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The Structural Analysis of Enola and Greenbrier, Arkansas Earthquake Swarms: Cause and Effect?

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The Structural Analysis of Enola and Greenbrier, Arkansas Earthquake Swarms: Cause and Effect?

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by

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Abstract

Almost 20 years after the remarkable earthquake swarm of 1982, near the town of Enola, Arkansas, with more than 40,000 micro-earthquakes, another event revisited the same North-Central Arkansas region in 2001. Nine years later, in 2010, a huge swarm event shook the northern part of Faulkner County, around the city of Guy. The following year, this seismic swarm event apparently migrated southward towards the city of Greenbrier, with an increase in the number of yearly recorded events. A 13km previously unrecognized, NE trending Guy-Greenbrier basement fault was revealed as a result of these swarm events.

Within the vicinity of the Greenbrier earthquake swarm in the eastern Arkoma basin, north of the Ouachita Mountains, the first waste water disposal well became operational in April 2009, and a total of six disposal wells are known to have been operating between 2009 and 2011. The deepest of these was the Wayne Edgmon well, which was injecting above the intersection of the Enders and the Guy-Greenbrier fault. The area experienced an increase in magnitude M $\geq$2.5 earthquakes during periods of Saltwater Disposal (SWD). The Enola and Greenbrier swarms are known to be in an intraplate setting and the generation of earthquakes in such a setting is uncommon. In the Enola swarm vicinity, a leveling survey in 1986 revealed a rise in measured elevation within the Paleozoic graben, where the swarm hypocenters are located, and correlated as a possible cause.

The Enola sequence still has unanswered questions and the Guy-Greenbrier swarm raises the possibility to find answers to these questions. Though both swarms are tectonically and geologically related, they do not seem to have similar triggering mechanisms as there were no disposal wells in the study area prior to 1982. The recent NGS levelling survey showed insignificant changes in elevation, thus graben uplift is still considered a triggering mechanism for

the Enola swarm. With the onset of SWD wells and increase in seismicity between the towns of Guy and Greenbrier during the same time, as well as responses to the seismic profiling questions in regards to background seismicity, injection practices, temporal and spatial correlations, the Greenbrier appears to be an induced event, while the Enola event appears to be unrelated to human activity.

Acknowledgements

There is a long list of good people that helped me make this work a reality.

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I would like to thank Dr. Gregory Dumond for his constant willingness to answer the questions I had in regards to the tectonics and structure of the study area Josh Stokes for explaining the basic principles of hydrofraking and various pressure components involved. Ginny Holcomb for her patience and assistance with ArcGIS. Gordon McCain, Fatimah Al_Asadi and Daigo Yamamura for their input and peer review.

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I. INTRODUCTION

The first event associated with the North-Central Arkansas earthquake swarm was detected by the Tennessee Earthquake Information Center (TEIC) permanent station OLY on January 12, 1982 (Johnston and Metzger, 1982). This event occurred in Faulkner County, near the town of Enola, 30 miles north of Little Rock and approximately 103 miles southwest of the most active seismic zone in the Ouachita-Appalachian Mountain Belt at the time (New Madrid Seismic zone) (Chiu et al., 1984). As of July 1983, 18 months after the first activity, more than 30,000 events had been recorded by the TEIC (Burroughs, 1988). These events included at least three shocks with body wave magnitudes (Mb) greater than 4.0 within the first six months of swarm activity, two in January and one in March (Johnston and Metzger, 1982). Eighteen months following the first recorded activity, there was a continuous decline in magnitude and frequency of the earthquakes (Johnston and Metzger, 1983). After 20 years of "quiet", a seismic event was felt again in North-Central Arkansas, near the town of Enola, on May 4, 2001. The area experienced a 4.4 magnitude earthquake and about 2,500 aftershocks in the following two months (Figure 1.5).

A total of six Saltwater Disposal (SWD) wells became operational within the study area, between 2009 and 2010, and by the end of 2010, the number of recorded events increased from 8 to 671 and 702 in 2011. The earthquakes implied a migrating pattern between the towns of Guy (2010) and Greenbrier (2011). These events "lit-up" the previously unrecognized NE trending Guy-Greenbrier Precambrian fault (Horton, 2012). The locations of both the mainshock and aftershocks of the Greenbrier events are within the same vicinity of the remarkable Enola earthquake swarm of 1982 and 2001 (McFarland and Ausbrooks, 2010)

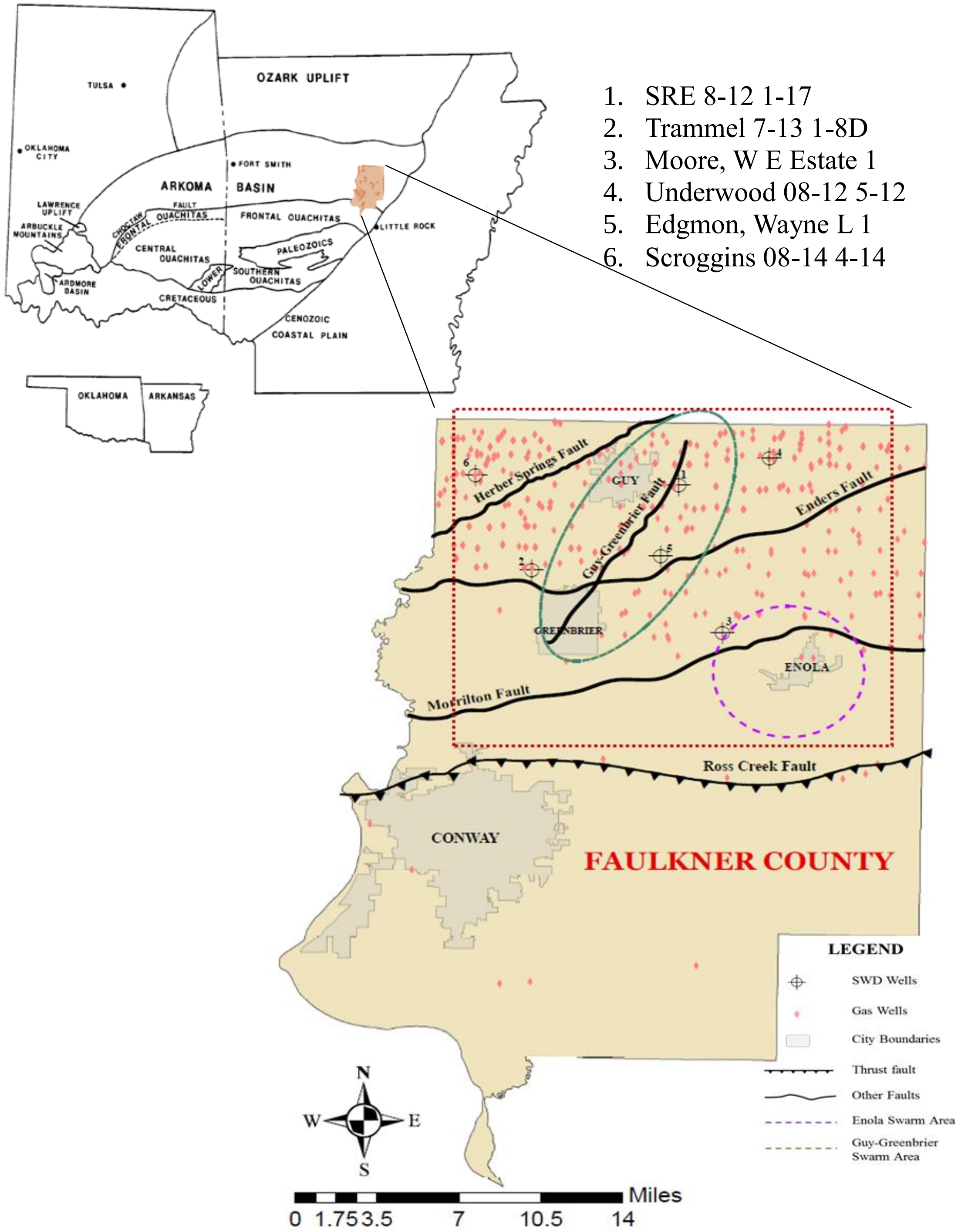

Figure 1.1: Regional location of the study area showing Arkoma basin and surrounding geologic provinces modified from Zachry and Sutherland (1984). Study area lies in the northern part of Faulkner County. Dashed circle represents Enola swarm area and solid oval represents Greenbrier swarm area. SWD well locations as shown on table 4.3 Faults georeferenced from (Burroughs, 1988; Horton, 2012)

PURPOSE OF STUDY

This study is undertaken to understand and possibly determine the cause of the Enola and Greenbrier Earthquake Swarms, particularly the differences and similarities between an induced and a natural seismic event. This study involves answering the following questions:

1) Is fluid (wastewater) injection the triggering mechanism for the Greenbrier swarm?
2) Does the Paleozoic graben uplift explain the concentration of the Enola swarm?
3) Could the Enola and Greenbrier swarms have similar triggering mechanisms due to their proximity, and similar geologic and tectonic history?
4) Can a natural and a (potential) induced seismic event be differentiated?

PREVIOUS INVESTIGATIONS AND LITERATURE REVIEW

The Enola and Greenbrier swarm events occurred in the eastern Arkoma Basin, north of the Ouachita Mountain frontal faults transition zone, within an intraplate setting (Figure 1.1). These intraplate zones are known to be relatively inactive in regards to seismicity. Following the onset of the 1982 Enola Swarm, geophysical investigations were undertaken in North-Central Arkansas, with several hypotheses proposed and analyzed to understand the geological and geophysical causes of these swarm events.

Johnston (1982) suggested a possible crustal magma intrusion that stimulated strike-slip motion along a previously antithetic fault, thus triggering the 1982 swarm. This hypothesis was not widely accepted because, for more than 80 M.Y, Arkansas is not known to be within a volcanically active zone, and it is questionable that these swarms were as a result of any intrusive igneous activity. Notwithstanding, Haar et al. (1984) conducted research using a geophysical digital recording survey in order to determine the potential source of the 1982 events. Though their report was inconclusive, they were able to confirm that the swarm was tightly clustered both vertically and horizontally, and the focal mechanisms show a combination of strike-slip and normal fault motions.

Ellison (1985) used gravity, magnetic and radon surveys across the Enola swarm area to determine the source and potential cause(s) as well. All surveys produced anomalies which correlate with each other and with the observed seismicity. It is possible that these types of anomalies could be evident in other parts of the Arkoma basin, as the geophysical surveys were limited in their aerial extent. Nonetheless, it corroborates part of Johnston (1982) hypothesis of reactivation of a pre-existing north-dipping antithetic fault.

Burroughs (1988) reevaluated the swarm area, and proposed a hypothesis of left-lateral transpression, compatible with the contemporary stress of the midcontinent, along the Enola fault. This transpression hypothesis was supported by evidence of vertical uplift of the surface (graben) and Atokan sediments over the hypocenter. In addition, within the vicinity of the hypocenter, the seismic reflectors demonstrate an apparent shattered nature and slight change in the strike of the Enola fault. There was a "pause" in the Enola swarm events until 2001, when a M 4.4 was recorded, followed by more than 2,500 earthquakes in the following two months (McFarland and Ausbrooks, 2010; Rabak et al., 2010).

In 2009, the first saltwater disposal (SWD) well became operational in Faulkner County. A total of six disposal wells were operated during the three year period (2009 - 2011) and were all plugged and abandoned by the end of 2011. The earthquake events within the county increased from 8 in 2009 to 671 in 2010, and 702 in 2011. These events are mostly centered between the towns of Guy and Greenbrier, located north of Little Rock and west of Enola (Figure 1.1). The number of earthquakes significantly declined after all SWD wells were plugged and abandoned following a state order. Due to the significant increase in the number of seismic events, geophysical investigations into the possible triggering mechanisms emerged again in North-Central Arkansas. Several of these reports provide substantial information and correlative data to support saltwater disposal as the possible triggering mechanism of these events (Horton, 2012; McClure, 2015; McGarr, 2014).

Fracking and Fluid Injection

Hydraulic Fracturing (also known as hydrofracking, fracking or hydro-fracturing) is an oil and gas well completion process that involves injecting water under high pressure into a subsurface hydrocarbon reservoir formation via the well bore. For over 100 years, the typical exploration technique of the petroleum industry has been to test potential reservoirs, by drilling vertically into sandstone and limestone units (Folger and Tiemann, 2014) (Figure 1.2). New technologies have allowed companies to drill horizontally into unconventional shale, tight sandstone, or coal beds to produce hydrocarbon resources. This technique often requires substantial amounts of water, which is first mixed with chemicals and fine sand (Figure 1.3), then pumped at extremely high pressures (up to 20.3 MPa (2994.3 PSI) for SWD wells for this study) into the rock strata to produce fractures that form pathways for the oil and gas to reach the well bore (Figure 1.2). The “frack” water is then recovered, along with the oil and gas (Folger and Tiemann, 2014). The recovered water, commonly in significantly higher quantities than the oil produced, needs to be disposed. A disposal well is drilled, and the usually very saline fluid, is pumped into an underlying porous geologic formation. Sometimes, pumping under high pressure might not be required, such as some areas of the Arbuckle Group in Oklahoma, where the formation is known to be very porous and takes frack water under low pressure (Chesapeake Employee, Personal Communication).

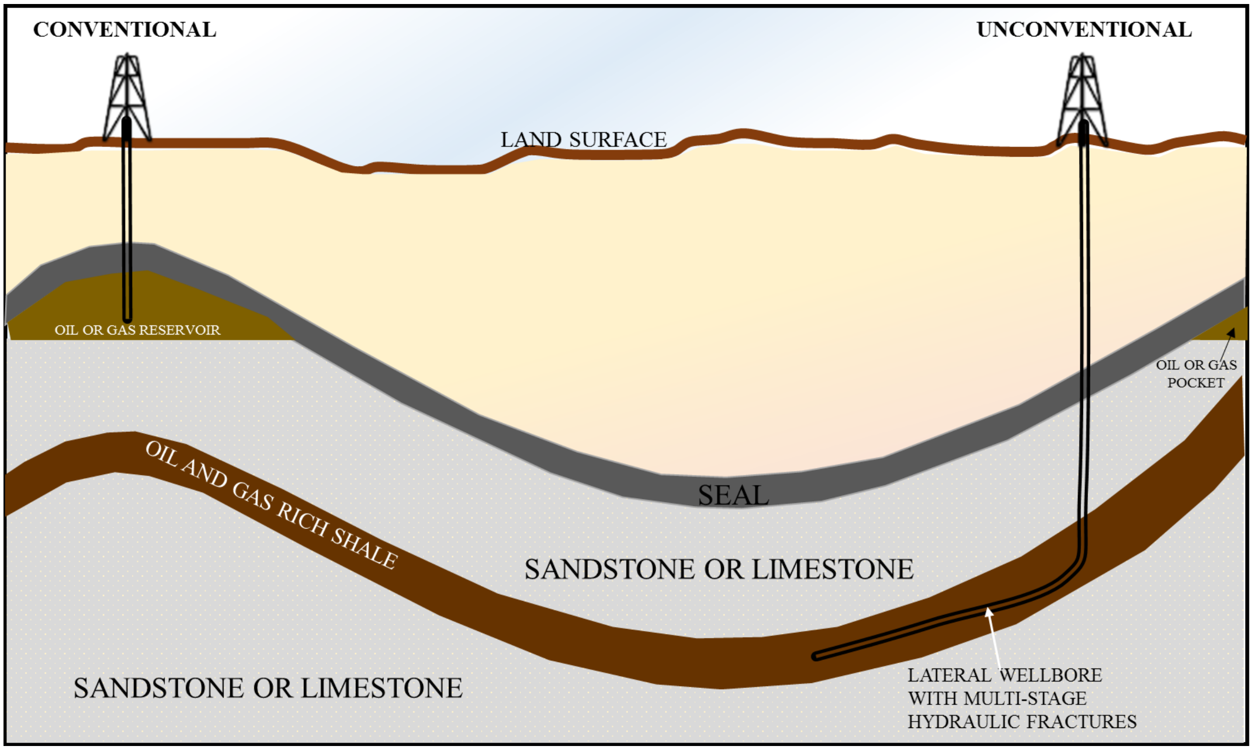

Figure 1.2: Conventional versus unconventional drilling

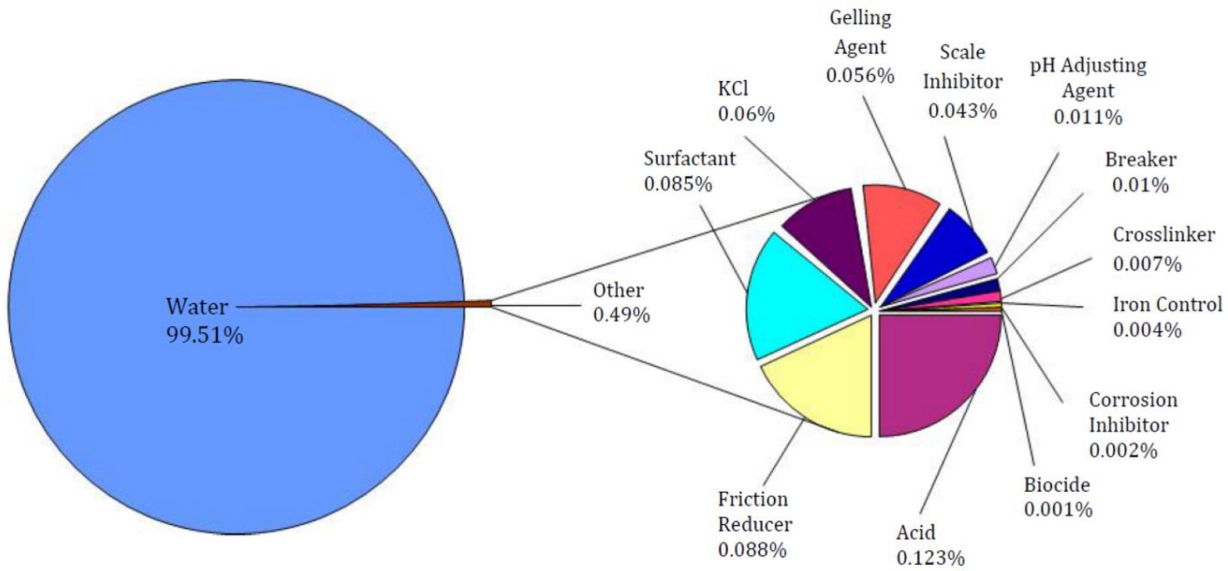

Figure 1.3: Volumetric composition of hydraulic fracturing fluid (Arthur et al., 2008)

Pore Pressure and Induced Seismicity

Water and other fluids have been injected into the subsurface for decades in enhanced oil recovery operations and for wastewater (or saltwater) disposal. In recent years, hydraulic fracturing and horizontal wells have allowed development of unconventional oil and gas reservoirs or redevelopment of conventional resources. Even with low oil-cuts, it is economic to produce some intervals, such as in the Mississippian, but there is a disproportionate increase in the co-production of water (Murray & Holland, 2014). After separating water from oil and gas at the wellhead, producers are left with water as a byproduct, having average concentrations of ~150,000 ppm of total dissolved solids, which must be disposed of via wastewater wells (McGarr et al., 2002).

Recording stations have registered an increasing number of seismic events in the Midcontinent, some of which are hypothesized to be potentially induced by fluid injection (Horton, 2012; Keranen et al., 2013; Van der Elst et al., 2013). Fluid injection, especially saltwater disposal (Horton, 2012; Keranen et al., 2013) have been shown to contribute to seismicity mainly by reducing normal stress allowing movement along pre-existing faults (Figure 1.4). Some of the largest magnitude earthquakes associated with saltwater disposal injections are centered in the states of Arkansas, Oklahoma, and Texas (Horton, 2012; Keranen et al., 2013). Research on the topic of induced seismicity recognizes the uncertainty and the difficulty in distinguishing between natural or induced seismic events (Llenos and Michael, 2013). One major limitation of this line to research relates to the unknown quality of underground injection control data, which includes the x-y location, z elevation, zone of completion, volume, and pressure (Murray and Holland, 2014). Integrated hydrogeologic, structural geologic, and seismologic studies are required since mechanisms for fluid induced seismicity are related to stresses and strength of faults, hydraulic properties of injection zones, and pressure diffusion (Ellsworth, 2013; Holland, 2013).

