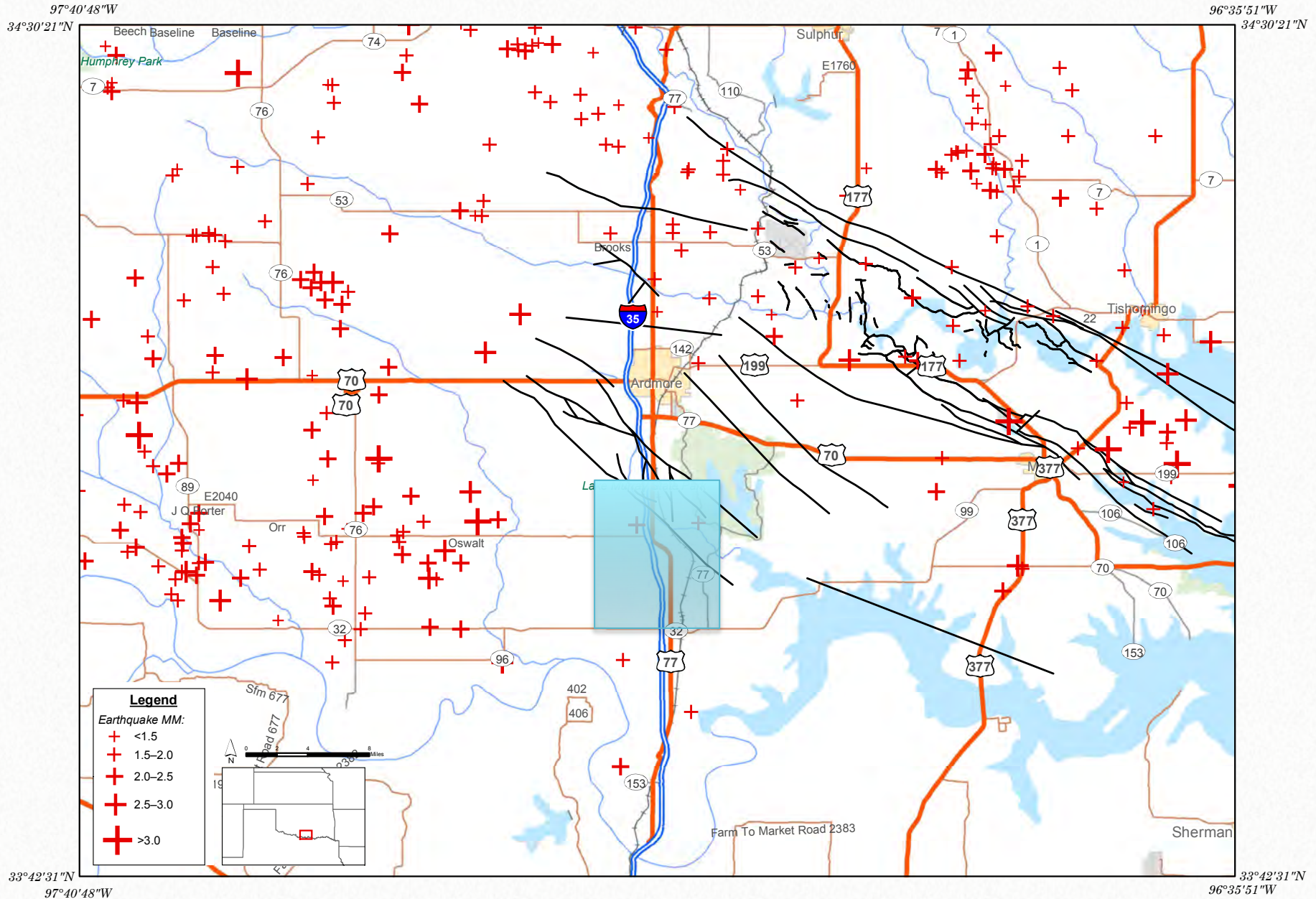
Temporary Network

- First station installed 9/25

- Currently operating now 4 stations in the area

- One will be permanent

- 2 stations have been removed due to logistical reasons

- Detection threshold about M 0.5 within the area

- Status is continuously reported
    - http://wichita.ogs.ou.edu/eq/love/stations/