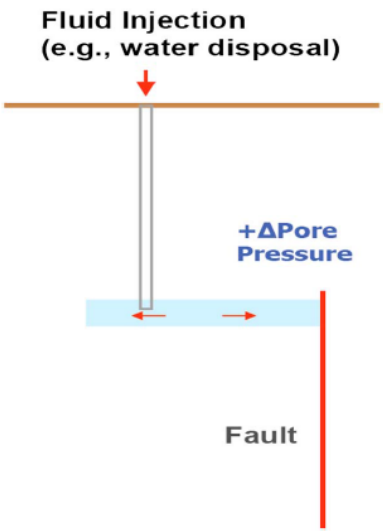

Figure 1.4: Wastewater is injected into a deep aquifer. Increase pore pressure is hydraulically transmitted to a nearby fault. Increase in pore pressure in the fault zone reduces the effective normal stress acting on the fault, stimulating a slip, which could lead to an earthquake. Modified from (McGarr, 2014).

The widely accepted mechanism for triggered seismicity by injection fluids at depth is the diffusion of pore pressure and its subsequent change within the fault (Holland, 2013). The relationship between normal stress, shear stress, and pore pressure is represented by the line equation:

$$\boldsymbol{\sigma_s = \mu(\sigma_n - \emptyset) + c}$$

Where: σ_s = shear stress, μ coefficient of friction (material property),
σ_n = normal stress, ∅ = pore pressure within fault zone, c = cohesion (McGarr et al., 2002).

This Mohr-Coulomb failure criterion equation shows shear stress is required for fault failure. If the shear stress (σ_s) is greater than $\mu(\sigma_n - \emptyset) + c$, then fault slip occurs. Increasing the pore pressure within and along the fault, by fluid injection or other means, decreases the normal stresses acting on the fault faces, bringing pre-existing fractures closer to failure (Figure 1.4). Normal stress acting on a fault surface creates friction and is responsible for locking a fault in place. Ultimately, if normal stress is decreased enough, a fault will yield to shear stress and slip. (McGarr et al., 2002).

The Mohr-Coulomb criterion could also be interpreted by use of the Mohr's Circle/diagram - " a circle which describes the normal and shear stress acting on planes of all possible orientations through a point in the rock" (Fossen, 2010). In order to do this, the orientation and magnitudes of the fault plane are needed to calculate the shear and normal stresses acting on the fault, to plot the point of that fault on the Mohr diagram. Any plots outside of the failure envelope (μ - coefficient of sliding friction) during the unstable phase are considered critically stressed (Figure 1.5) (Fox et al., 2013).

$$\boldsymbol{\sigma_e = (\sigma_T - \emptyset)}$$

Where: σ_e = effective normal stress, σ_T = total normal stress, $\emptyset$ = pore pressure within fault zone

This shows that an increase in the pore (fluid) pressure leads to a decrease in the effective normal stress and as a result, the Mohr circle will slide to the left (Figure 1.5). This mechanism shows that fractures and/or faults that were originally dormant could become critically stressed and eventually fail with an increase in pore pressure (Fossen, 2010; Fox et al., 2013).

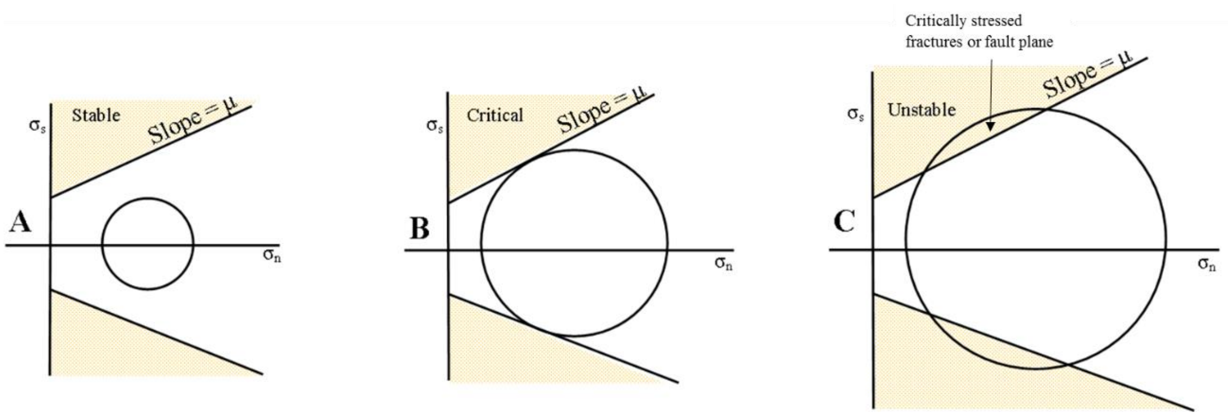

Figure 1.5: (A) stable state of stress (B) critically stressed, where circle touches envelope. The rock is on the verge of failure. (C) Unstable situation where the state of stress is higher and failure is occurring. Modified from (Fossen, 2010; Fox et al., 2013).

EARTHQUAKE ORIGIN AND HISTORY

Though the general mechanisms for induced seismicity have been well documented, it is still quite challenging to predict when and/or where an induced event will occur. There is an ongoing debate on the causes of a significant increase in the number of earthquakes in Oklahoma, Kansas and Arkansas. This study focuses on the swarms in North-Central Arkansas.

Enola

The Enola earthquake swarm began quite suddenly on January 12, 1982 with over 30,000 micro-earthquakes by July 1983 (Johnston and Metzger, 1983). The largest events were a magnitude 4.5 on January 21, 1982, 4.1 on January 24, 1982 and 4.0 on March 01, 1982 (Johnston and Metzger, 1982, 1983; McFarland and Ausbrooks, 2010). This swarm is considered unusual because of its occurrence within a stable intraplate setting. Most earthquakes are commonly known to occur near divergent plate boundaries in association with volcanic activities. This could be the reasoning behind Johnston's (1982) hypothesis of a shallow magmatic intrusion. But, intrusion alone could not explain the gravity anomaly observed by Ellison (1985). Though the hypothesis represents a possible cause, it is not unique to the Enola swarm. As a result, a third order leveling survey was conducted in 1986, leading to the conclusion that a continuous uplift along a deep Paleozoic graben caused the Enola swarm (Burroughs, 1988). The earthquakes do not occur on the bounding faults of the graben, but they seem to be contained within the graben (Figure 2.3). Due to the lack of continuous reflectors in the analysis done by Schweig et al. (1991), it is hard to determine whether there are parallel faults within the graben. Moreover, fluid migration could play a role in the velocity characteristics of the swarm area recorded by Chiu et al. (1984), but whether it is magma, water or natural gas, is unknown. Nevertheless, the regional geology of the Enola swarm area suggests that migrating magma is unlikely (Burroughs, 1988).

After 18 years of seismic silence, the May 4, 2001 Enola earthquake sequence resumed. A "mainshock" of magnitude M=4.4 was recorded on May 4, 2001, just north of the city of Enola, and two aftershocks were recorded in the same area a few hours later; magnitude M=2.7 and magnitude M=2.5 the next day (May 5, 2001). A total of 2,500 aftershocks were recorded in the following two months (Rabak et al., 2010). The locations coincide with the remarkable swarm of 1982 (Figure 1.6), but they did not rupture any previously mapped faults, though the rocks of the Enola area are highly fractured. Therefore, the mainshock could have played a significant role in triggering the subsequent aftershocks (Chiu et al., 1984; Rabak et al., 2010).

A tremendous number of these events have smaller magnitudes ($M<3$) and mostly occurred at depths of ~ 4km (above the Precambrian basement). The Enola region lacks mapped faults, therefore there are speculations about natural fluid migration that aided in slip along fractures. The events showed neither a specific fault plane alignment, nor clusters of separate fault planes, but the proximity of their hypocenters indicate a likely occurrence along a single fault with a NW-SE trend (Rabak et al., 2010).

Guy-Greenbrier

Though the residents of Faulkner County are no strangers to seismic activities, nine years after the Enola event, there has been relative calm with only small occasional events. The recent increase in seismic activities have been hypothesized to be as a result of wastewater injection into subsurface aquifers and reservoirs that overlie faulted Precambrian basement (Horton, 2012). According to the Arkansas Oil and Gas Commission (AOGC), two gas companies agreed to suspend disposal operations at their wells, because their work was spatially and temporally coincident with nearby upper crustal seismicity. One well, in particular, the Arco Exploration I Wayne Edgmon (#5 in Figure 1.5 and Table 4.3), terminated about 5000ft above the Precambrian basement with an injection depth between 7805ft – 12162ft, and most of the swarm activities are known to be occurring within the basement regime (Horton, 2012; VanArsdale and Schweig, 1990).

Data obtained from the Arkansas Geological Survey (AGS) indicates that, in 2009, only 37 earthquakes were recorded in Arkansas with eight of these in Faulkner County. The first waste disposal well became operational within the swarm region in April of 2009 and the Edgmon well in August of 2010, though it was first completed in 1998. The AGS earthquake data also indicate that Faulkner County experienced 671 earthquakes by the end of 2010, mostly clustered around the town of Guy, 50 miles north of Little Rock, and 702 in 2011, mostly around the city of Greenbrier, 43 miles north of Little Rock. Most of the SWD wells operational in Faulkner County were plugged and abandoned by mid-2012 (Table 4.3). This was followed by a significant decline in the number of seismic activity within the county, from 13 in 2012 to 2 in 2013, and 5 in 2014.

The largest recorded Greenbrier event was on February 27, 2011 with M = 4.7, followed by M = 4.1 on February 18, 2011, and 4.0 on October 11, 2010. There were 30 registered events with magnitudes between 3 and 3.9.

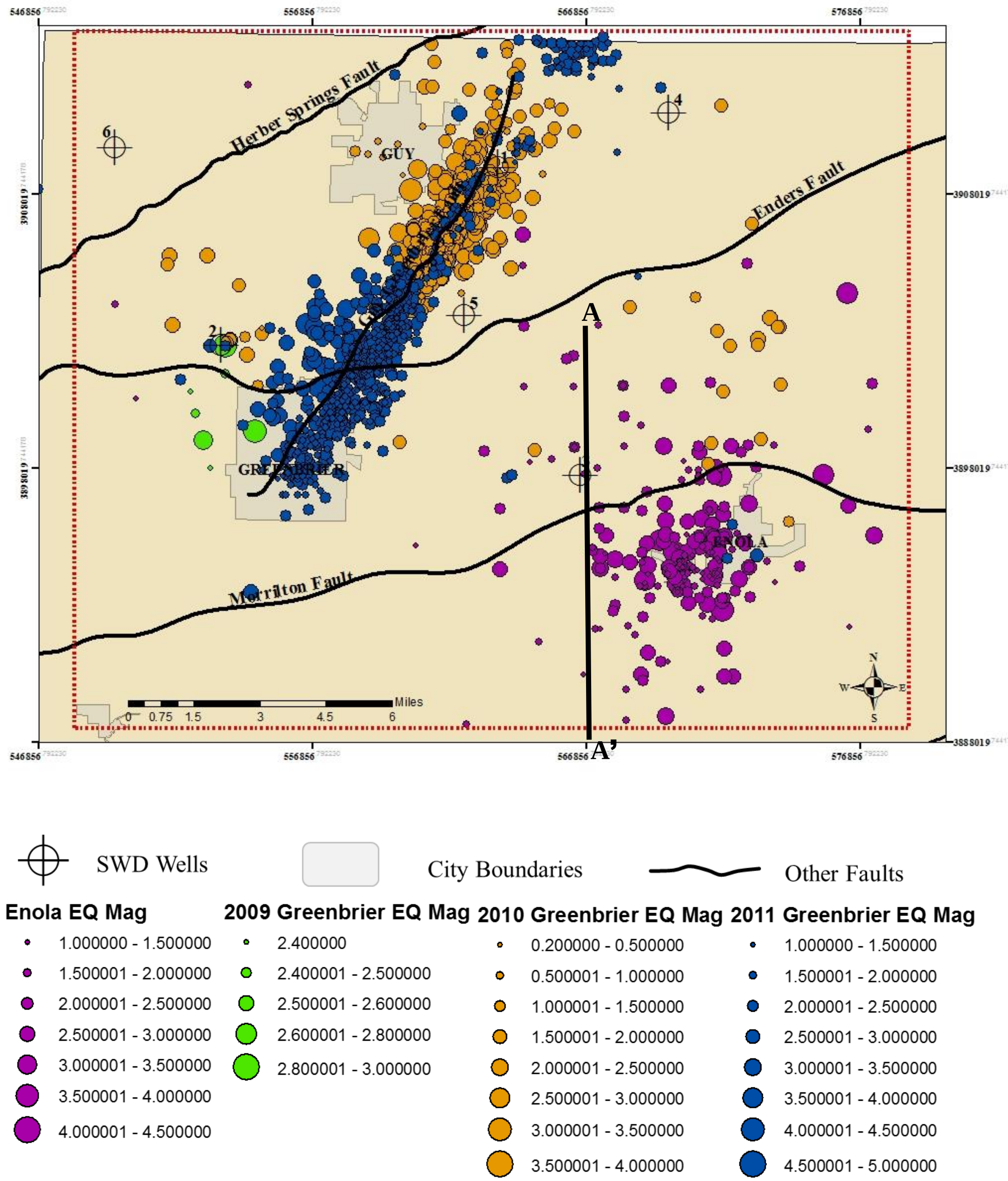

Figure 1 6: Locations of Enola and Greenbrier earthquakes with magnitudes ≥ 0.5 within the study area. Labeled SWD well locations correspond to numbers on Table 4.3. The line A - A' corresponds to figure 2.3 cross section.

II. GEOLOGIC HISTORY

GENERAL GEOLOGY OF THE STUDY AREA

The Enola and Greenbrier seismic events occur in Faulkner County, Arkansas, within a complex sequence of folded and faulted Paleozoic sediments of the eastern Arkoma Basin, north of the 80km-wide Ouachita orogenic belt (Suneson, 2012). The Arkoma Basin is 250 miles long and 20 - 50 miles wide (Figure 1.1). This narrow, prolific, petroleum-producing peripheral foreland basin lies in southeastern Oklahoma and west-central Arkansas. It was formed as a result of the collision between the North American and Gondwanan plates during the Carboniferous period (early Mississippian to middle Pennsylvanian). It is bounded to the north by the Ozark Uplift and Cherokee Plateau in Arkansas and Oklahoma respectively, and dominated by complex folds and broad synclines, separated by narrow anticlines (Zachry and Sutherland, 1984).

A common characteristic of Foreland Basins, they are commonly adjacent to compressional orogenic belts. Consequently, the structural and tectonic history of the Arkoma basin is closely related to that of the Ouachita fold-and-thrust belt, which consists predominantly of Paleozoic siliciclastics, chert and shales (Perry, 1995; Suneson, 2012). Down-to-south growth fault development aided in changing the Arkoma basin to a depositional basin in the middle Atokan (middle Pennsylvanian) (Zachry and Sutherland, 1984).

Late Pennsylvanian sediments reflect the latest tectonic episode in the Arkoma Basin, represented by thrust faulting and folding from compressive stresses produced by the Ouachita Orogeny on its south flank. The thrust faults displace the upper Atoka sediments and may have also displaced and/or reactivated some older growth faults within the area. The Enola earthquake epicenter is known to be located along the axis of the late Pennsylvanian Menifee Syncline (Figure 2.3) (Burroughs, 1988) .

STRATIGRAPHY

The stratigraphy of the study area within the eastern Arkoma Basin consists of a dominantly carbonate Cambrian to Devonian section, Lower Mississippian Boone Formation (limestone and chert), Upper Mississippian Pitkin through Moorefield Formations (limestones, shales and sandstones), Pennsylvanian Morrowan Series (sandstones and shales) and the Pennsylvanian Atokan Foramtion (sandstones and shales) (Figure 2.1).

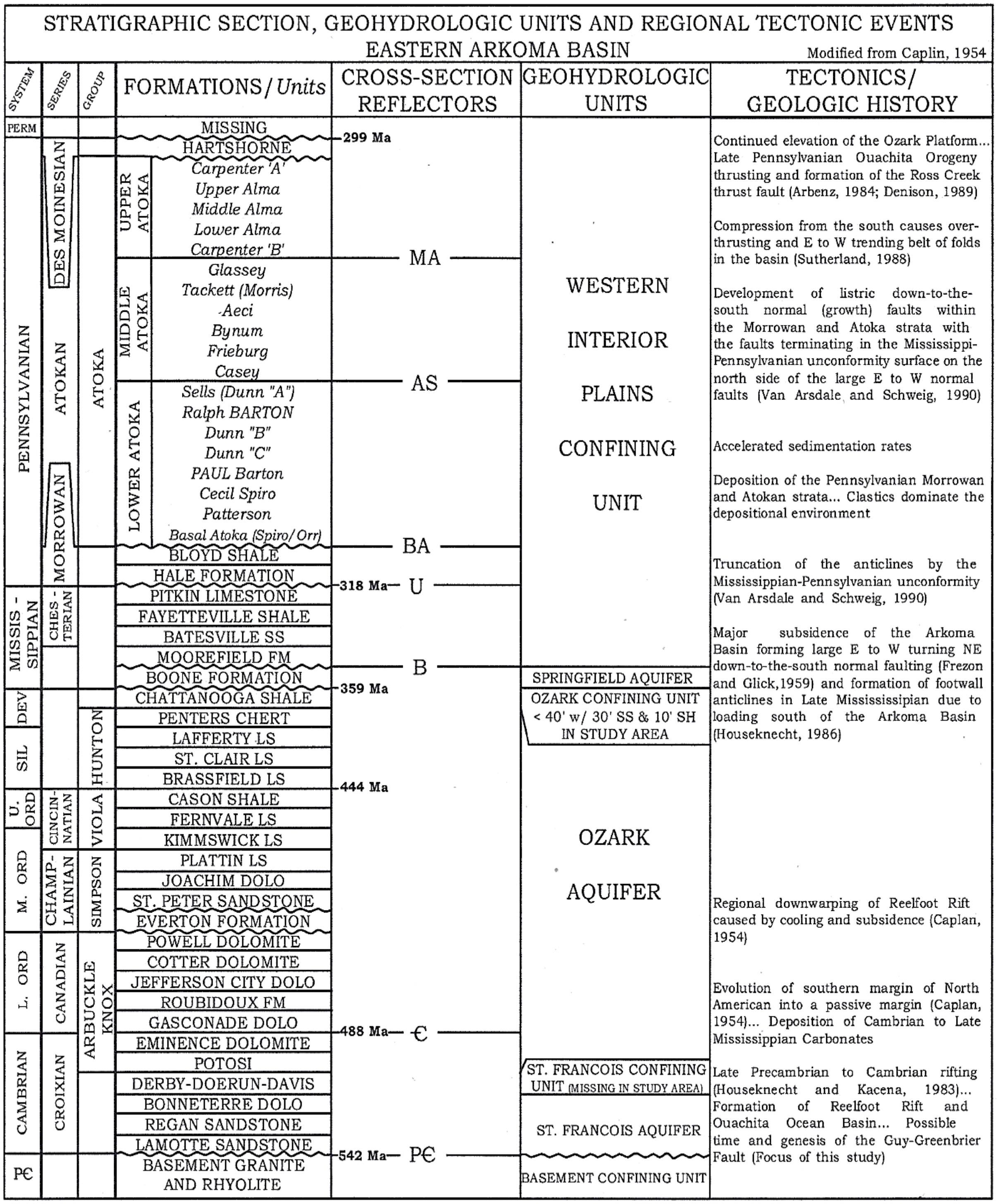

Figure 2.1: Stratigraphic section. Regional hydrological units and tectonic history of study area (Horton, 2012).

STRUCTURAL EVOLUTION

The subsurface structure of the Eastern Arkoma Basin (Arkansas) has been interpreted to have different structural characteristics compared to the western part (Oklahoma) (Figure 1.1). The structural evolution of the eastern Arkoma Basin starts with early Cambrian rifting and then deposition of an essentially unbroken Cambrian to Mississippian succession. There is normal faulting, and the footwalls typically develop into anticlines in the late Mississippi. The anticlines are then truncated by the Mississippian - Pennsylvanian (pre-Morrowan) unconformity. Deposition of the Pennsylvanian Morrowan and Atoka strata comprise basin-fill. Listric normal faulting occurs within the Morrowan/Atoka interval during the early-middle Pennsylvanian. The Ross Creek and associated thrust faulting reflects the Ouachita Orogeny (Schweig et al., 1991), forming a fold-and-thrust belt (Figure 2.3).

Surface Structure

The east-west-trending, box-shaped synclines and narrow anticlines are the dominant structures of the Arkoma basin (VanArsdale and Schweig, 1990). The surface structure of the Enola swarm area is composed mainly of high angle east-trending folds. To the south, these folds are bound by the Cadron anticline, offset by the hinge of the major Ross Creek Fault (Chiu et al., 1984). The Enola swarm is known to be located specifically beneath the nose of the Menifee syncline. Therefore, the swarm area is confined by a zone of mostly deep, steep normal faults to the north and listric normal and thrust faults to the south (Burroughs, 1988).

Subsurface Structure

A detailed study of the subsurface structure of the eastern Arkoma Basin (Schweig et al., 1991), revealed that its structure and history are very different from that of previously recorded studies.

A VanArsdale and Schweig (1990) seismic reflection profile (Figure 2.2 and 2.4), and a Burroughs (1988) detailed structural analysis (Figure 2.3) identified three sets of faults that have accommodated deformation in the region (prior to discovery of the Guy-Greenbrier fault). These are:

(1) Deep, basement-penetrating steeply-dipping normal faults related to formation of the Cambrian Iapetan rifted margin (Thomas, 2011) (such as the Enders fault in (Figure 2.3). The basement faults are continuous from the Precambrian basement rock upwards into the Mississippian Fayetteville Shale, and are abruptly terminated by a decollement at the base of the Morrowan Hale Formation (Burroughs, 1988) (Figure 2.3). The decollement could be interpreted as a boundary marker between the deep-seated high-angle normal faults and shallow listric faults above.
(2) Shallow-dipping and large listric normal faults related to deformation of the Paleozoic Arkoma foreland basin, mostly within the Morrowan and Atokan sections. These listric faults are interpreted to become shallow into a decollement at the base of the Morrowan Hale Formation (Burroughs, 1988), and do not continue into the deeper basement faults.
(3) Thrust faults that postdate all normal faults and represent contraction during the Pennsylvanian Ouachita orogeny (immediately south of the section shown in Figure 2.3 and 2.4) (Schweig et al., 1991).

The Boone Formation within the graben formed between the Mount Vernon and the Enola faults is down-thrown approximately 105 m (Figure 2.3 and 2.4). However, the basal Atokan above the Morrowan unconformity have been uplifted approximately 30 m, forming a gentle, broad anticline (Schweig et al., 1991).

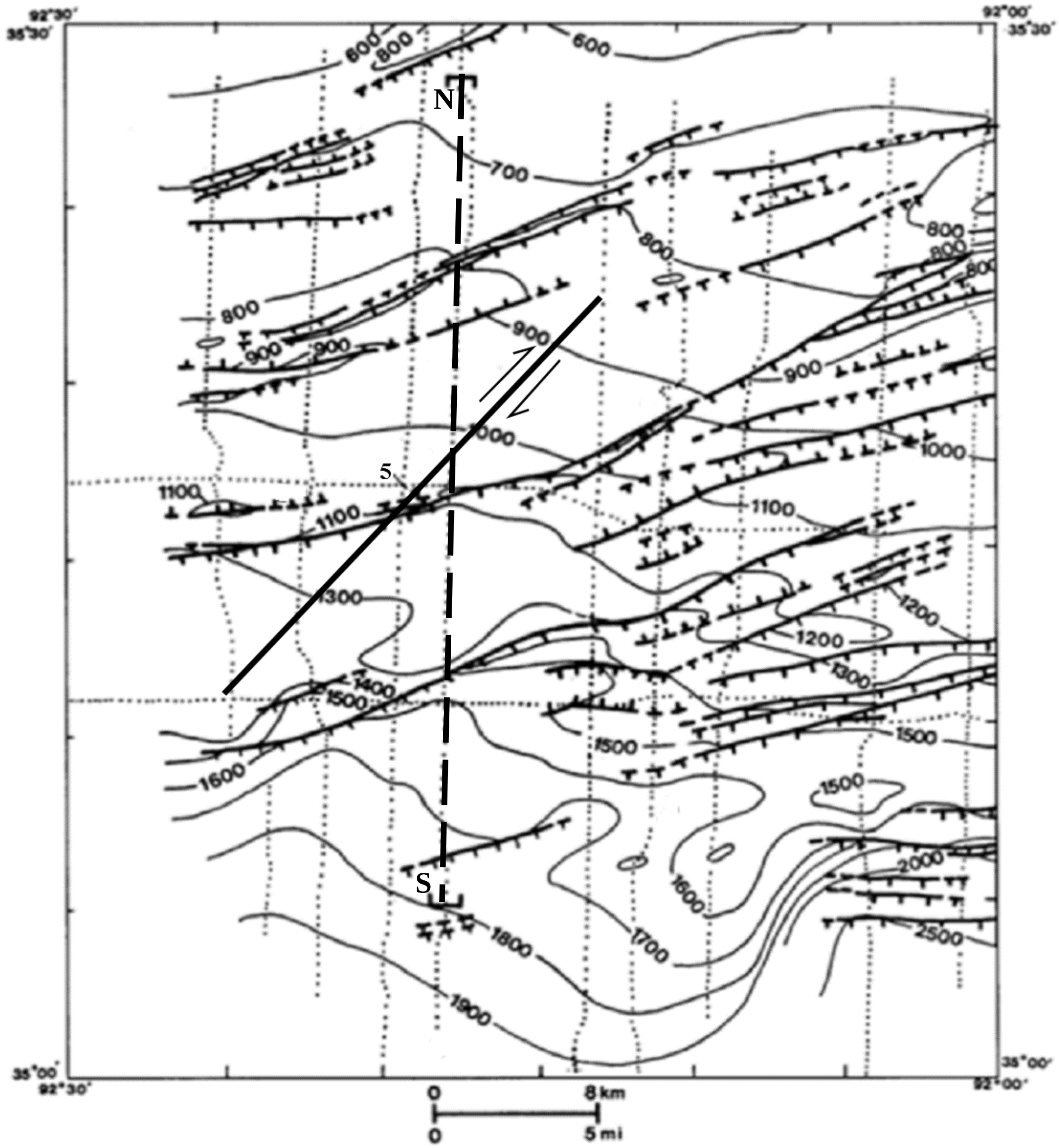

Figure 2.2: Two-way travel-time structure map of the Boone Formation, contours in msec. Bold lines are normal faults, barbs on downthrown side. Dotted lines are locations of the seismic reflection lines. 5 = Arco Exploration Wayne L. Edgmon well. Solid NE trending line represents the Guy-Greenbrier fault, not imaged in the seismic profile. Dashed NS line of cross section shown in figure 2.3. Modified from (VanArsdale and Schweig, 1990)

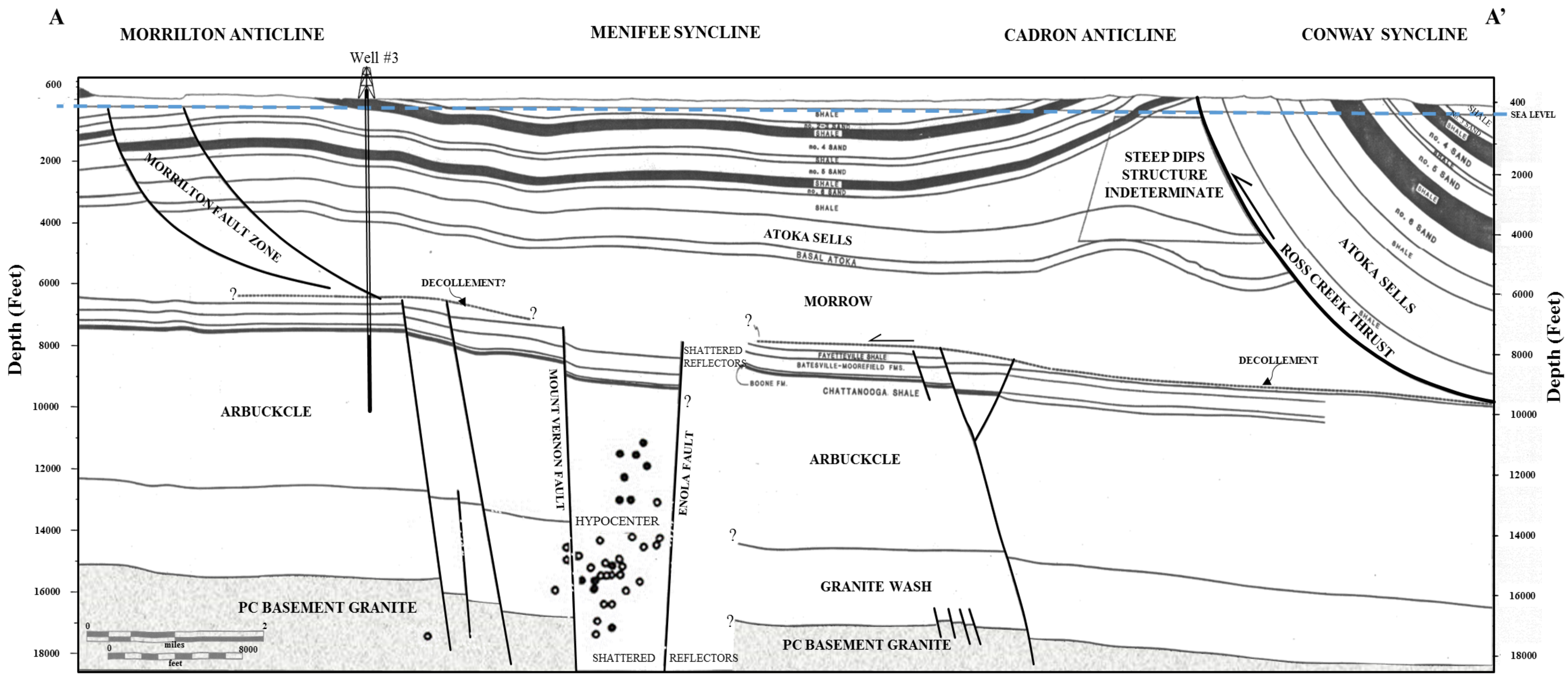

Figure 2.3: North-South cross section of study area showing deep-seated high angled normal faults, shallow listric normal faults and Ross Creek Thrust Fault. Earthquakes are those relocated by Pujol (1989); Open circles represent USGS data from 1982; closed circles are Portable Array for Numerical Data Acquisition (PANDA) data from 1987. Approximate location and drilling depth of well #3, solid black portion at well bottom indicates interval of fluid injection. Modified from VanArsdale (1991) and Burroughs (1988). Line of cross section shown in figure 1.6

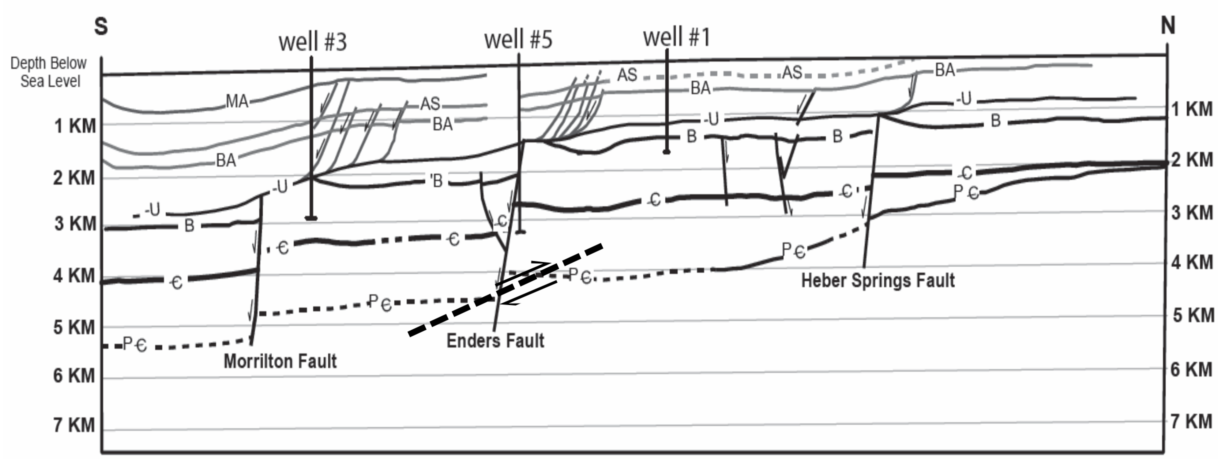

Figure 2.3: Line of cross section from Figure 2.2 depicting the fault locations and saltwater disposal wells within the study area. Well numbers correspond to the SWD wells in Figure 1.5 and Table 4.2. Dashed line is approximate location of the Guy-Greenbrier faulting trending NE. Modified from (VanArsdale and Schweig, 1990).

TECTONIC EVOLUTION

The following tectonic evolution model of the Arkoma Basin is modified from Ellison (1985) and Houseknecht and Kacena (1983). The depositional and structural history is divided into five episodes shown in figure 2.5 that led to the formation of the Arkoma Foreland basin.

The first tectonic episode is the major rifting that led to the opening of a pro-Atlantic ocean basin during the latest Precambrian and earliest Paleozoic era (Figure 2.5A). This rifting separated North America from the southern Llanoria landmass (Houseknecht and Kacena, 1983), and led to the development of numerous other smaller rift basins. Deposits of these basins could be present beneath the Arkoma basin and the Ouachita. In the early and middle Cambrian, the Reelfoot basin experienced continuous rifting, and it was during this time that the Anadarko basin developed fully into an aulocogen. The strata present within the Reelfoot and Anadarko Basins are the best known remnants of the Precambrian tectonic event.

Secondly, during the Late Cambrian to Devonian periods (Figure 2.5B), following the proto-Atlantic rifting, the southern part of North America evolved into a passive, Atlantic-type margin. There was sediment accumulation under the influence of subsidence as a result of thermal cooling from mid-ocean ridge migration. Most of these sediments were shales, quartzose sandstones and limestones, deposited beyond the shelf margin (Zachry, 1983). They later became known as the classic Ouachita Facies that are now thrusted northward into the core areas of the Ouachitas, and are thought to be representative of slope, rise and abyssal sediments deposited in a starved basin (Houseknecht, 1986).

During the Devonian or early Carboniferous (Mississippian), the ocean basin (Proto-Atlantic) began to close gradually. This initiated a southward subduction along the Llanorian northern margin (Figure 2.5C) that continued throughout the Mississippian (Ellison, 1985). Though it is hard to determine when the subduction began, Carboniferous volcanic rocks, associated with magmatic arcs along the northern Llanorian coast, encountered in the subsurface south of the Ouachitas, along the flanks of the Sabine uplift, indicate that the subduction must have been well underway through the Mississippian (Houseknecht, 1986). Associated with the subduction zone within this convergent tectonic setting, the incipient Ouachita Orogenic belt began to form as an accretionary prism. Throughout the closing-period of the ocean basin, Atokan miogeoclinal and coeval eugeoclinal strata were being deposited, by shedding sediment from the Appalachian Uplift, the Ozark Dome and the Witchita Uplift (Ellison, 1985).

By the early Atokan (Early Pennsylvanian), the ocean basin had been completely consumed by the northward advancing subduction zone-complex (Figure 2.5D). Large normal faults began to form along the continental margin as a result of the flexural bending resulting from the subduction processes. These faults offset both basement as well as overlying Cambrian to Atokan strata, influence their sedimentation, and are also responsible for the southward thickening of lower - middle Atoka strata. Because this area no longer resembled the remnant ocean basin, it was termed an incipient peripheral foreland basin. Throughout this time interval, the Arkoma-Ouachita Basin remained a major sediment sink, as receiving sediment shed from highlands northward across the Black Warrior peripheral foreland basin, and westward into the incipient peripheral foreland basin of the Arkoma-Ouachita system.

By the end of the Atokan (middle Pennsylvanian) time, the most intense structural deformation by collision of the subduction complex with the North American continent had ceased (Figure 2.5E). Prior to ceasing, it had resulted in formation of the Ouachita Mountains and the associated Arkoma and Black Warrior Foreland Basins, as a result of uplift of the subduction complex (Llanoria). With the Permian, only very minor deformation continued.

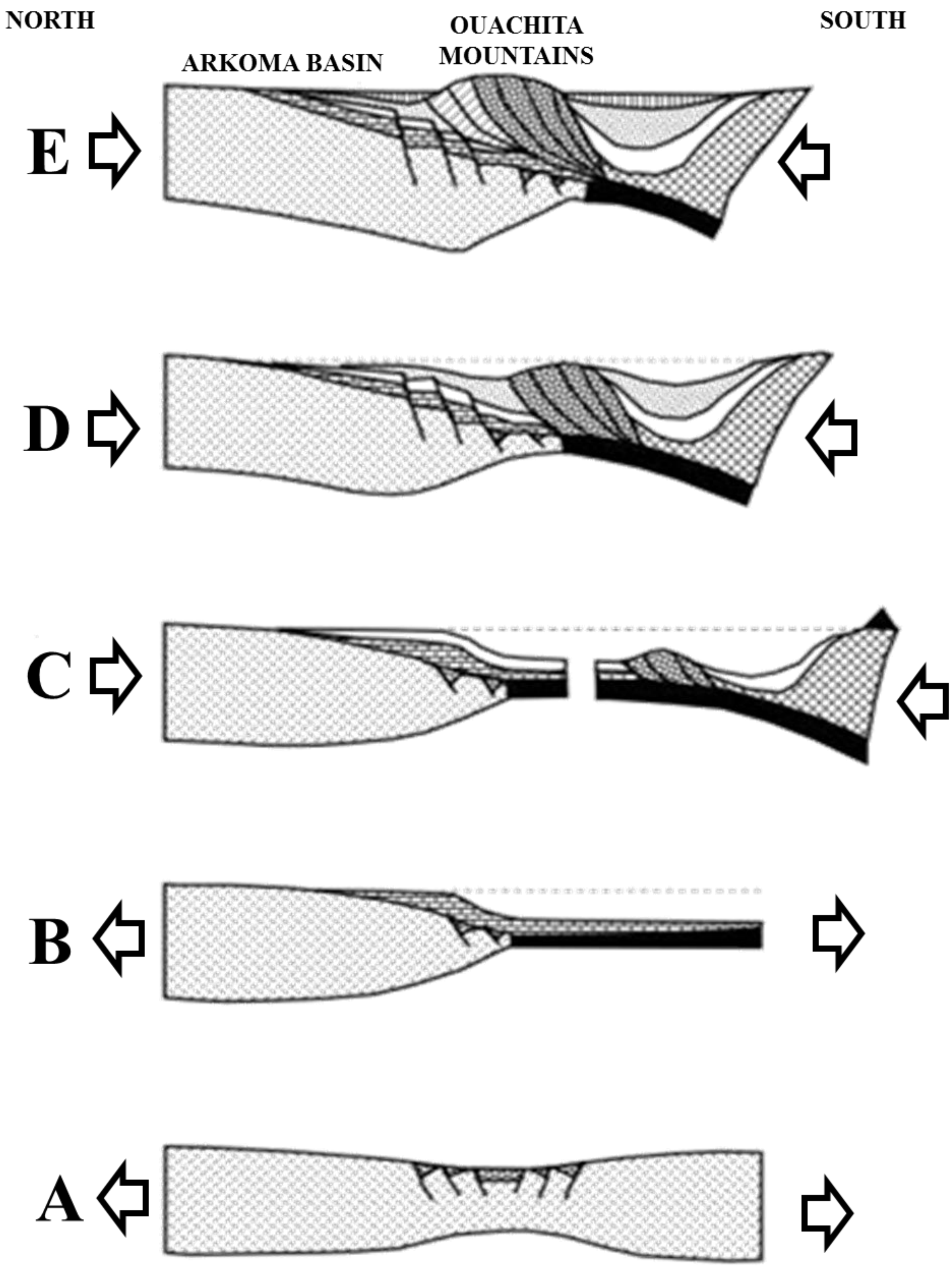

Figure 2.4: The tectonic evolution of the Arkoma Basin and the Ouachitas Modified from (Houseknecht, 1986)

III. METHODS OF INVESTIGATION

A third order leveling a survey conducted in the northern region of Faulkner County within the Enola swarm area in 1986, and demonstrated a change in elevation of 0.47 ft. (Burroughs, 1988; Schweig et al., 1991; VanArsdale and Schweig, 1990). A resurvey was conducted by the National Geodetic Survey (NGS) in 2011, and elevations adjusted and published and in 2014 (Brain Ward, Personal Comm.). This data was analyzed to determine any recent elevation changes and possible correlation to the seismic events. The Enola and Greenbrier earthquake swarm data obtained from the Arkansas Geological Survey (AGS), with the help of David Johnston, Arkansas Earthquake Geologist, and Scott Ausbrooks, Arkansas Assistant State Geologist, was processed independently. Initial analysis involved correlating the various events based on the number of daily recorded occurrences and highest magnitudes. This will aid to determine any similarities and/or differences in the earthquake activities. Volumes and pressures of SWD wells, available through the Arkansas Oil and Gas Commission and with the assistance of James Vincent, will be used to determine correlations between fluid disposal and the Greenbrier swarm events.