Earthquake Locations

- prior to local network
- with local net
- Avg depth ~2 km
- Not enough events recorded with both networks to constrain relative locations
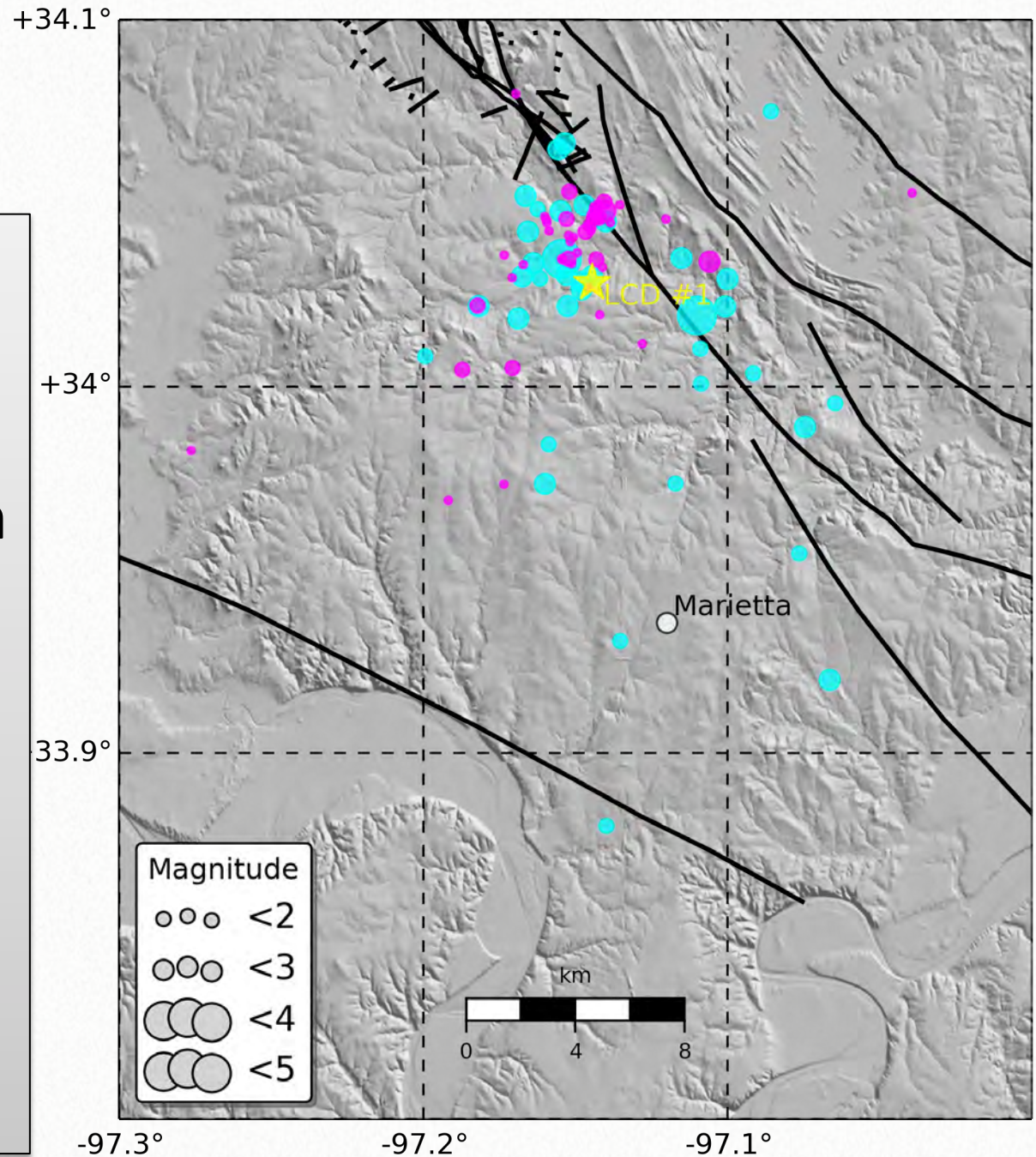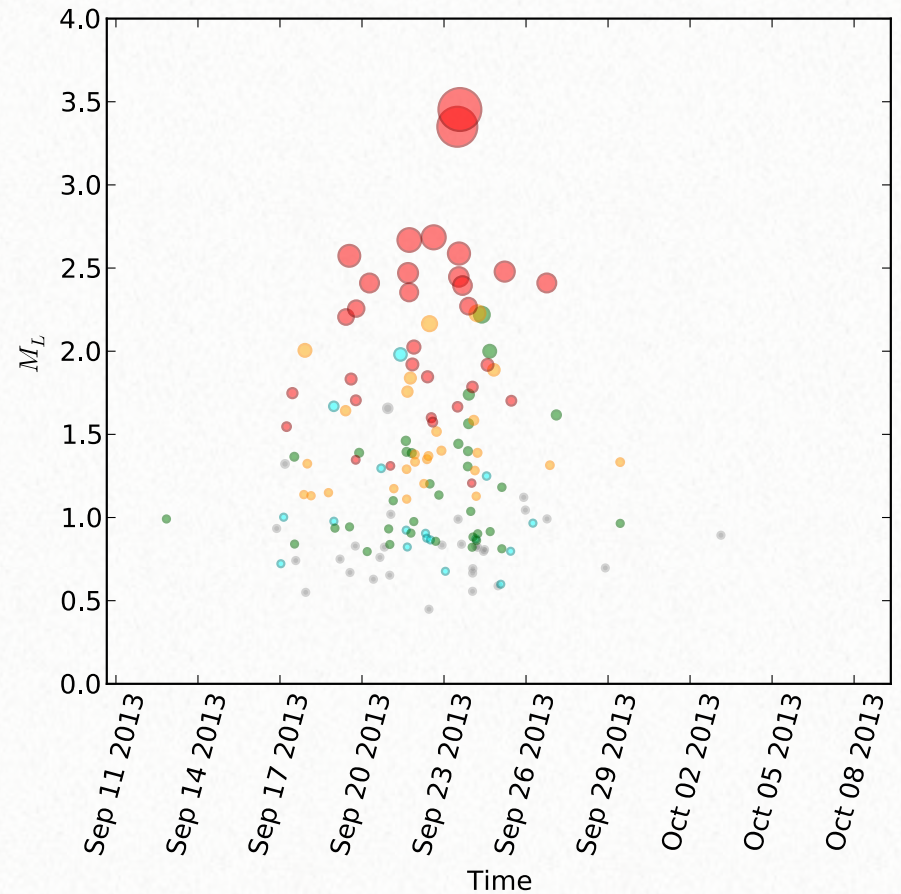