LEVELING SURVEY

Haar et al. (1984) indicated that a leveling survey conducted by an Arkansas State Surveyor showed a 20 cm uplift within the vicinity of the Enola Swarm area, since emplacement of the benchmark in 1961. In 1986, a third order leveling survey, under the supervision of Mike Satterfield, Geologist and Land Surveyor, recorded vertical change between two benchmarks, and the possible correlation to the 1982 Enola earthquake swarm (Burroughs, 1988; VanArsdale and Schweig, 1990). The survey was a 3-wire, double rodded level loop between benchmark USC&GS Y 209 located outside the swarm perimeter and benchmark (BM) USGS 3 SAN 1961 located within the swarm perimeter. This 5.75 mile loop showed an uplift within the swarm area of 0.47 ft.

Unfortunately, both 3 SAN and Y 209 benchmarks have been destroyed. Nonetheless, the National Geodetic Survey (NGS) installed and regularly monitors several benchmarks within the study area, in Faulkner County. U 333 BM was emplaced in Enola, and it is within the vicinity of the Enola swarm. In addition, Y 209 reset, M 208 (destroyed) and M 208 reset were installed (table 4.2). A 14 miles leveling survey loop conducted by NGS in 2011 started at K 208, running counter-clock-wise through U 333, Y 209 and M 208 resets, 20 RHM Reset, Z 209 Reset, 23 RHM Reset, L 208, 25 RHM (moved and reestablished), 26 RHM and back to K 208. The elevations at K 208 and L 208 were constrained to adjust for the other BMs being surveyed (Brian Ward, Personal Comm.). These surveyed elevations were then adjusted and published by NGS in 2014 (Figure 3.1). Prior to being destroyed, the published adjusted elevation for Y 209 was 309.80 feet as of June of 1991. The published elevation for 3 SAN 1961 was increased from 310.361 ft. to 310.381 ft. in 1962, due to a change from NGVD 29 to a more consistent and reliable NAVD 88 datum.

DATA PROCESSING

The Enola and Greenbrier seismic data obtained from the Arkansas Geological Survey (AGS) were plotted using Microsoft Excel to understand the distribution and occurrences of the seismic events with time. The magnitudes and depths of these events were also mapped in ArcGIS to examine the regional distribution and understand possible triggering mechanisms.

Volumes and tubing pressures of SWD wells operational within the study area were plotted in Microsoft Excel as well, to determine a correlation with the Greenbrier seismic events

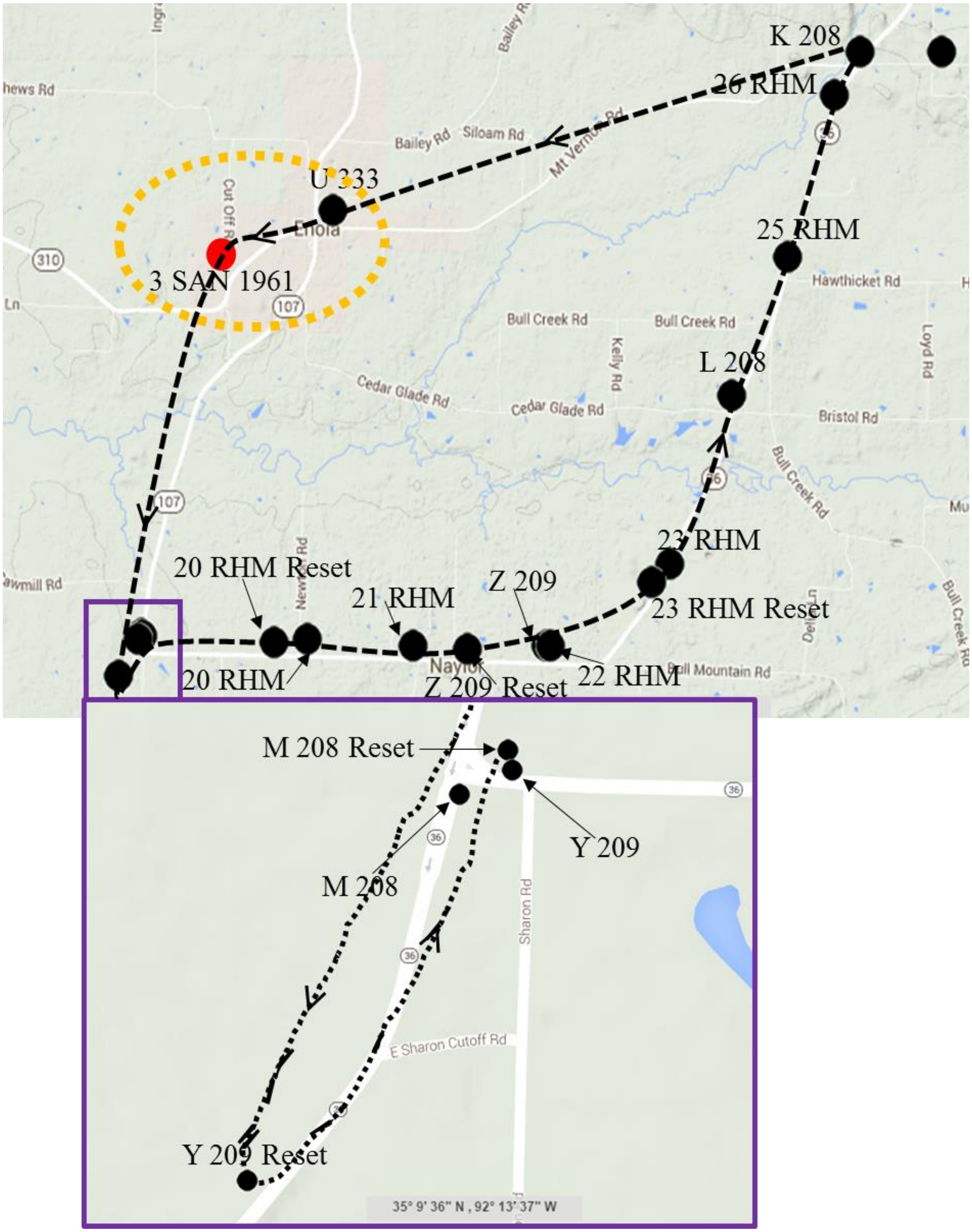

Figure 3.1: Locations of benchmarks (black dots) utilized for leveling survey with published elevations shown in tables 4.1 and 4.2. Red dot indicates approximate location of BM 3 SAN. Orange dotted oval indicates the approximate location of the Enola Swarm. Locations obtained from NGS

IV. INTERPRETATION

LEVELING SURVEY

The 1986 third order leveling survey, recorded a 0.019ft/year (0.57cm/year) uplift rate, with vertical uplift of 14.3cm (0.47ft) for the USGS 3 SAN 1961 benchmark (table 4.1) within the Enola swarm area, relative to the USC & GS Y 209 BM, outside of the swarm perimeter (Burroughs, 1988; Schweig et al., 1991). The anticipated additional vertical elevation, assuming a constant rate of uplift, should be approximately 15.4cm (0.51ft) and a total predicted elevation of 29.7cm (0.97ft) as of 2015.

Burroughs (1988) leveling procedure was accurate, but the results are ambiguous. This is due to the fact that, accepting both published elevations as good without cross-checking with other BMs can lead to questionable results on both. On the one hand, the graben could be experiencing uplift within the swarm area as previously recorded (BM 3 SAN). On the other hand, there could be subsidence outside of the swarm area (BM Y 209), as most of the BMs in this area are known to commonly show evidence of subsidence rather than uplift (Personal Communication with Brian Ward).

A new BM (U333) placed within the vicinity of the Enola Swarm area, approximately 3 miles east of the now destroyed 3 SAN BM, shows a significantly higher published elevation (table 4.1) in comparison to other benchmarks outside of the swarm perimeter [Y 209 (Reset), M 208 (Reset)]. This is solely because U 333 is located in a topographically higher region, when compared to both Y 209 and M 208 Resets. In order to determine changes in elevation over time, individual BMs should be monitored over long periods and levelled with existing BMs, to get a regional understanding of the elevation. The 0.027 ft. change in elevation of Y 209 between 1962 and 1991 is mathematically influenced, due to changes in datum from NGVD 29 in 1962 to NAVD 88 in 1991 (table 4.1). This BM was destroyed in 2011 and later replaced by Y 209 Reset, which was part of the 2011 NGS survey. Other BMs within the study area were recently resurveyed in 2011, destroyed BMs replaced by “Resets” and their elevations adjusted and published in 2014 (Table 4.2).

U 333 is a new NGS benchmark within the Enola swarm area and located a few miles east of the now destroyed 3SAN (Figure 3.1). These also showed an elevation difference of +11.479ft (Table 4.1), but these elevations are not tied together because 3SAN is a USGS benchmark, and not monitored by NGS. Moreover, U 333 is also located topographically higher than 3 SAN, thus the reason from the large elevation difference.

Y 209 and 3 SAN used in Burroughs’ (1998) survey have been destroyed. Y 209, prior to be being destroyed had an elevation of 309.80ft as of 1991, and was replaced with Y 209 Reset with an elevation of310.18ft, a few miles south of its original location (Figure 3.1). There is an elevation increase between these two benchmarks of +0.38 ft. (Table 4.1). This change in elevation is not geologically influenced, but solely topographic.

M 208 is located close to Y 209 and prior to being destroyed, it showed an adjusted and published elevation of 308.04ft in 1991 (Table 4.1). After being destroyed, this elevation was tied to M 208 Reset, and its elevation was then adjusted to309.34 ft in 2014. M 208 Reset is located close to both M 208 and Y 09 benchmarks and when their elevations are compared, they show a -0.46 ft and +1.30 ft between M 208 Reset and Y 209 and M 208 respectively.

These elevation values are ambiguous and are mostly for benchmarks outside of the swarm area. The published elevations showed no significant difference within the given time frame, considering that the expected elevation change between a BM within the swarm area and that outside the swarm area is expected to be a 0.51ft increase, assuming the elevation rate of 0.019ft/year set by Burroughs is kept constant. Unfortunately, the previous BMs have been destroyed and the resets do not have leveling history for comparison and U 333 was just established in 2011 and elevations adjusted and published in 2014.

BM	NGS Data (YYYY) NAVD 88	Burroughs' Data (YYYY) NGVD 29		Difference	Condition
Y 209	309.80 ft. (1991)	309.773 ft. (1962)		+ 0.027 ft. 29 yrs.	Destroyed
Y 209 Reset	310.18 ft. (2014)				Good
M 208	308.04 ft. (1991)				Destroyed
M 208 Reset	309.34 ft. (2014)				Good
U 333	321.86 ft. (2014)				Good
3 SAN		310.381 ft. (1962)	310.851 ft. (1986)	+ 0.470 ft. 24 yrs.	Destroyed

Table 4.1: Years of published adjusted elevations of various NGS benchmarks in comparison to adjusted elevations from Burroughs (1988).

BM	NGS Data (2014) NAVD 88	NGS Data (1991) NAVD 88	23 year Difference	Condition
L 208		342.92 ft.		Good
25 RHM	**364.81 ft.**	**364.89 ft.**	**- 0.08 ft.**	**Good**
26 RHM	**374.02 ft.**	**374. 01 ft.**	**+ 0.01 ft.**	**Good**
K 208		379.26 ft.		Good
20 RHM		328.58 ft.		Destroyed
20 RHM Reset	327.92 ft.			Good
21 RHM		334.15 ft.		Destroyed
Z 209 Reset	327.17 ft.			Good
Z 209		336.70 ft.		Destroyed
22 RHM		337.27 ft.		Destroyed
23 RHM		335.89 ft.		Destroyed
23 RHM Reset	334.20 ft.			Good

Table 4.2: Representation of all benchmarks within the NGS Survey loop of 2011 in Enola. Destroyed benchmarks were replaced by “Resets”. Bold BMs have more than one survey value with NAVD 88 datum. Elevations adjusted and published in 2014. Data obtained from NGS/NOAA.

DATA PROCESSING

Enola Seismicity

The Enola swarm event was recorded mostly around the city of Enola, with a highest recorded daily events of 26 in July 4, 1982, followed by 13 on January 20, 1982 (Figure 4.3). The magnitudes range from <1.0 (not shown in this study) to 4.5 Mb, the highest daily magnitude recorded on January 20, 1982. The second highest magnitude of 4.3 was recorded on May 4, 2001, at the start of the second swarm event (Figure 4.4). Earthquakes recorded locally with digital instruments show an elongate east-west trend at depths from 3 to 7 km (Chiu et al., 1984; Rabak et al., 2010). There is no clear linear decline or increase in the number of events and magnitudes throughout the swarm event. Nonetheless, after the main shock, subsequent aftershocks show decline in magnitude, until the emergence of the 2001 swarm event. The overall daily magnitudes of this event shows a hummocky pattern (Figure 4.4).

The Enola seismic swarm occurred predominantly within the graben and do not lie directly on the bounding Mount Vernon and Enola faults (Figure 2.3). Two-way traveltime structure maps by (Schweig et al., 1991; VanArsdale and Schweig, 1990) did not image any faults within the graben, due to the lack of continuous reflectors during the study, thus limiting the possibility to determine the occurrence of parallel faults within the graben (Figure 2.3 and 2.4).

The lower seismic velocities within the Enola swarm area and changes in the V_p/V_s ratios over short time periods (Pujol et al., 1989) could be interpreted as influenced by fluid migration. The origin of the fluid is unknown, though, from the regional geology, migrating magma as suggested by Johnston (1982) is unlikely. Therefore water or natural gas could be considered as this area is known to be a prolific field for natural gas from the Fayetteville Shale (Figure 1.1 and Figure 4.1).

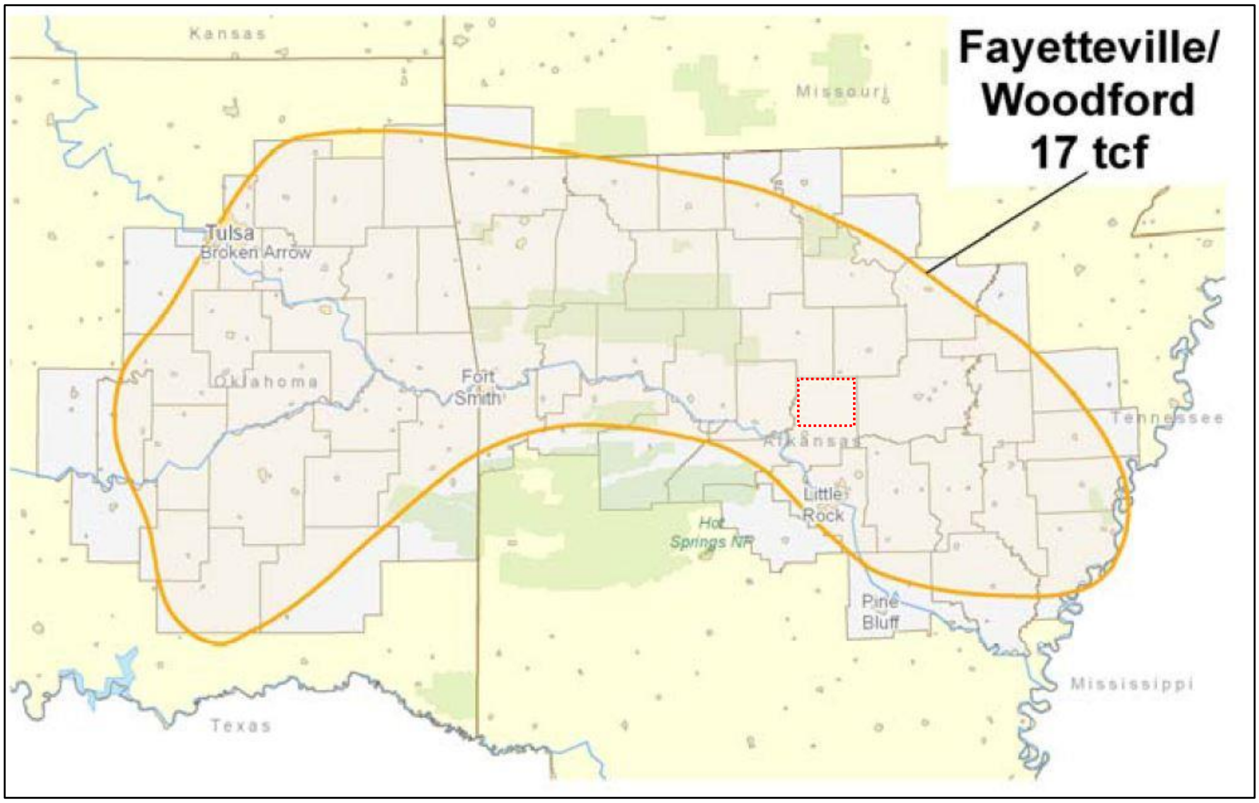

Figure 4.1: Location of Fayetteville Shale in the Arkoma Basin. Red dotted box is approximate location study area. Modified from (Arthur et al., 2008).

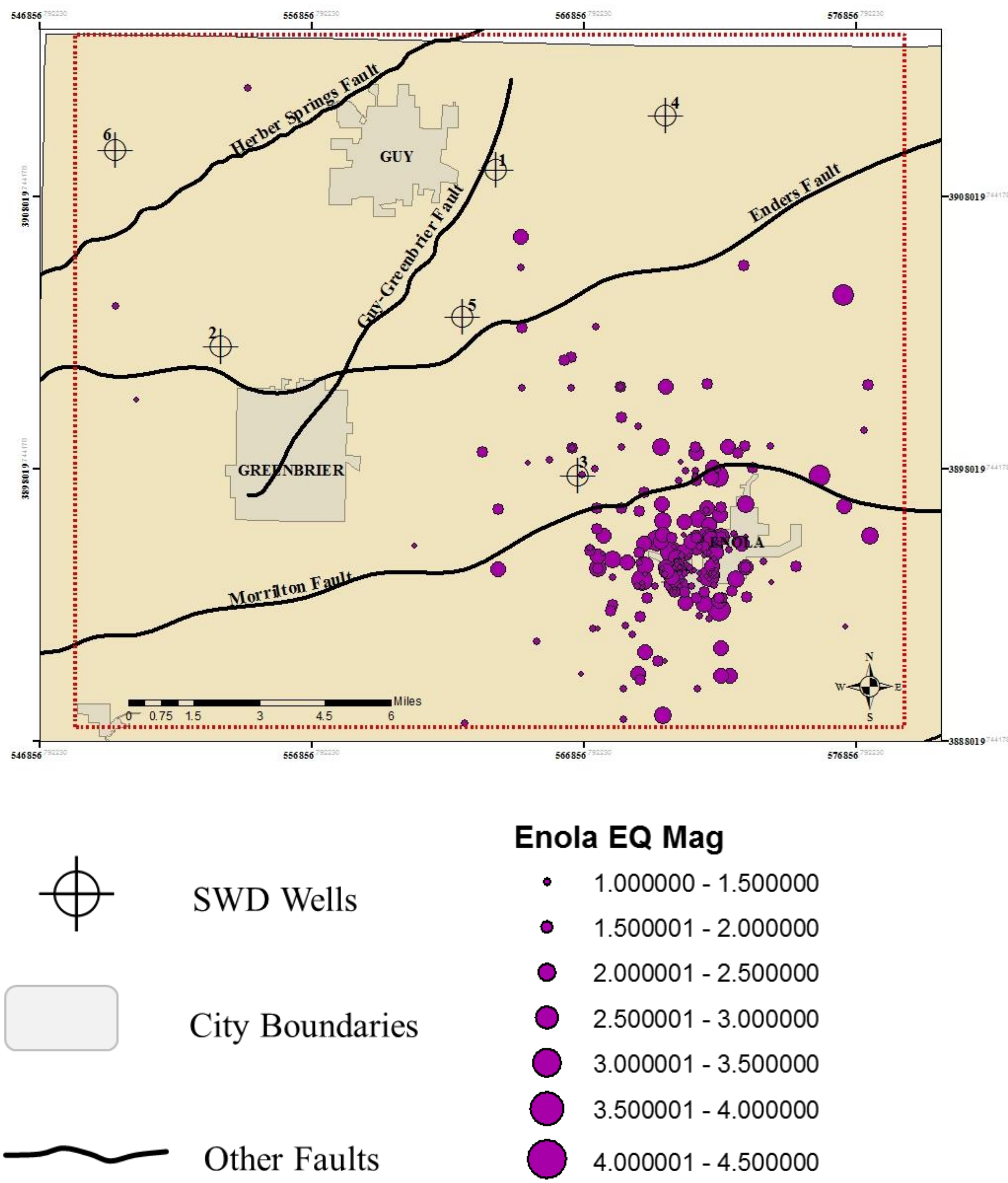

Figure 4.2: Enola swarm events from 1982 through 2001, for Enola earthquakes with magnitudes ≥ 1.0.