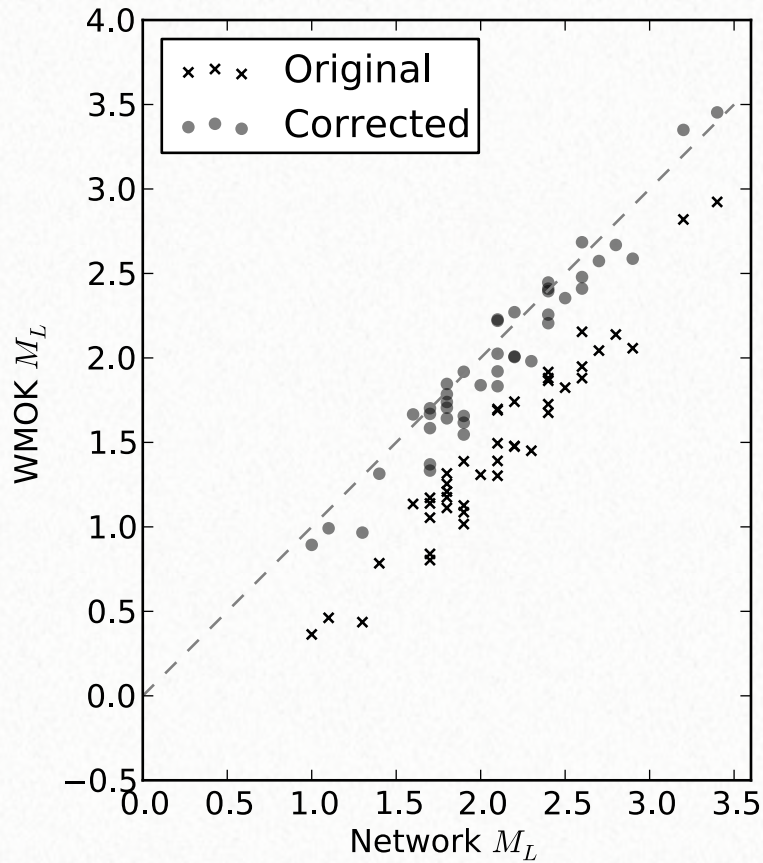# Event identification using cross-correlation
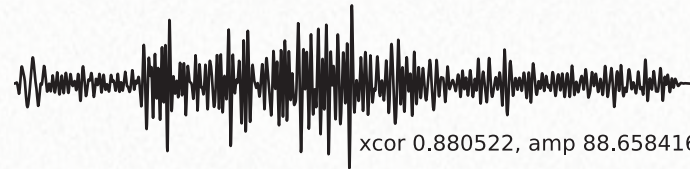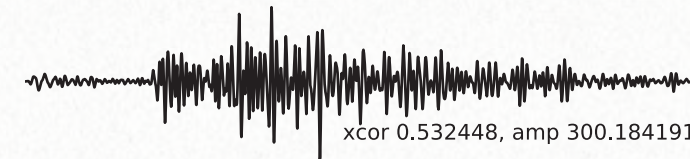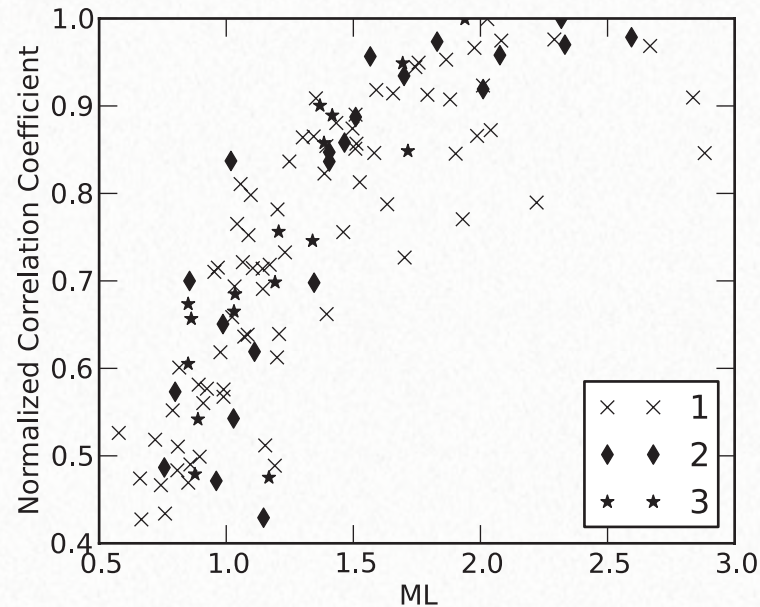
Cross-Correlations for Love County