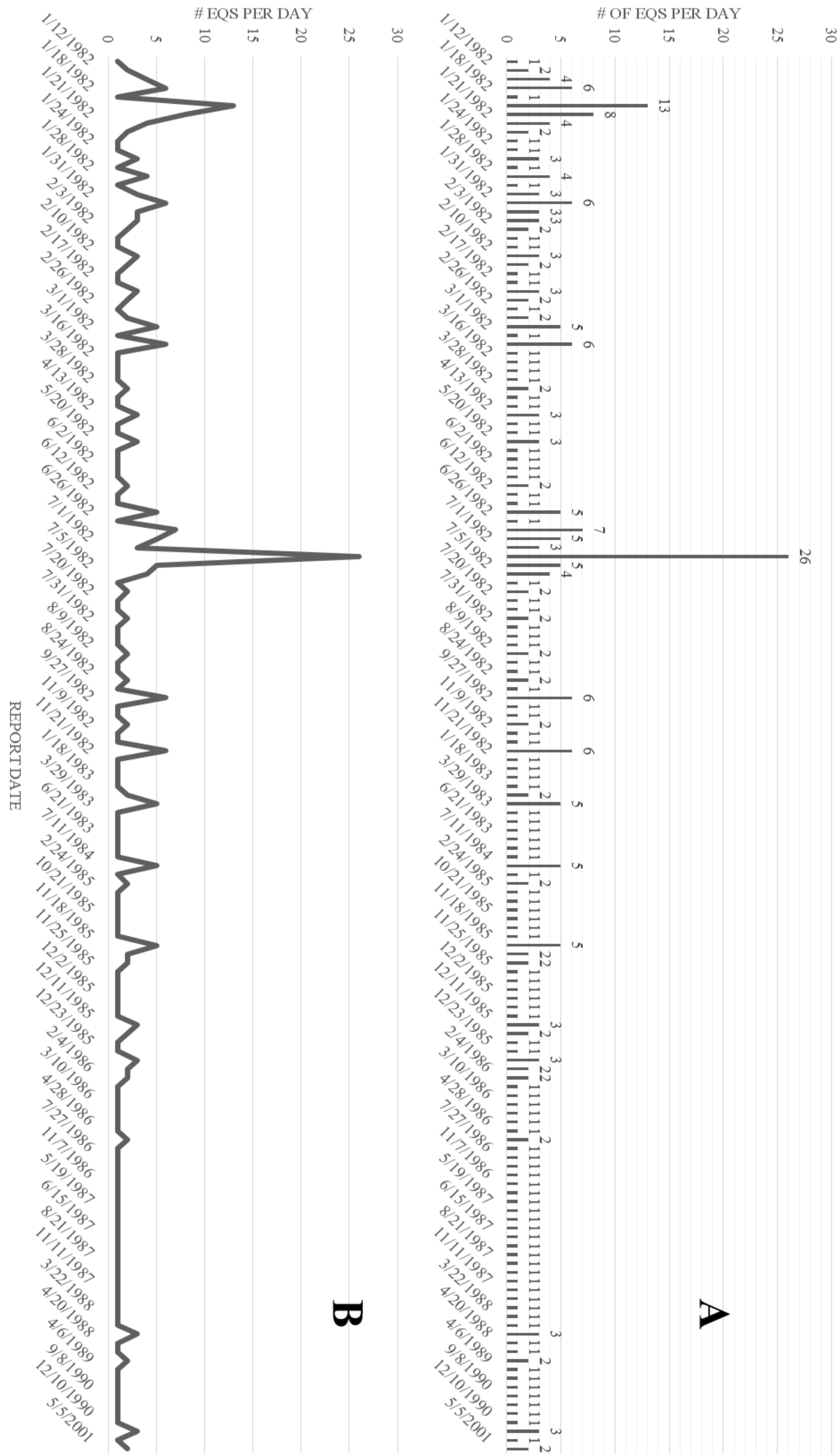

Figure 4.3: Histogram (A) and line plot (B) showing number of daily Enola earthquake events recorded from 1982 through 2001.

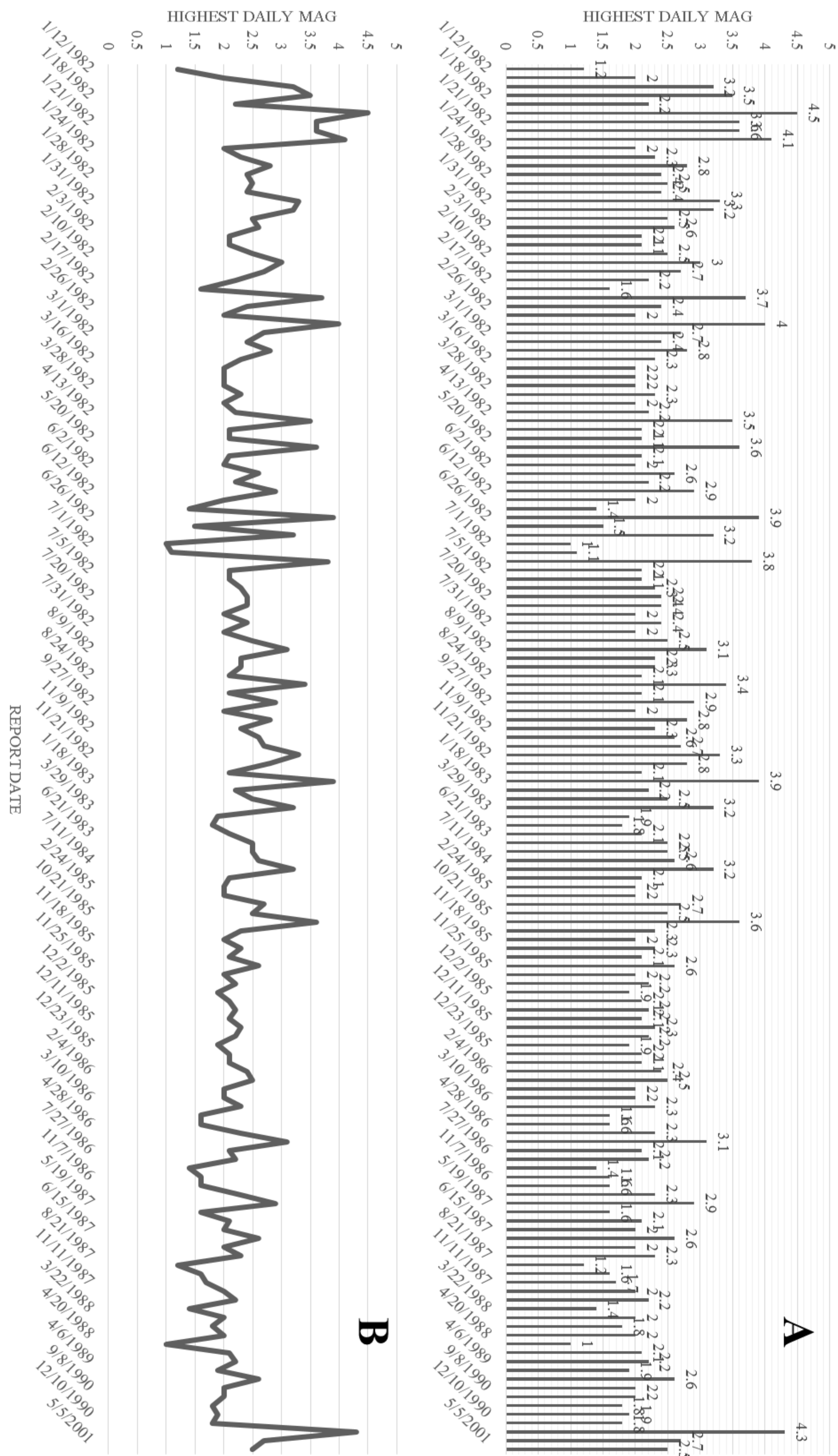

Figure 4.4: Histogram (A) and line plot (B) showing highest daily magnitudes of recorded Enola seismic events from 1982 through 2001.

SWD Wells

A total of six SWD wells were operational in Faulkner County between April 2009 and October 2011 (Table 4.3). Pressures and volumes of water injected vary with each well. BHP-SRE (Well #1) has the highest injection volumes for all the wells operational during the seismic period in North Central Arkansas. Deep Six - Moore (#3) and Clarita - Wayne Edgmon L1 (#5) stand out in regards to their pressures and injections depths. All three wells are in close proximity to the Greenbrier swarm.

Well	Permit	Operator - Well Name	Volume (bbls/month)	Volume (m^3/month)	Pressure (PSI)	Pressure (Mpa)	Start Date Stop Date (mm/dd/yyyy)	Injection Depth (m)	Injection Formation
1	43266	BHP - SRE	525,509.8	62,662	1711.4	11.8	07/07/10 03/03/11	1,821 1,969	Boone / Hunton
2	41079	BHP - Trammel	453,353.0	54,058	2291.6	15.8	04/15/09 06/20/11	1,982 2,009	Boone
3	39487	Deep Six - Moore	196,535.7	23,435	2944.3	20.3	06/15/09 07/27/11	2,365 3,231	Arbuckle
4	42981	Seeco - Underwood	248,011.6	29,573	739.7	5.1	01/15/10 10/15/10	1,713 1,926	Boone / Chattanooga / Penters / Hunton / Viola
5	36380	Clarita - Wayne Edgmon L1	164,206.1	19,580	2842.7	19.6	08/16/10 03/03/11	2, 379 3,344	Arbuckle
6	42989	Seeco - Scroggins	156,231	18,629	464.1	3.2	04/05/10 10/15/11	678 706	Orr

Table 4.3: SWD wells permitted in study area. See figure 1.1 for well locations. Volume and pressure are peak values observed during injection period. Modified from (Horton, 2012).

Well #2, originally operated by Chesapeake until 2011, was first completed as a dry hole in 2008, and in April 2009, it became operational as a SWD well. A total of 6,099,400 barrels of water was injected into this well, at an average tubing pressure of 2022 PSIG over its 26 month well life. Well #4 and #6, both operated by Seeco Inc. started SWD disposal in April and January 2010 respectively. Well #4 was plugged and abandoned after 10 months of operation and well #6 was plugged and abandoned a year later.

Tubing pressures and injection volumes for well #2, #4 and #6 do not show direct correlations with the Greenbrier seismic events (Figures 4.5, 4.6 and 4.7). However, well #1, #3 and #5 a close correlation, are in close proximity to the swarms, have higher injection peak pressures and show correlation with the Greenbrier seismic events (figure 1.5 and table 4.3).

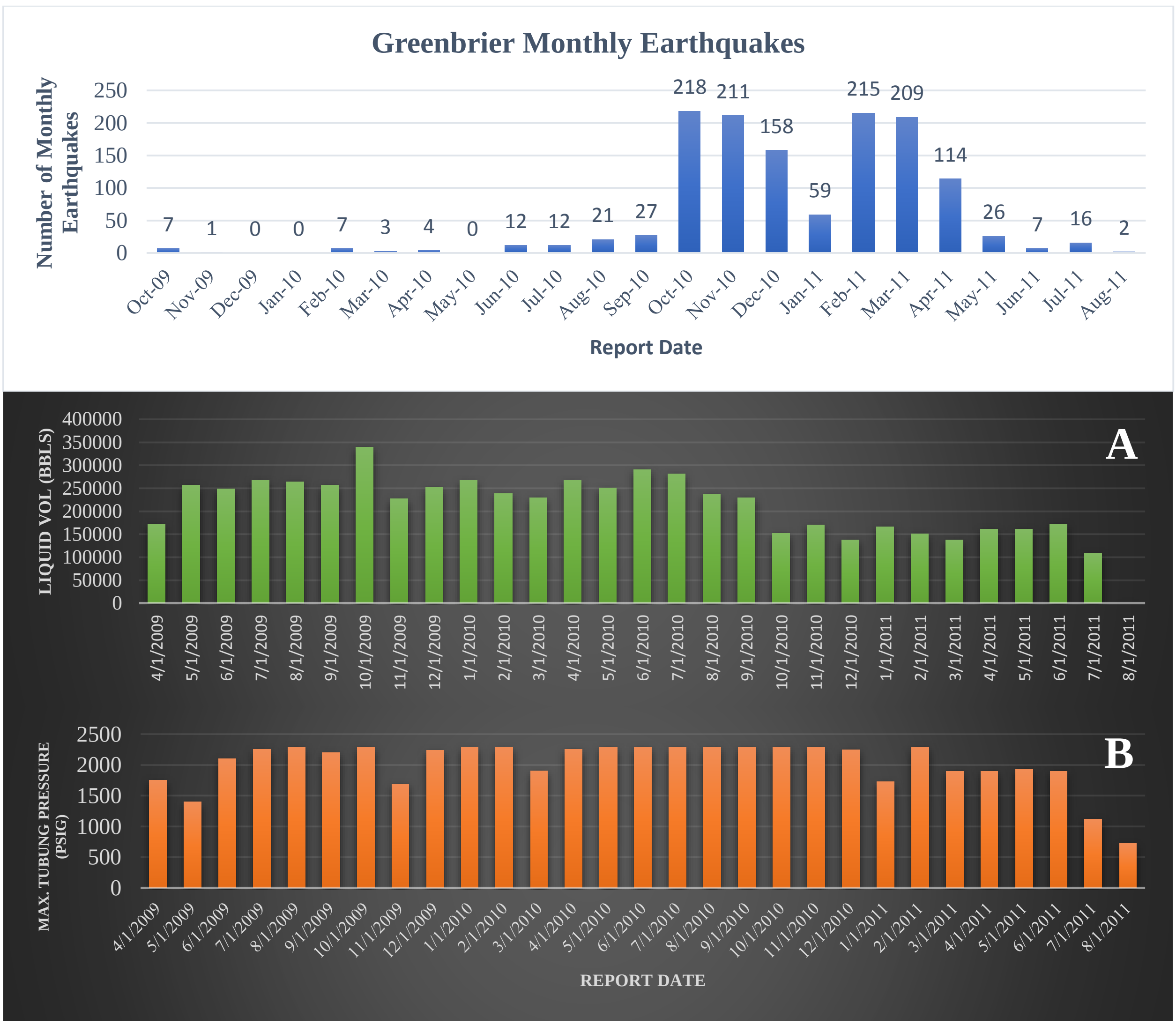

Figure 4.5: Monthly histograms of injection volumes in barrels (A) and tubing pressure in PSIG (B) for BHP-Trammel (#2) in comparison to monthly recorded Greenbrier swarm events. Earthquake data obtained from AGS, well data from AOGC.

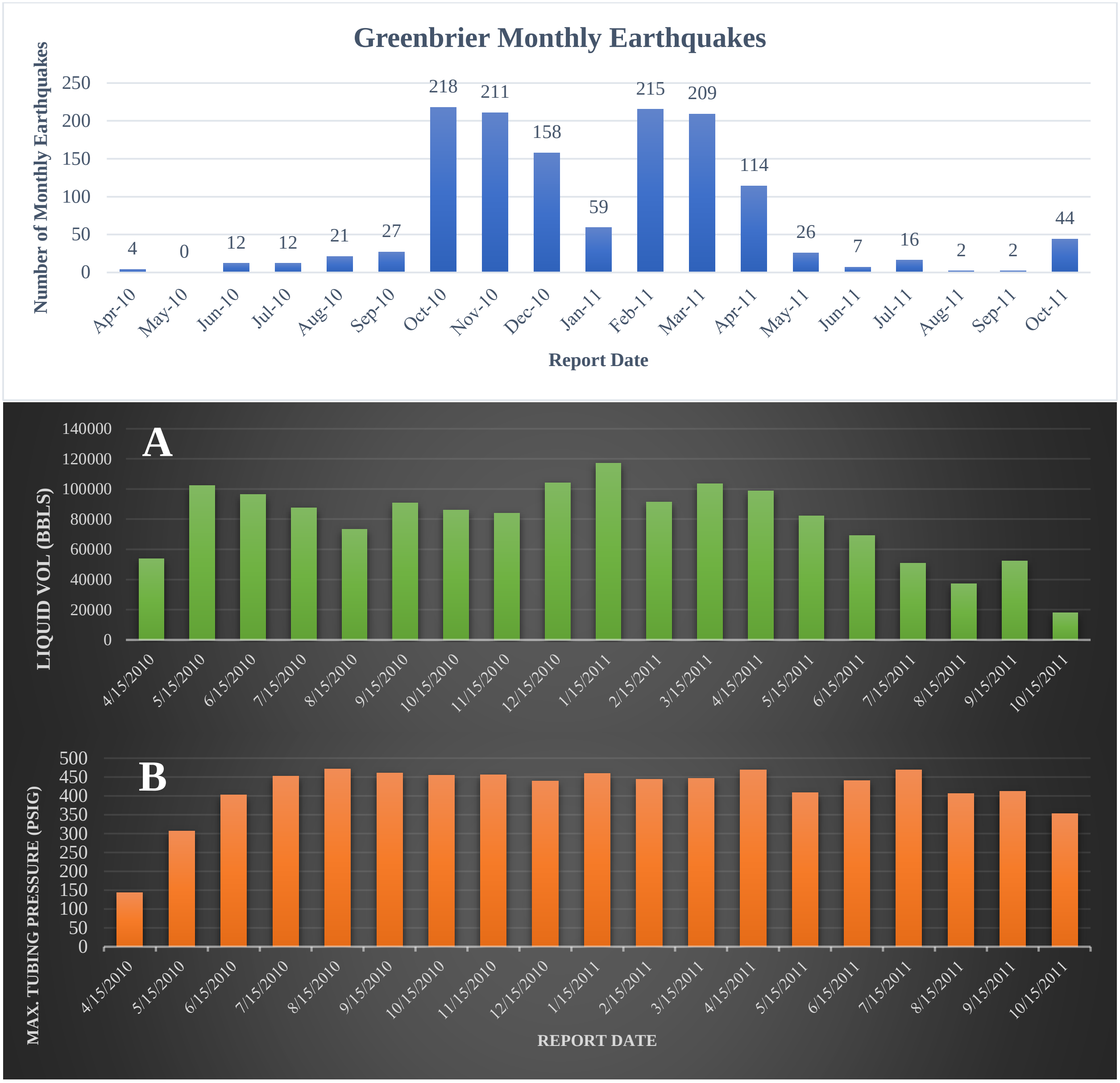

Figure 4.6: Monthly histograms of injection volumes in barrels (A) and tubing pressure in PSIG (B) for Seeco-Scroggins (#6) in comparison to monthly recorded Greenbrier swarm events. Earthquake data obtained from AGS, well data from AOGC.