142 Unique Events Identified through cross-correlation
Using station WMOK
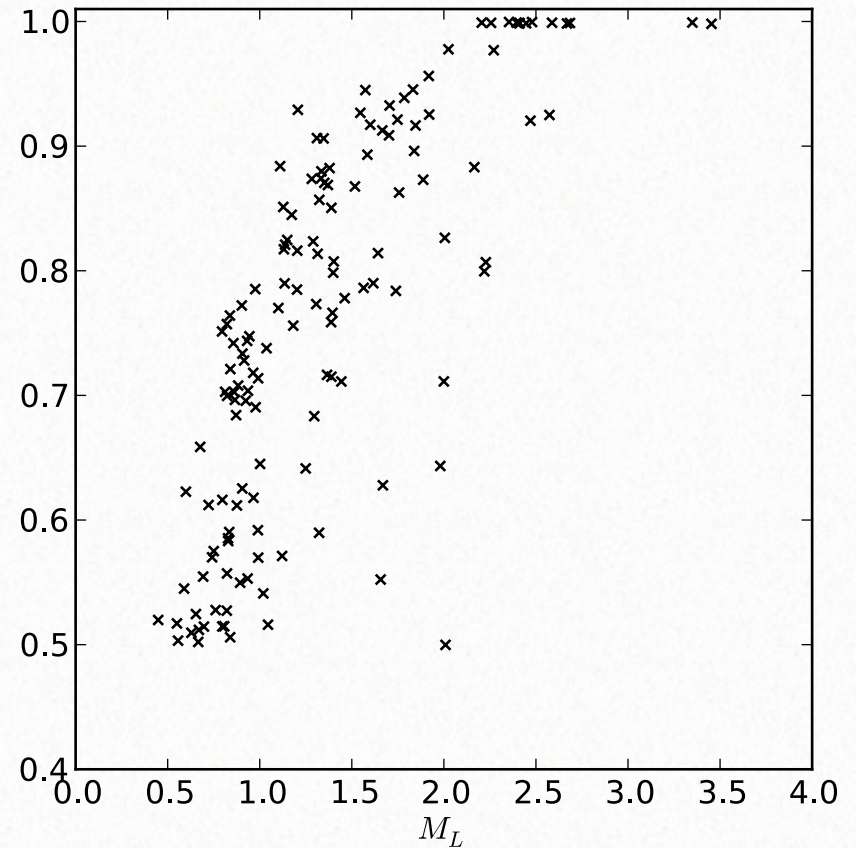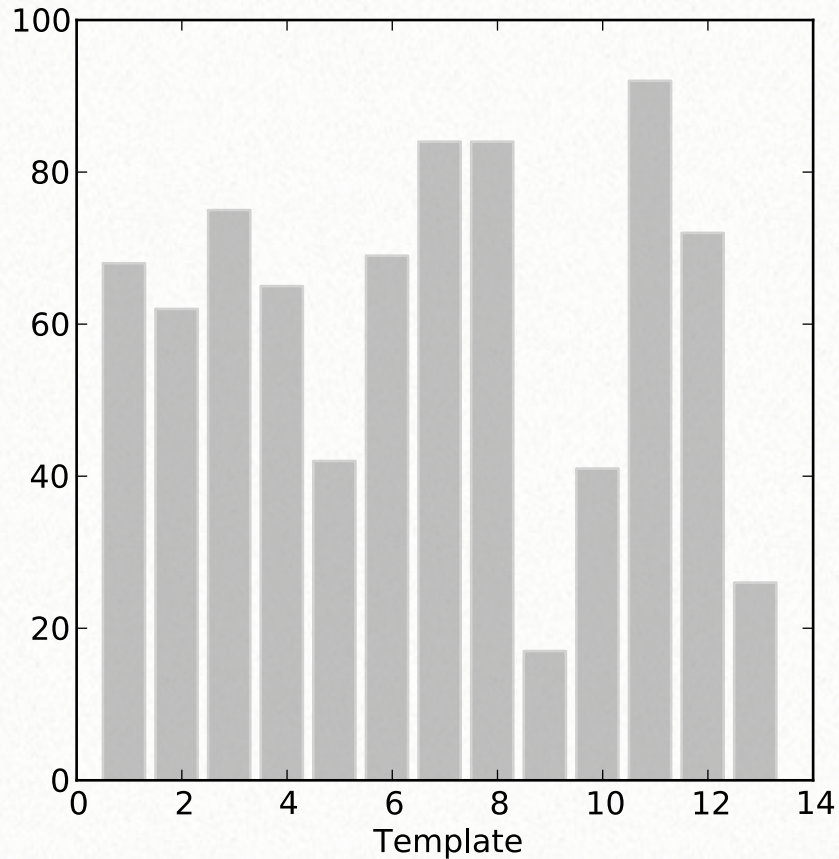
Magnitude Calculations for Love County