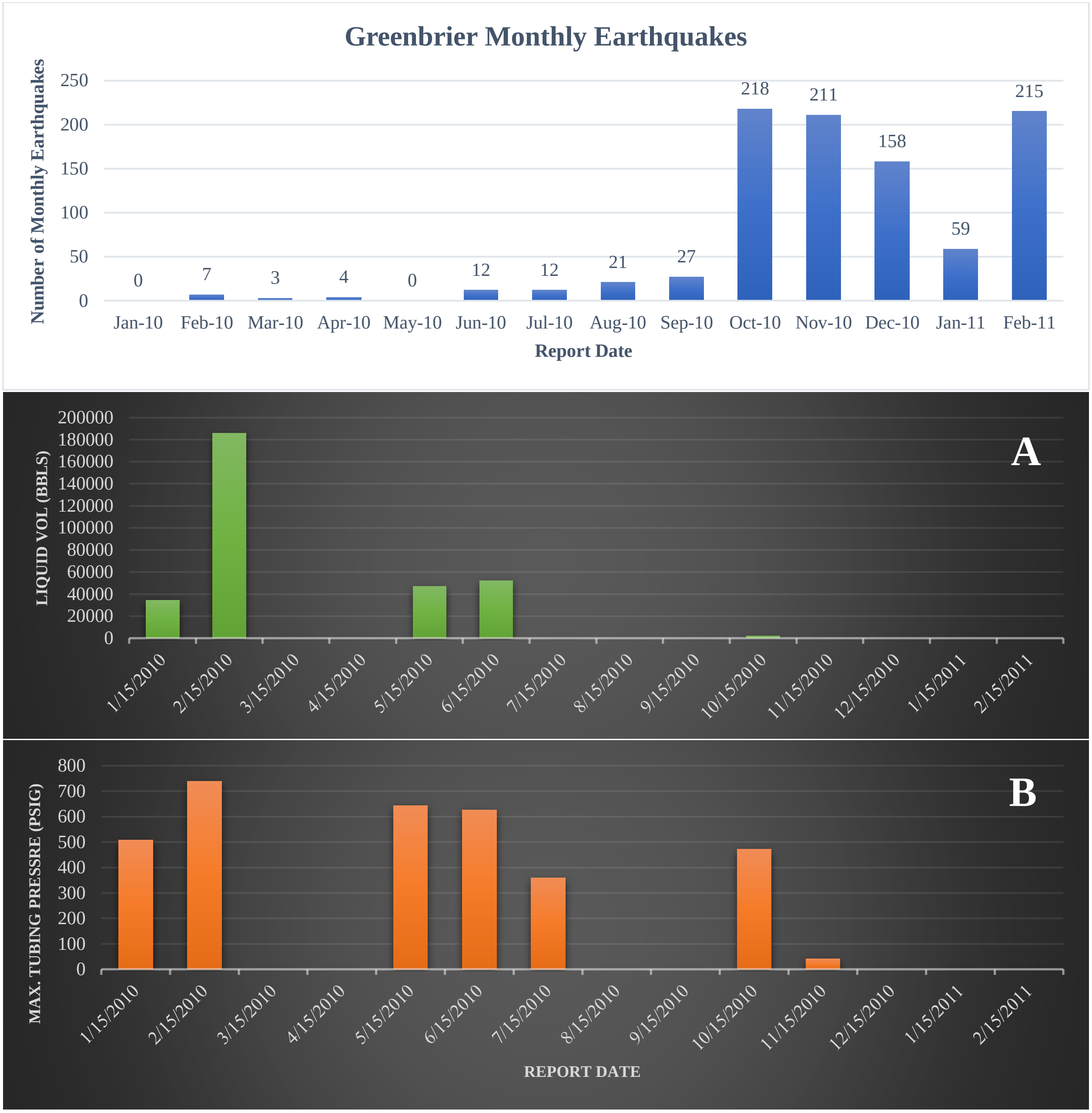

Figure 4 7: Monthly histograms of injection volumes in barrels (A) and tubing pressure in PSIG (B) for Seeco-Underwood (#4) in comparison to monthly recorded Greenbrier swarm events. Earthquake data obtained from AGS, well data from AOGC.

Well #1 has been operational as a disposal well from July 2010, and changed operators in 2011 from Chesapeake Operating, Inc. to BHP Billiton Petroleum (Fayetteville), LLC. It has peak injection pressures and the highest peak injection volumes (in comparison to other five disposal wells) of 11.8 MPa (1711.4 PSI) and 62,662 m^3/month (525,510bbls/month) respectively. Injection depths ranged from 1,821 - 1969 m (5975 - 6460ft), into the Lower Mississippian Boone and Silurian Hunton formations (Table 4.3). This well is located within the 2010 (Figure 4.11) swarm and also shows a significant correlation between the pressures and volumes of injected fluid and registered seismicity in the area. The peak volume in October 2010, corresponds to a peak in the month earthquake registered in the study area (Figure 4.8). Injection volumes declined subsequently, but the monthly registered events were still underway. Injection volumes were increased again between November 2010 and February 2011, and there was an increase in the number of recorded events, from 29 to 215 from January to February respectively (Figure 4.8). This well was eventually plugged and abandoned in September 2011, but injection had ceased five months prior.

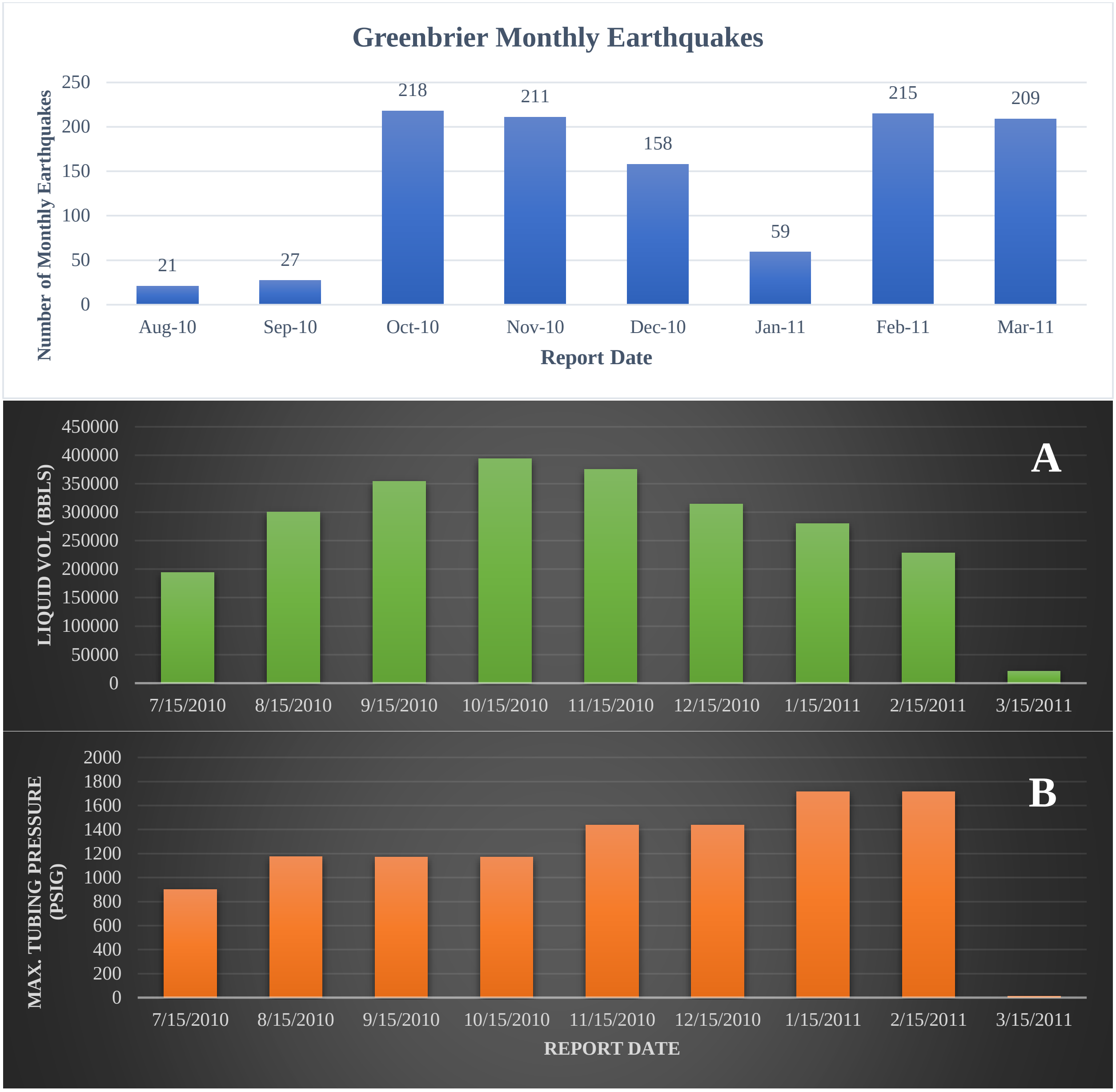

Figure 4.8: Monthly histograms of injection volumes in barrels (A) and tubing pressure in PSIG (B) for BHP-SRE (#1) in comparison to monthly recorded Greenbrier swarm events. Earthquake data obtained from AGS, well data from AOGC.

Well #3 began operation in 1973 and was completed as a dry hole in 1974. Reentry was then completed in 2008 as a SWD well and disposal started on June 15, 2009. Peak injection pressure and volume recorded were 20.3 MPa (2944 PSI) and 23,435 m^3/month (196,535.7bbls/month) respectively. Injection depths ranged from 2,365 m (759ft) to 3,231 m (10600ft) into the Arbuckle

(Table 4.3). Comparing the volumes and pressures of injected fluid to the seismic events within its vicinity, there is little correlation, especially in regards injected volumes. However, the tubing pressures is relatively constant for the initial 15 months of injection, after which there is a decline for the following four months. This decline is then proceeded by an increase, twice the initial amount, and during that month (March 2011) there were 209 events recorded within the vicinity of the SWD well (Figure 4.9). It was eventually plugged and abandoned four months later, the seismicity seemed to decline significantly.

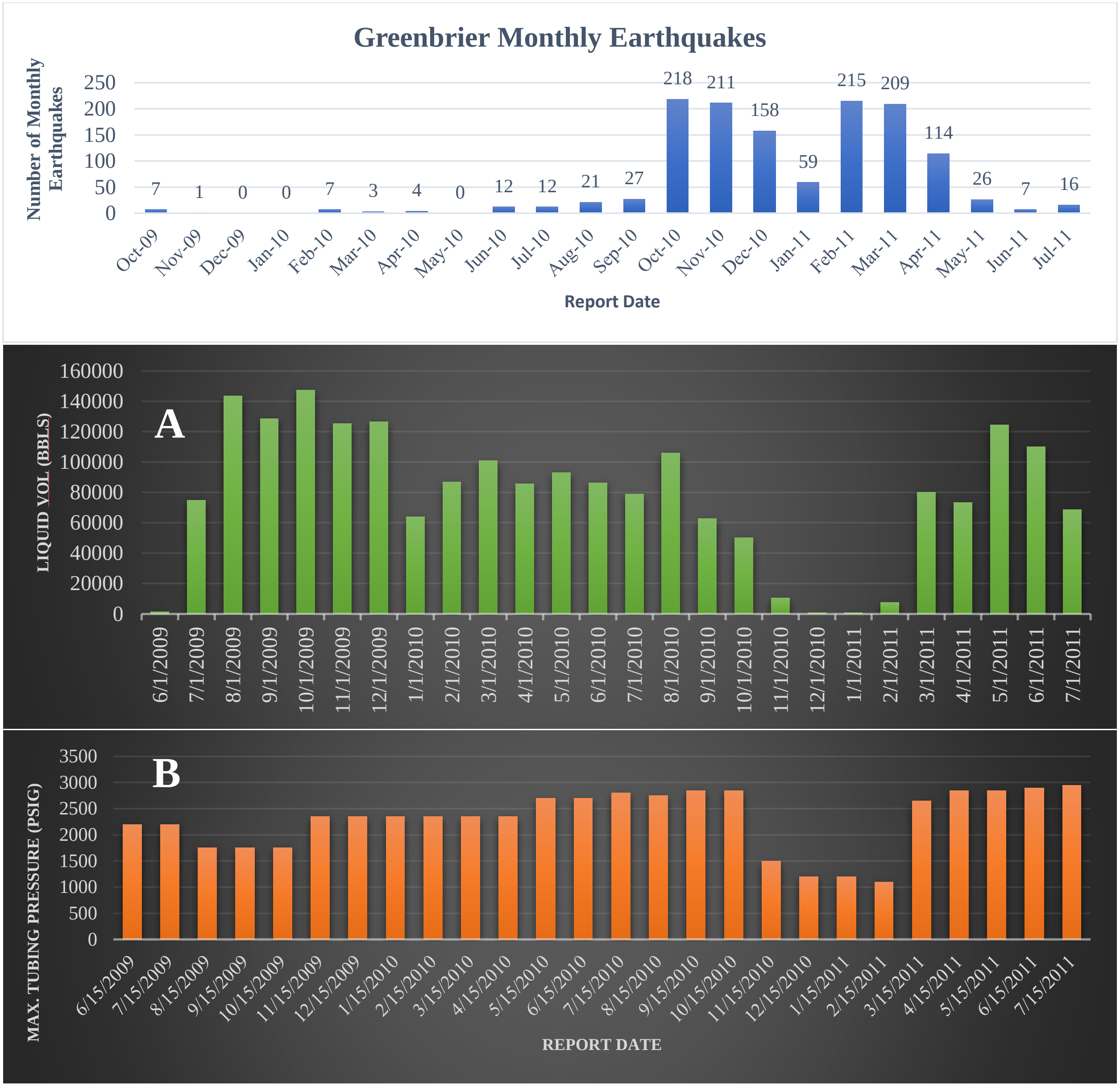

Figure 4.9: Monthly histograms of injection volumes in barrels (A) and tubing pressure in PSIG (B) for Deep Six-Moore (#3) in comparison to monthly recorded Greenbrier swarm events. Earthquake data obtained from AGS, well data from AOGC.

Wayne Edgmon L1 (well #5) initially commenced in 1983 under Hegco Inc., during which it was completed as a dry hole and was plugged and abandoned that same year. It was reentered in 1998 and this was completed in the Arbuckle the following year with no reports on production values. In 2010, the operator changed from Hegco Inc. to Clarita Operating LLC and became operational as a Class II or Class V SWD well, with peak pressures and volumes of 19.6 MPa (2843 PSI) and 19,580 m^3/month (164,206bbls/month) respectively. Injection depths ranged from 2379 to 3344 m (7805.118ft to 10971.13ft) into the Arbuckle/Ozark Aquifer (Table 4.3, Figure 5.1). The volumes and pressures of injected fluid show a good correlation with the monthly seismic events recorded in its vicinity. Injection volumes show a linear increase for the first couple of months. The peak injection volumes of about 120,000 barrels in November 2010 corresponds to an increase in the number of seismic events experienced in the area during that month (Figure 4.10). The tubing pressures and injection volumes were then decreased and number of seismic events declined as well. Nonetheless, an increase in the tubing pressures for the last two months of operation was followed by an increase in the number of seismic events as well. 59 in January 2011, and tubing pressures and volumes were 1850PSIG and 41702bbls respectively; 215 in February and 209 March and tubing pressures were increased to 2850PSIG and 2800PSIG. Injection pressures and volumes as well as seismicity declined in the following months, following a state order for the well to be plugged and abandoned.

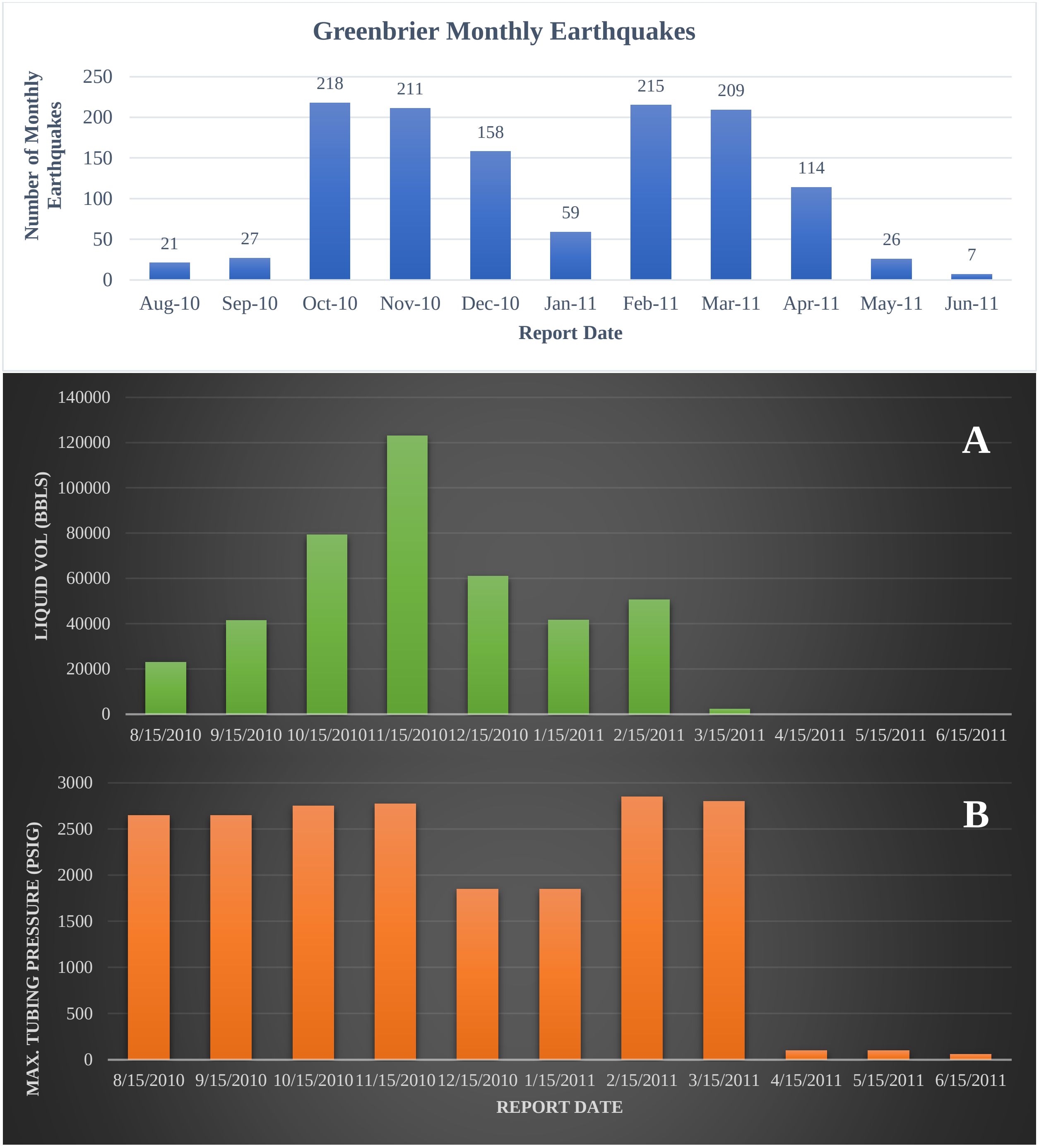

Figure 4.10: Monthly histograms of injection volumes in barrels (A) and tubing pressure in PSIG (B) for Clarita-Wayne Edgmon L1 (#5) in comparison to monthly recorded Greenbrier swarm events. Earthquake data obtained from AGS, well data from AOGC.

Greenbrier Seismicity

Greenbrier seismicity was first recorded and linked to SWD in 2009 after eight earthquakes occurred approximately 5 km from well #2 and in 2010, scattered seismicity continued within the area. The large E-W trending Enders Fault occurs just south of well #, and cuts the Springfield Aquifer into which well #2 was being injected. (Horton, 2012). (Figure 4.11)

After injection started in well #1, scattered seismic events began to be recorded within ~5km radius of the well and the first earthquakes occurred along the Guy-Greenbrier fault approximately a month following initiation of injection. Fluid injection at well #5 began 16 August 2010 and an array of seismometers were installed in the vicinity of well #1 and #5 (Horton, 2012). By September, hundreds of moderate events were recorded to the south of well #1. By February the following year, the swarm activities were even more intense along the same trend, but occurred several kilometers to the south, leaving a gap on the upthrown side of the Enders fault (Horton, 2012). By the end of the 2011 swarm, the previously unrecognized Guy-Greenbrier fault was approximately 13km long, cross-cutting the Enders fault on its southern end.

The 2010 swarm is mostly located close to the city of Guy, within the vicinity of well #1 and #5, with magnitudes ranging from 0.2 to 4.0, and depths of 0 to 13 km (Figure 4.12 and 4.13). The 2011 swarm presumably migrated southward along the same linear Guy-Greenbrier Fault trend, with magnitudes ranging between Mb 1 and 5, and depths of 0.1 to 8km, also in close proximity to well #2 and #5 (Figure 4.14 and 4.15).