LCD #1 Injection and Earthquakes
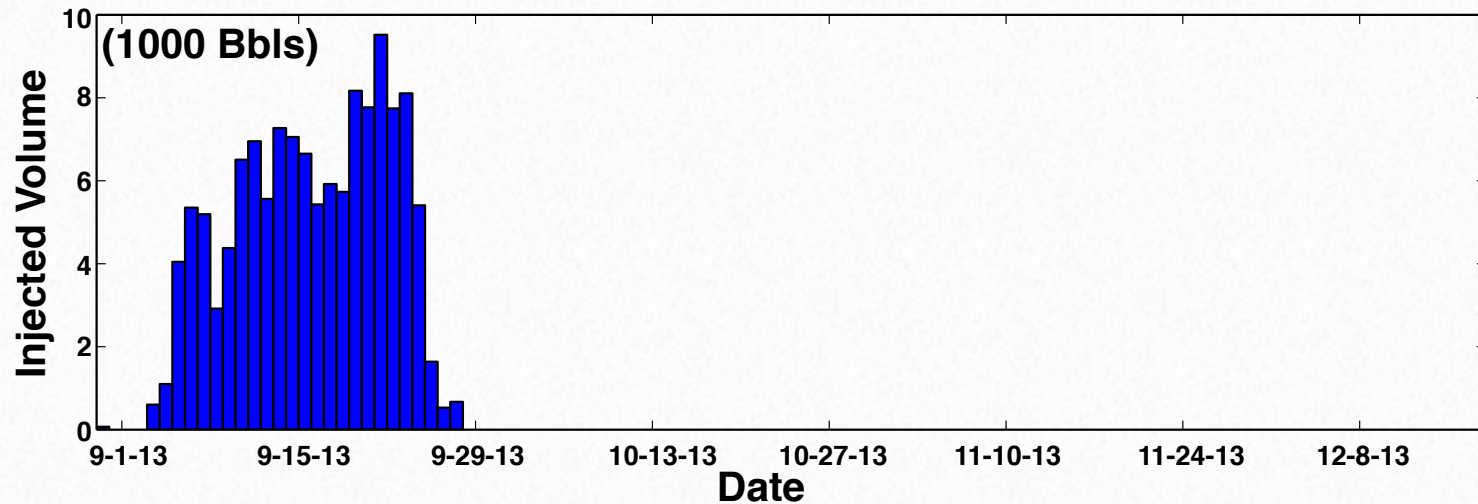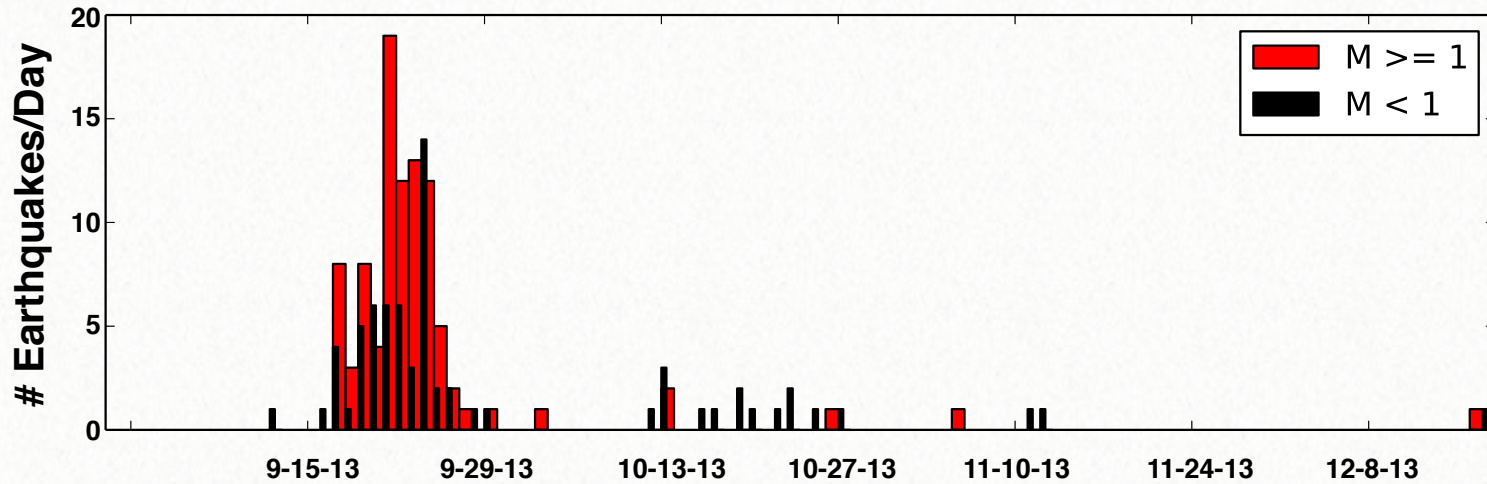
Recurrence and b-values