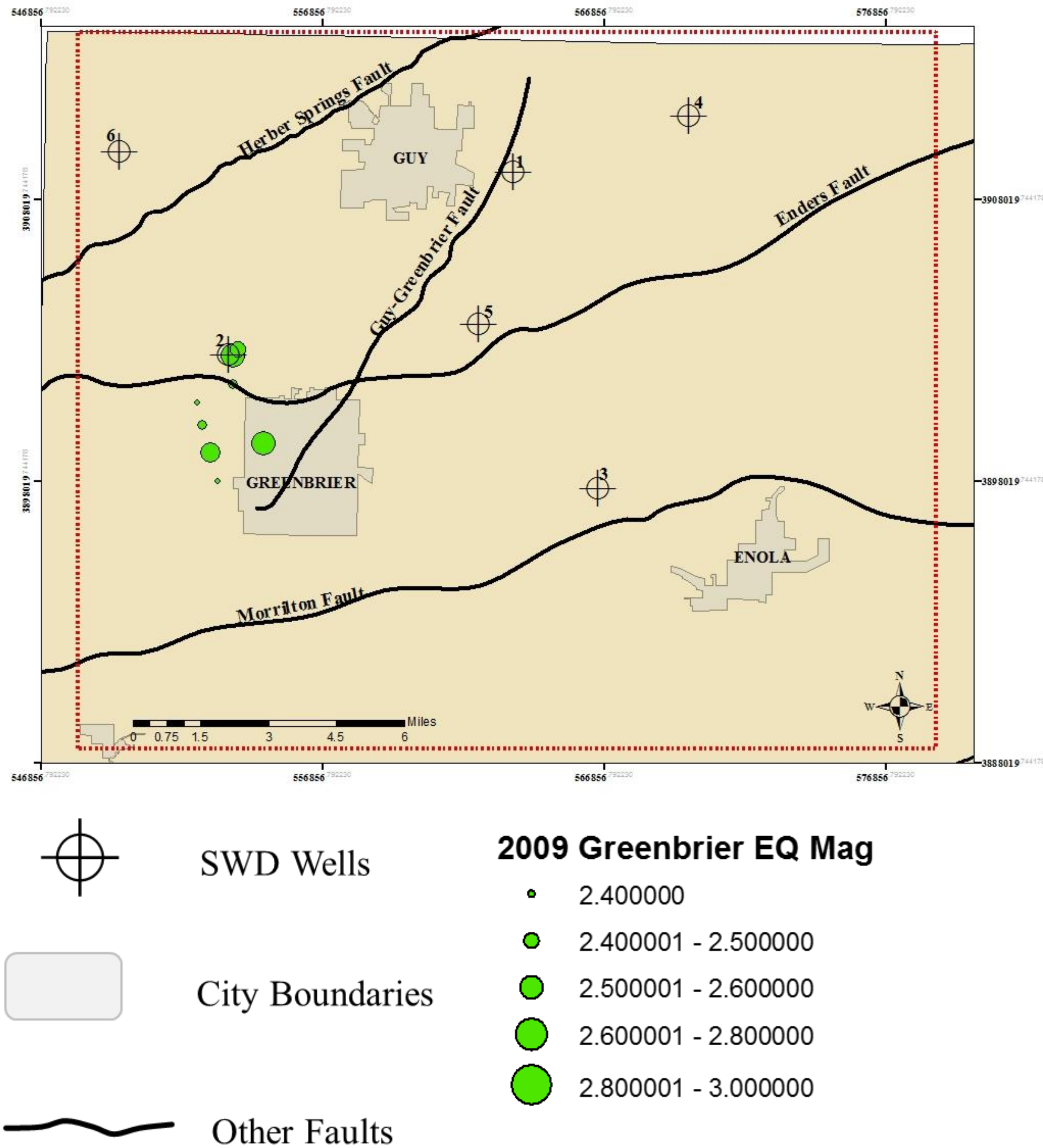

Figure 4.11: Greenbrier 2009 earthquake magnitudes ≥0.5. Data provided by AGS.

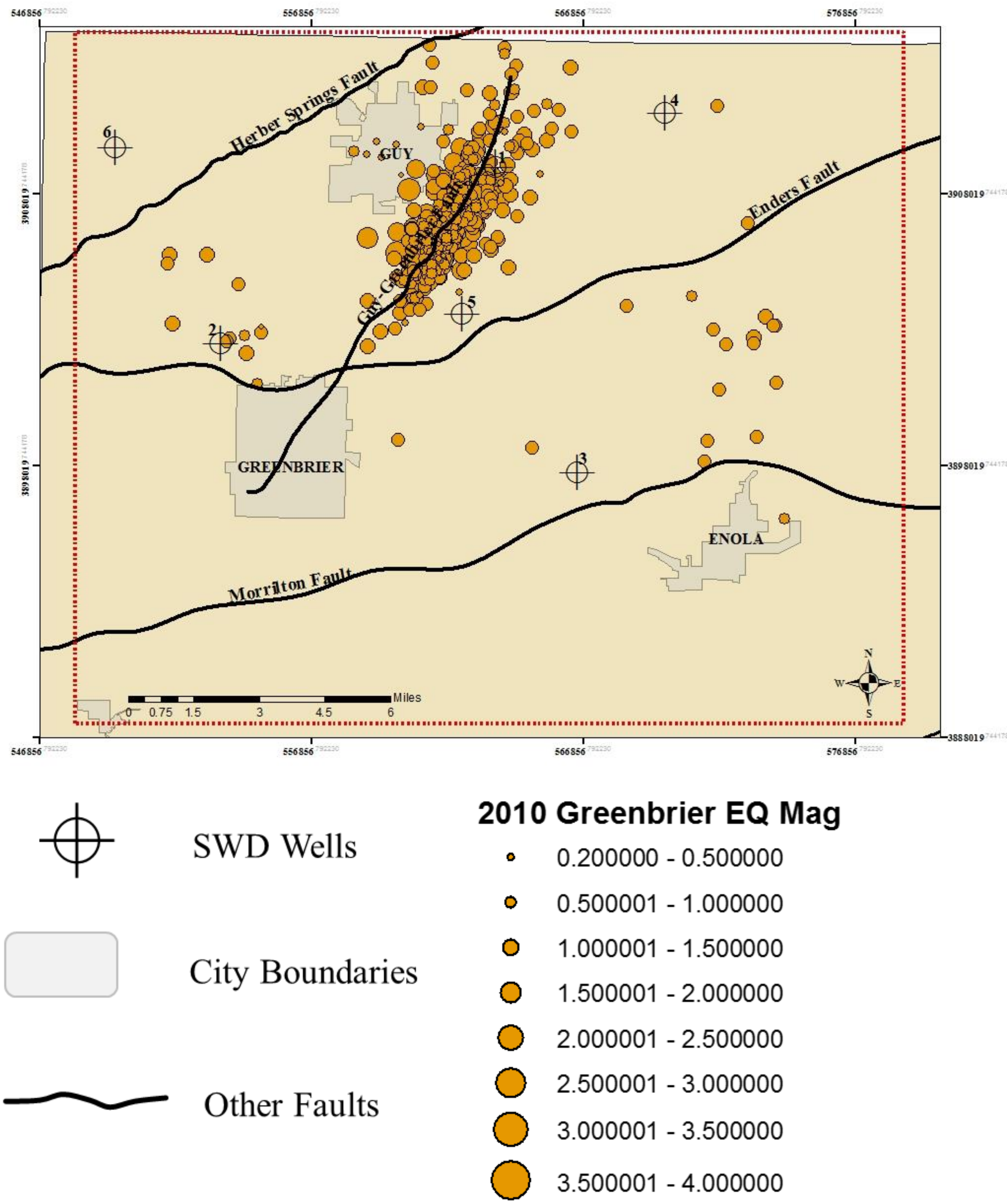

Figure 4.12: Greenbrier 2010 earthquake magnitudes ≥0.5. Data provided by AGS.

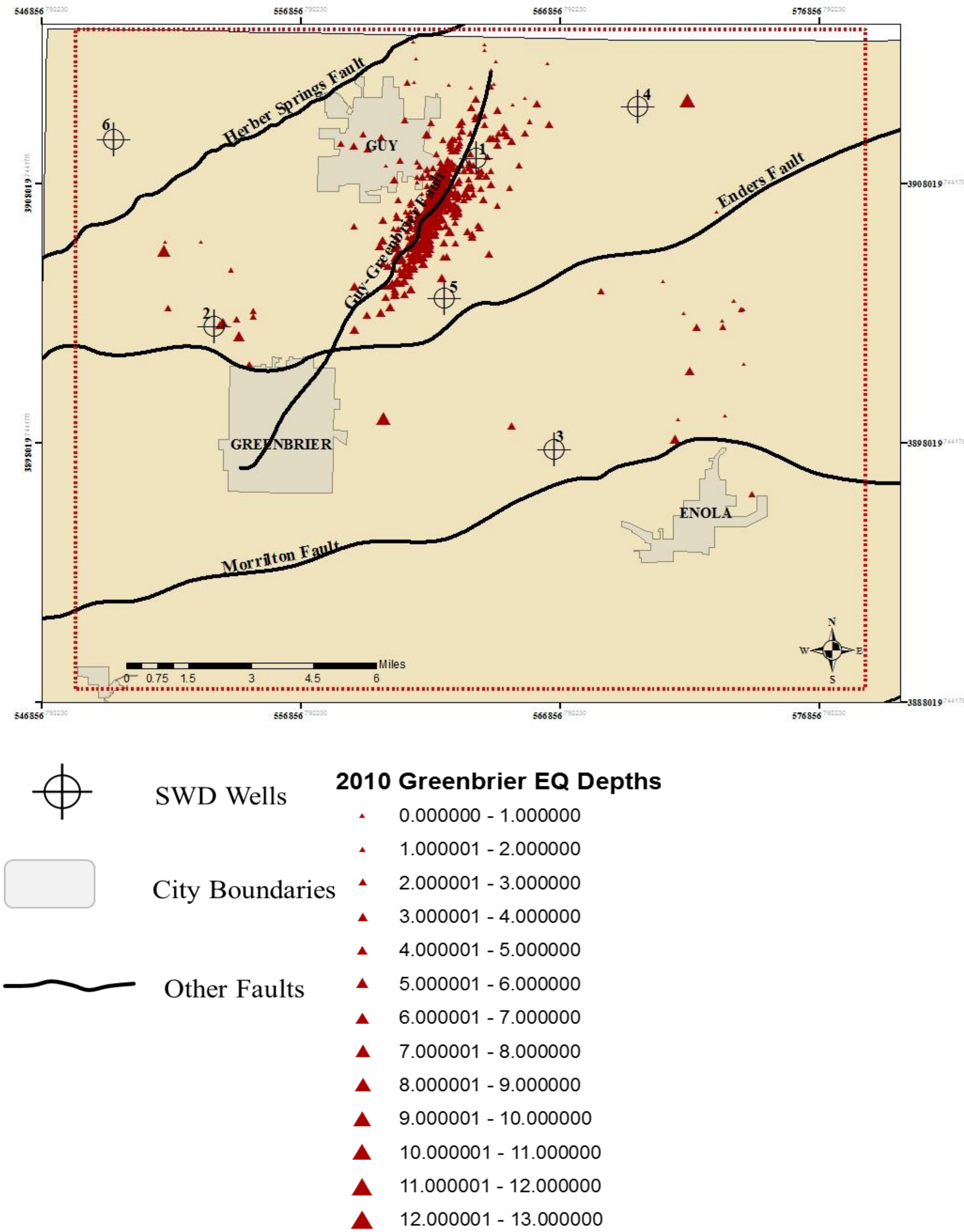

Figure 4.13: Greenbrier 2010 earthquake depths. Data provided by AGS.

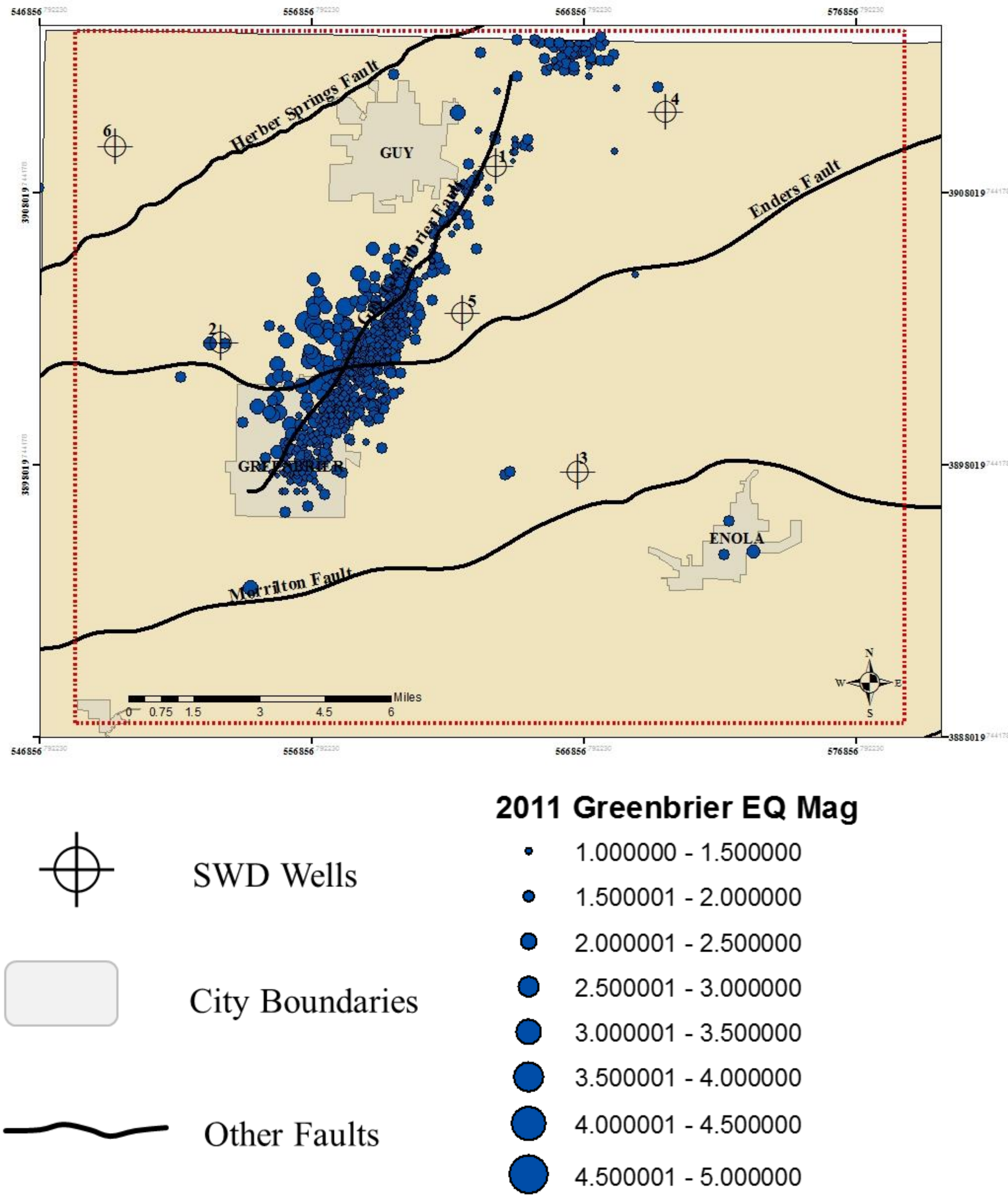

Figure 4.14: Greenbrier 2011 earthquake magnitudes ≥0.5. Data provided by AGS.

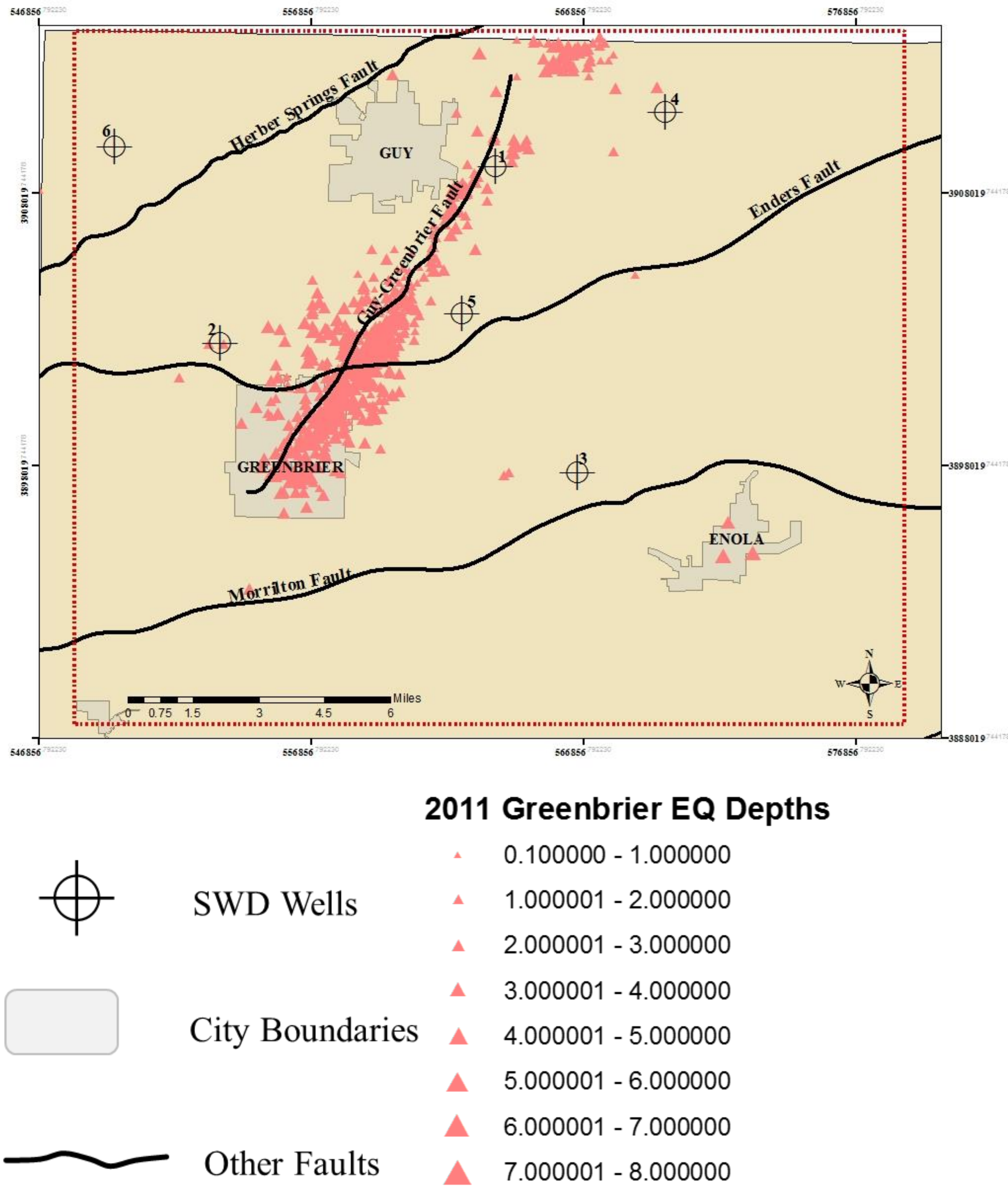

Figure 4.15: Greenbrier 2011 earthquake depths. Data provided by AGS.

The overall number of daily recorded seismic events from 2010 to 2011 show a bell-shaped pattern, with three phases which correspond to periods of highest recorded counts in seismicity, between October 8, 2010 and April 24, 2011 (Figure 4.16 and 4.17). These also correlate to the time during when most of the SWD wells were operational within the study area, and #1, #2, and #5 are closest in proximity to the earthquake epicenters. These phases are:

Phase 1

This is a 19 day period between October 8, 2010 and October 26, 2010. During which an average of 10 daily earthquakes were recorded with 2.8 average magnitude. Five recorded events showed magnitudes ≥ 3, and the highest magnitude was 4.0 on October 11, 2010. This corresponds to a high injection volume for the well #1 (Figure 4.8), high tubing pressure for wells #3 (Figure 4.9) and #5 (Figure 4.10).

Phase IIA

This is a 33 day long sequence between November 10, 2010 and December 13, 2010. This period recorded a total of 317 events, averaging at 10 events per day and an average magnitude of 2.4. Only two of these events recorded magnitudes ≥ 3; Mb 3.9 on November 20 and Mb 3.1 on December 13. This phase corresponds to the period of highest injection volumes and tubing pressures for well #5 (Figure 4.10). Also, well #1 showed an increase in tubing pressure at the beginning of November, which could be associated with the increase in seismicity during this period (Figure 4.9).