WMOK Cross Correlations
Events from: 9/16 - 9/29/13
Magnitude of Completeness: Mc~1.0

$log_{10}N = 1.69 - 0.79 \, M_L$
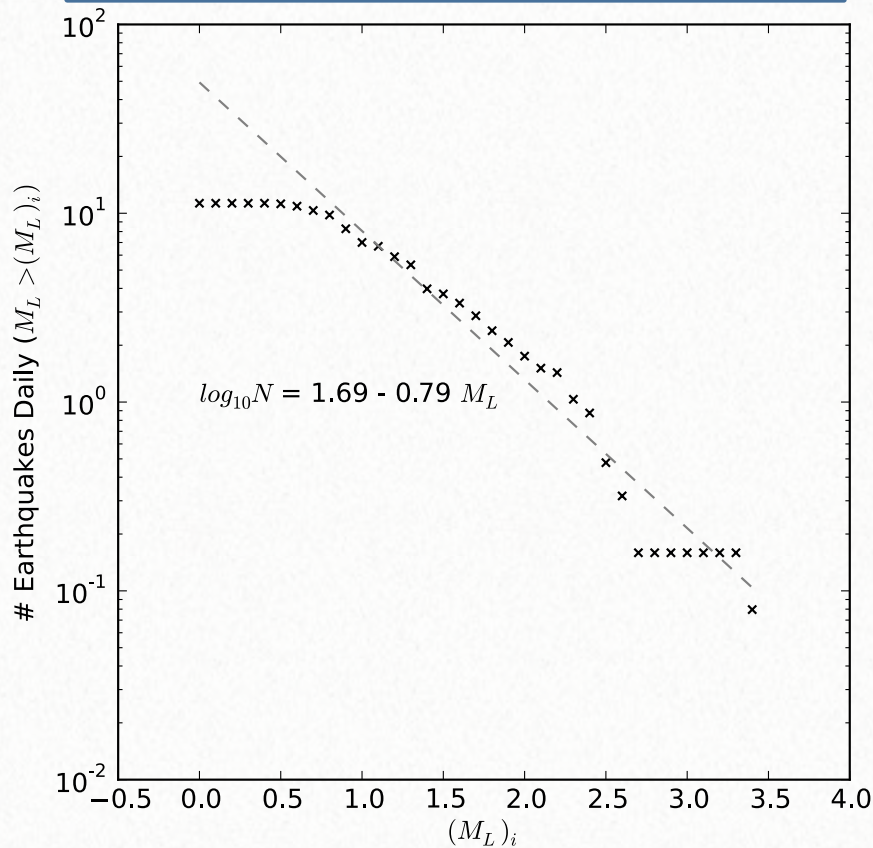
Earthquakes located using local network
Events from: 9/29 - 4/25/14
Magnitude of Completeness: Mc~0.5

$log_{10}N = -0.64 - 0.90 \, M_L$

Rate of earthquakes much greater during injection

Why inject under a yellow light condition

- Cannot definitively state that the earthquakes were directly caused by injection at LCD #1
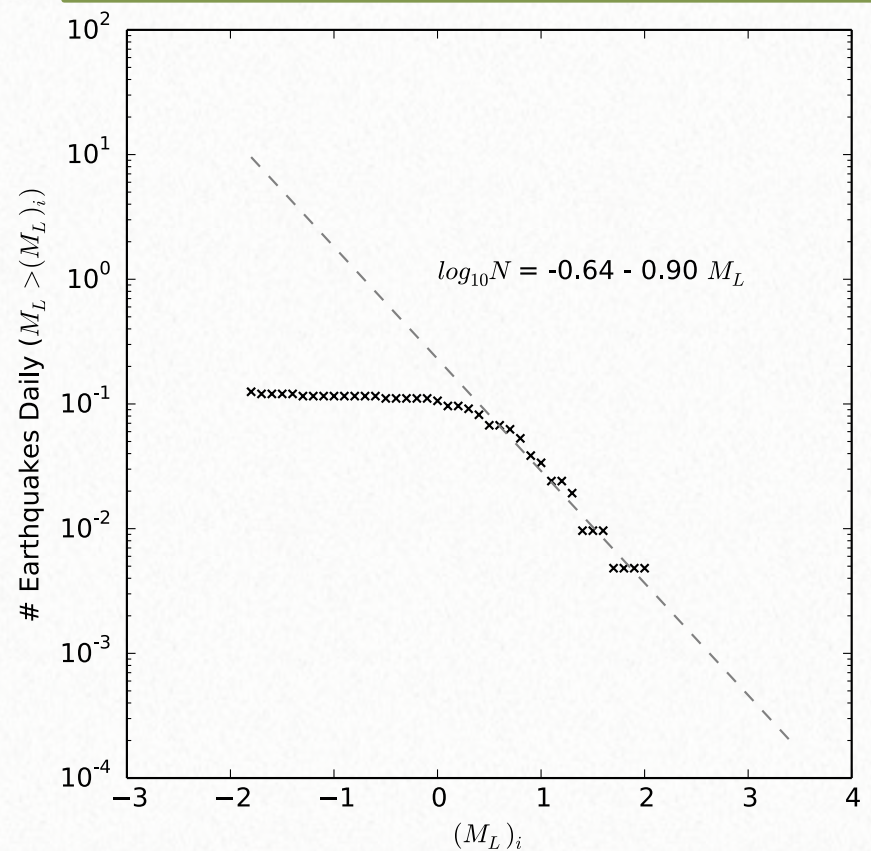 - The earthquakes are similar in characteristic to past swarms in the area and could simply be an unlikely coincidence
- Developed traffic light criteria that would minimize risk should the operator to potentially continue operating
  - Cannot predict earthquakes and there is some risk in resuming injection
- There is still a financial incentive for the operator to attempt injection
  - Damage from the M3.4 is much less than the cost of a disposal well
  - Rate and pressure limits of yellow light are significant for operations
  - Operator may resume injection "soon"

Traffic Light Example

To resume at the yellow light with initial injection starting at the current rate (3,000 bbl/day) and pressure limit (375 psi)

- If all red light criteria are not met for ~21 days

- Injection could potentially increase to two pumps ~6,000 bbl/day and be held at this level for ~14 days

- If all is still fine injection, increase to full scale, but under the yellow light condition
  - Earthquake monitoring continues and a red light could occur if any of the earthquake conditions are met.

Potential Red Light Criteria

If any one of these criteria is met a red light on injection is recommended

- M1.8 or verifiable felt earthquake
- If the rate of earthquakes increases after injection begins
  - such that at the 95% confidence interval that the rate of earthquakes is distinct from background
- If the probability based on the Gutenberg-Richter law is 95% for at least one M1.8 earthquake in the next 7 days

Are single magnitude thresholds appropriate?

Probability of at least one M magnitude or greater in 60 days

	a	% Prob M 1.8	% Prob M 2.5
Background	-0.7522	38.41	10.6
2σ – 95% CI	-0.5743	57.78	15.97
Injection	1.722	100	100

- Significant probability of a M 1.8 earthquake during yellow light condition.
- A magnitude 2.0 occurred within the study area within the 60 days from calculating these

Fixed b-value 0.8
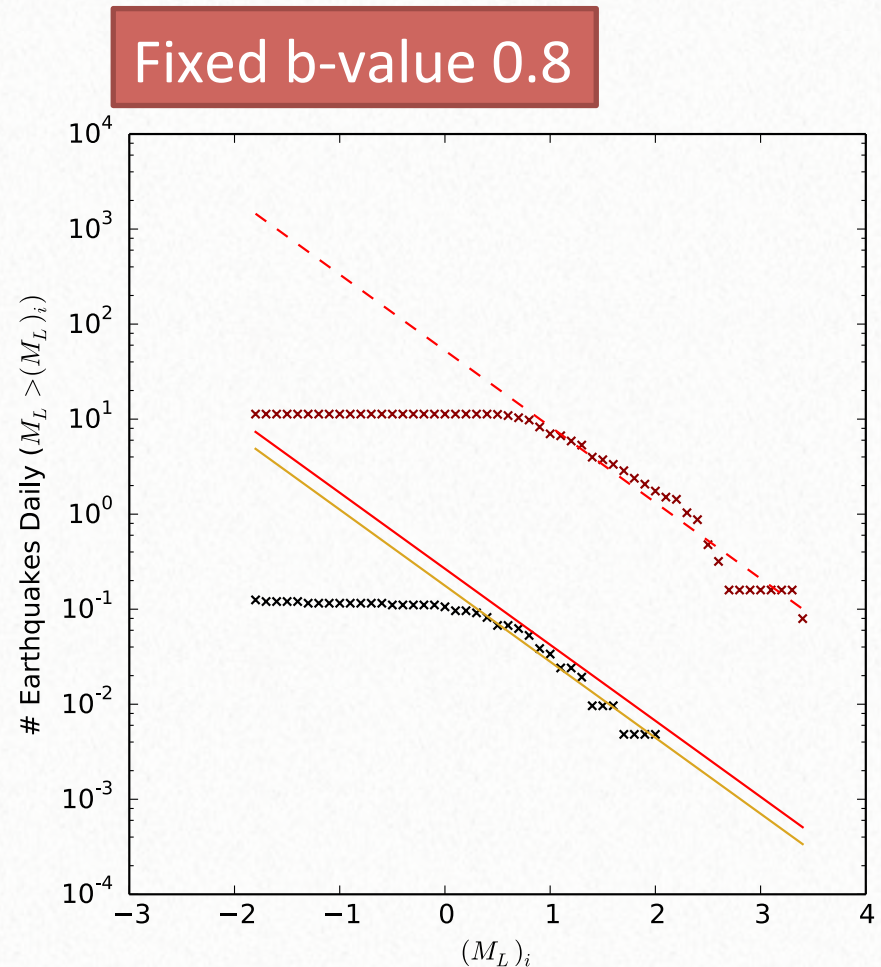
Where are we?

- More than a year later, does the light turn red, green or stay yellow

- Operator is applying to begin operations under yellow light conditions

- Seismic monitoring remains in the area

- How do we construct meaningful stoplights that are responsive and do have the potential to change colors?

  – Operational forecasting?

Felt Reports to Modified Mercalli Intensity

Maximum MMI = VII

ROMAN #2

M3.4, 23 Sep 2013 13:56

LCD #1 SWD

Oswalt

Marietta

Legend
- Report Locality

Earthquake MMI:
- III
- IV
- V
- VI
- VII

Modified from Holland (2013) OGS OF1-2013V2013.9.30

Created 4:00 PM (CST) 09/26/2013
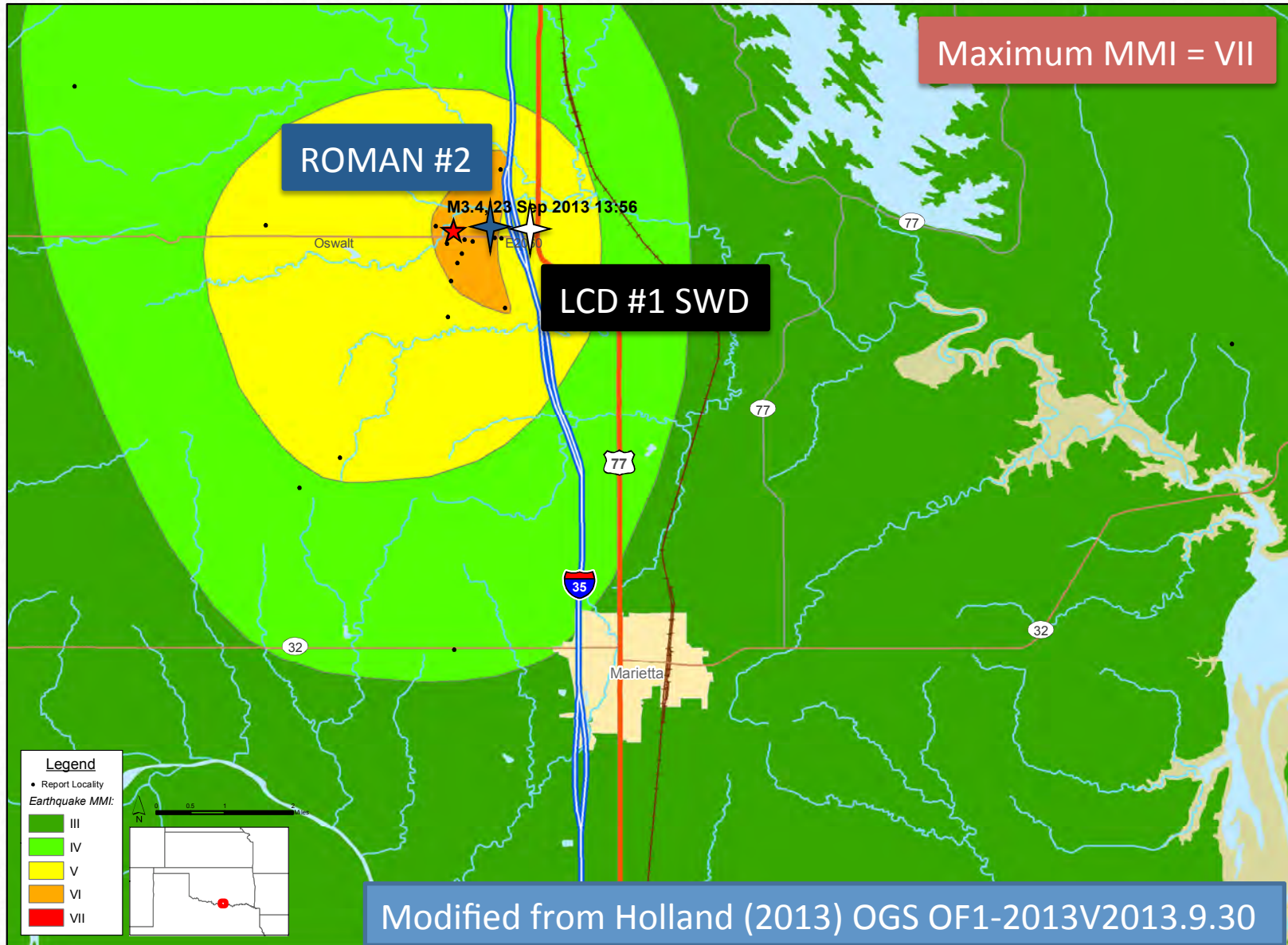
Abstract

On September 17, 2013, a swarm of earthquakes began in Love County, Oklahoma, north of Marietta. These earthquakes began occurring about two weeks after injection began at a nearby disposal well. The largest earthquake was a magnitude 3.4, which did minor damage to structures in the epicentral area and had a maximum Modified Mercalli Intensity of VII. Local residents consistently feel magnitude 1.8 earthquakes. The earthquakes are occurring at shallow depths consistent with injection depths of the nearby disposal well. The sequence included 22 earthquakes of magnitude 2.0 or greater with more than 100 earthquakes identified during the period which injection occurred. Regional seismic stations provide poor coverage of the earthquakes, in part due to the shallow focal depths. A temporary network of six seismic stations was deployed in the area. This network greatly enhanced earthquake locations and dramatically improved the magnitude of completeness. Earthquakes continued after injection ceased but at a lower frequency and smaller magnitudes with only one felt earthquake. This area has seen similar shallow earthquake swarms in the past. It is important to address whether or not this swarm of earthquakes is caused by fluid injection at the nearby disposal or simply an unlikely coincidence. Techniques used to improve event identification and locations of the earthquakes are presented. A statistical method to quantitatively address seismicity changes is adopted and implemented in a monitoring system, in the event injection resumes in the disposal well or in a nearby well that was recently completed.   The operator of the disposal well is currently restricted on injection rates and volumes and has ceased operations, if injection resumes the results of the statistical monitoring and traffic light system will be presented.