Phase IIB

This phase shows a total of 40 events within an eight day period from January 8, 2011 to January 18, 2011 separated by periods of relative quiescence, after phase IIA and before phase III. The seismic magnitudes for this phase averages at about 2.2, and an average number of five daily events. All recorded magnitudes for this phase were greater than 1.5 but less than 3.0 (Figure 4.17). The tubing pressure and injection volumes for well #5 were decreased during this period, which correlates to the overall decrease in seismicity seen during this phase (figure 4.10). A significant decrease in injection volumes for well #3 could also be associated to the decrease in recorded seismicity seen during this phase (Figure 4.9).

Phase III

This is the longest and most explosive phase of the Greenbrier seismic swarm. It lasted for two months (60 days) from February 15, 2011 to April 24, 2011 and a total of 522 events were recorded. These averaged at 9 events per day with average magnitude of 2.8. 23 earthquakes with Mb $\geq$ 3 were recorded during this phase. The highest magnitude for the entire Greenbrier swarm (Mb 4.7) was also recorded within this phase on February 27, 2011. The next was a 4.1 recorded on February 18, 2011. These correlate to an increase in tubing pressure for well #5 from 1850 PSIG to 2850 PSIG (Figure 4.10), and significant increase in tubing pressures and injection volumes during this period of well #3 - from 1100 PSIG in February to 2650 PSIG in March for pressures and 680bbls in January to 7540bbls in February and 80154bbls in March for its injection volumes (Figure 4.9).

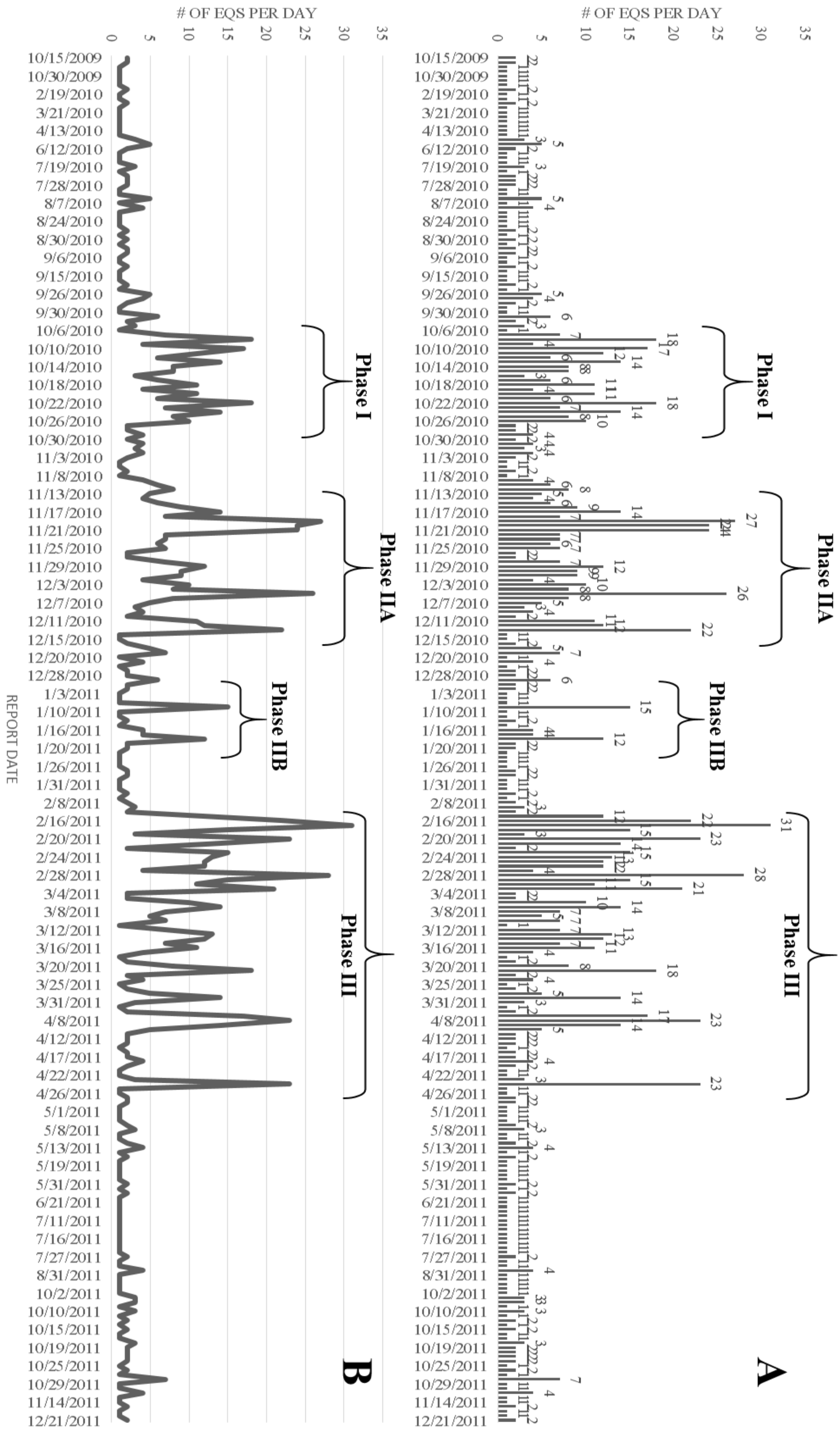

Figure 4.16: Histogram (A) and line plot (B) showing daily number of Greenbrier seismic events. Data obtained from AGS.

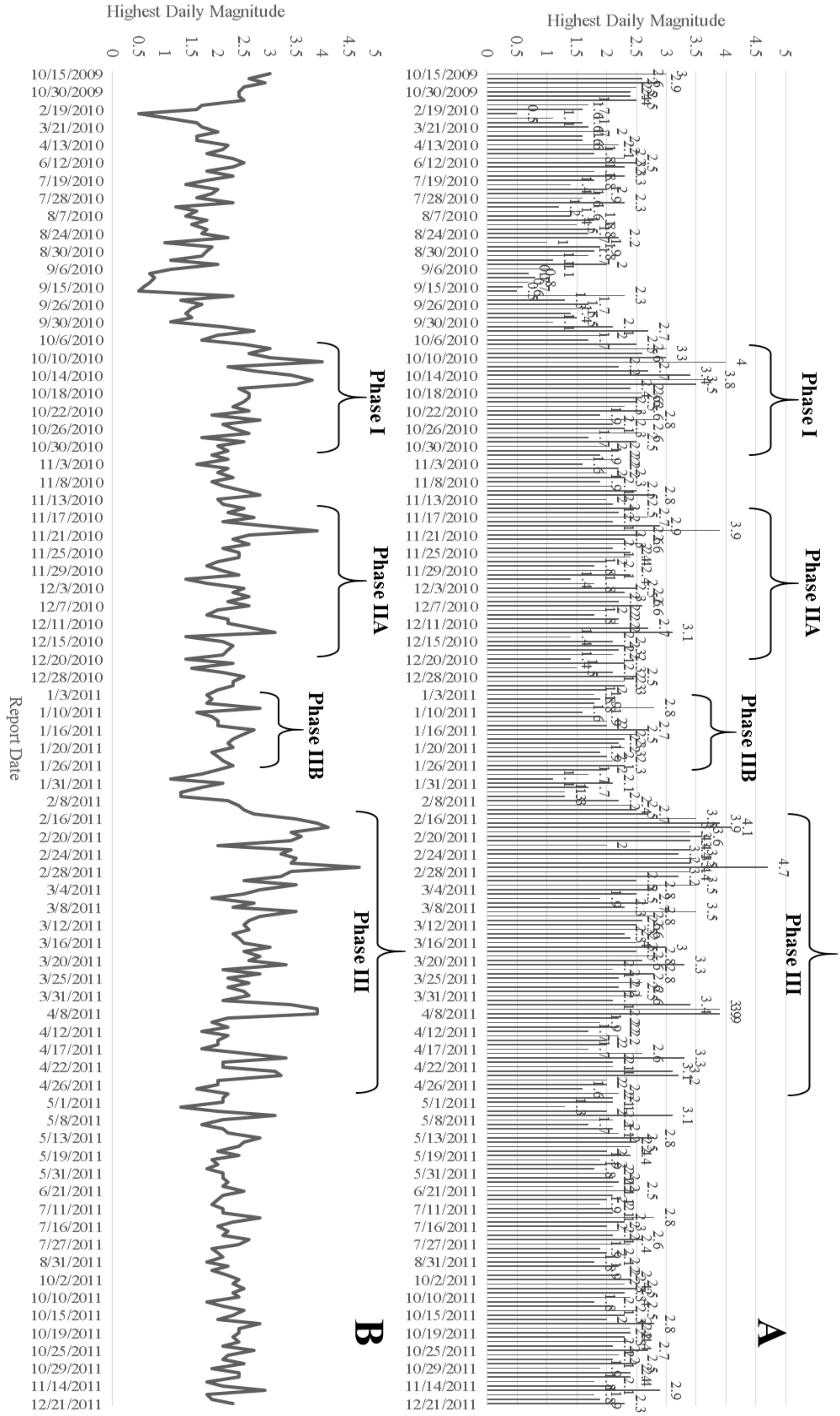

Figure 4.17: Histogram (A) and line plot (B) showing the highest registered daily magnitudes for Greenbrier earthquake swarm. Data obtained from AGS.

V. DISCUSSION

Looking at the elevations from the recent leveling survey conducted by NGS, the BMs show no significant elevation changes. This should be expected considering the fact that no very limited seismic activities have been recorded within the area. This however is concerning because Burroughs' evaluated a rate of uplift of 0.019ft/year that resulted in the 0.47ft of graben uplift and approximately 100ft of Atokan sediment uplift and this was suggested to have occurred over the last 5000 years. This uplift was interpreted by Schweig et al. (1991) to be as a result transpression focal mechanism, due to the thrusting component of the slip. This means that the graben is being squeezed up as a result of compressional and shear stresses across the graben. Though the age of the uplift is unknown, it is definitely ongoing and has occurred within the last 50 years. If the uplift rate is constant, then the leveling survey should reveal about a 0.51 ft. of uplift over the last 29 years. However, resetting the BMs to a different elevation hiders continues elevation survey, as new BMs do not have preceding records and published elevation values. The small elevation changes for BM Y 209 (table 4.1) are mathematically influenced by the conversions from NGVD 29 to NAVD 88. The elevation changes of 25 RHM and 26 RHM (table 4.2) are interpreted as instrument error and are not considered to be geologically influenced.

As a result, the Enola area does not show any significant changes in elevation and corroborates the relative seismic silence in the area. Without continuous data and levelled elevations for the benchmarks surveyed by Burroughs (1988), it is difficult to determine elevation changes between the swarm area and its surrounding. Therefore, the leveling survey of the Enola swarm area for this study is inconclusive and the Paleozoic graben uplift hypothesis set forward by Burroughs (1988) remains valid until further information and survey data becomes available.

Comparing the Greenbrier swarm to the SWD wells, #4 and #6 do not show anomalous correlations with the seismic events. Nonetheless, the four significant wells for the Greenbrier seismicity are wells #1, #2 #3 and #5. These wells were located in closer proximity to the swarm events, showed injection at greater depths (well #3 and #5), with higher volumes (well #1) and pressures of injection (well #3 and #5). Wells #1 and #5 were operational during similar time intervals, during which higher rates of seismic events were registered. These were then plugged and abandoned in early 2011, but seismic events were still slowly underway. These events could then be related to the increased tubing pressures of the #3.

Wells #1 and #5 were shut down following a state issued order by the AOGC, but the Guy-Greenbrier swarm did not stop immediately. Nonetheless, there is a significant decline on the rate and magnitudes of the earthquakes. This could be related to the fact that pore pressures that were built up during the months of injection will require some time to return to pre-injection levels. Regardless of the fact that the wastewater was injected into the Paleozoic sedimentary rocks, precisely the Arbuckle Group for well #5 and #3, and Boone/Hunton for well #1 and the earthquakes in question occurred largely in the Precambrian crystalline basement (Figure 5.1), the structural geology of the area suggests there may be hydraulic connectivity between the wastewater disposal well injection depths and the earthquake depths (Horton, 2012). The Guy-Greenbrier fault cuts across the Precambrian basement into the overlying Paleozoic sediments, and thus a conduit for fluid migration from the Ozark Aquifer into which well #1 and #5 were being injected (Figure 5.1). Well #5 also cuts the Enders fault, thus providing a hydraulic connection to the earthquakes that were recorded to the south of the Fault. More so, well #5 was drilling directly above the intersection of these faults (Figure 2.3 and 5.1).

Looking at the really high peak pressures of wells #1, #2, #3 and #5 and the high peak volumes of wells #1 and #2 surrounding the Guy-Greenbrier Fault (Table 4.3, Figure 1.5), it is fair it say that significant pore pressures are likely to build up within the Ozark Aquifer. Pore pressures will also increase within the fault zone due to the connection between the Ozark Aquifer and the Guy-Greenbrier Fault. Only expansion of the pore pressure into the Guy-Greenbrier fault zone is needed for an induced seismic event to occur, the fluid does not need to migrate the entire distance (Horton, 2012). From the mechanics of induced seismicity, a fault could remain locked as long as the applied shear stress is less than the strength of the contact. But, with increasing shear stress, reduction of the normal stress, and/or increasing the pore fluid pressure can bring the fault to failure and trigger an earthquake (Ellsworth, 2013). This could be the reason why there are speculations of some induced events occurring shortly after industrial activities begin and others taking months or years, long after the induced events have been under way or even ceased.

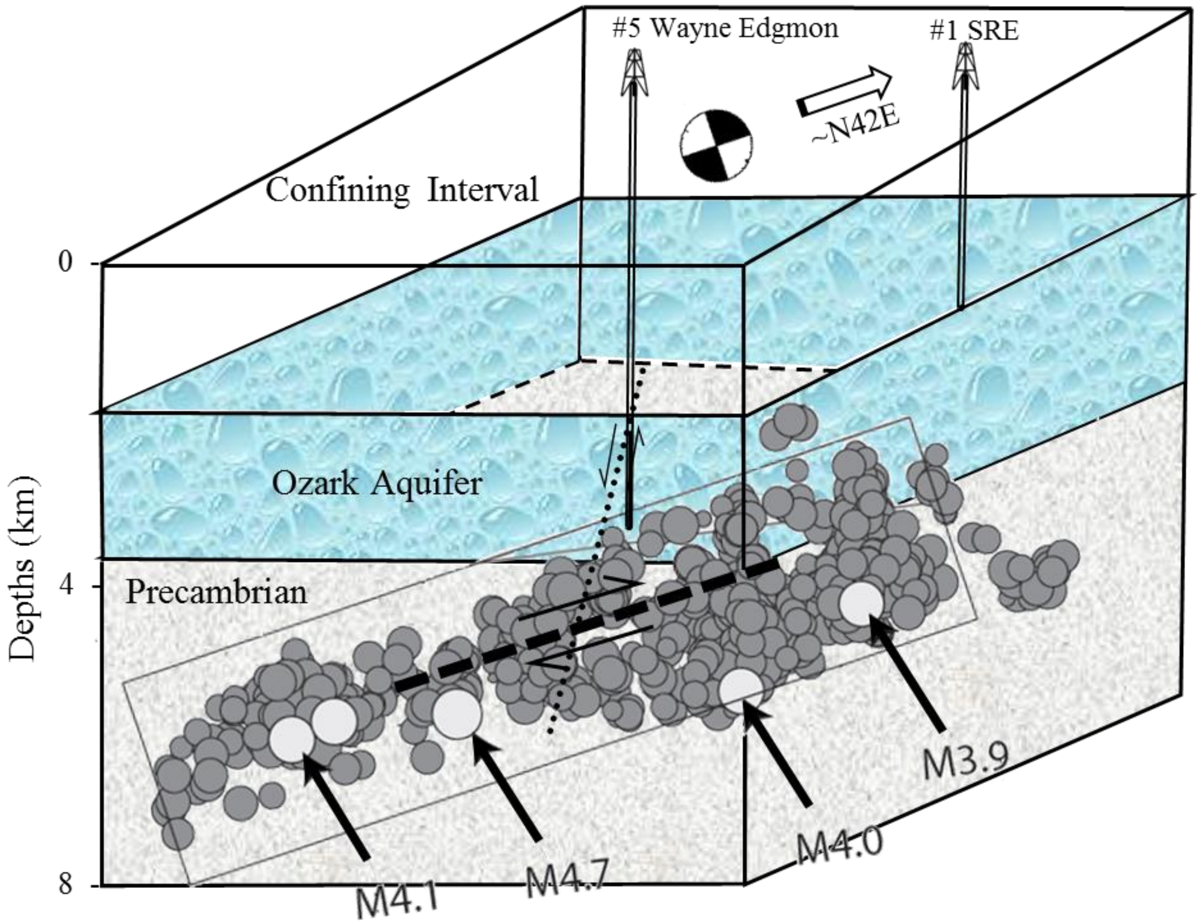

Figure 5.1: Block Diagram of study area showing approximate injection depths of well #1 and #5 into the Ozark Aquifer in relation to earthquake hypocenters in the Precambrian basement rock. Solid black portion at the bottom of each well indicates the interval of fluid injection. Location of larger earthquakes (white circles), known to rupture deeper portion of the Enders Fault indicated by dotted line. Approximate depth and location of guy-Greenbrier fault indicated as dashed lines with right lateral slip fault mechanism. Modified from Horton, 2012. Sketched by Gregory Dumond.

NATURAL OR INDUCED?

Geological and geophysical research on earthquake seismicity recognize the difficulty in accurately distinguishing between a natural and an induced seismic event (Llenos and Michael, 2013). However, Davis and Frohlich (1993) have been able to establish a rational criteria for considering a seismic event as triggered. This is comparatively based on significant proximity of the events to the injection wells and an anomaly in the records of previously recorded seismicity in the area. The tabular illustration of "yes" and "no" phrased questions will help to answer the concerns about possible causes of well-known and documented induced or non-induced events. These responses corroborate previously documented hypothesis that the Greenbrier event is most likely induced, while the Enola event is natural.

Question	Earthquakes Clearly NOT Induced	Earthquakes Clearly Induced	I Denver, Colorado	II Painesville, Ohio	III Guy-Greenbrier, Arkansas	IV Enola, Arkansas
Background Seismicity						
1. Are these events the first known earthquakes of this character in the region?	NO	YES	YES	NO	NO	YES
Temporal Correlation						
2. Is there correlation between injection and seismicity	NO	YES	YES	NO	YES	NO
Spatial Correlation						
3a. Are epicenters near wells (within 5km)?	NO	YES	YES	YES?	YES	NO
3b. Was there active injection at the site?	NO	YES	YES	YES?	YES	NO
3c. Do some earthquakes occur at or near injection depths?	NO	YES	YES	YES?	YES	NO
3d. If not, are there known geologic structures that may channel flow to sites of earthquakes?	NO	YES	[1]YES	NO?	YES	YES
Injection Practices						
4a. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity	NO	YES	YES	YES	YES	NO
4b. Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?	NO	YES	YES?	NO?	YES?	NO?
TOTAL "YES" ANSWERS	0	8	8	4	7	2

Table 5.1: Eight questions forming a profile of a seismic sequence. Guy-Greenbrier and Enola events have been added for comparison. Modified from (Davis and Frohlich, 1993); [1]SWN personal communication.

VI. SUMMARY

The study area is within a stable intercontinental craton and seismicity within this area is almost inconceivable until the Enola swarm of 1982 and 2001, followed by the Guy-Greenbrier swarms of 2010-2011.

The Paleozoic graben uplift could explain the concentration of the Enola swarm, as previously analyzed by Burroughs. But, due to the destruction of BM USGS SAN 3Y and BM Y 209, a recent correlation could not be made. Nonetheless, the BM resets made available by NGS do not show a significant change in vertical elevation within the given time frame. Fortunately, these BMs have been securely placed and future monitoring will be beneficial for a more effective correlation between the Enola Swarm and the Paleozoic graben uplift.

The Guy-Greenbrier swarms show good correlations with the SWD wells operational within the area during the seismically active periods. In addition, the swarms declined significantly a few months after the disposal wells were no longer operational. Thus, this swarm event could be likely associated with the increase in injected volumes and pressure of the SWD wells.

Despite the close proximity, similar geologic and tectonic history of Enola and Greenbrier swarms, it is unlikely that these two events have similar triggering mechanisms. The Enola swarm occurred during a period when no SWD wells were operating, and no previous seismic activities had been recorded within the study area either (except in the New Madrid Seismic Zone, North-East of study area). Additionally, though it could be difficult to differentiate between an induced and a natural seismic event, the eight profiling questions of a seismic sequence developed by Davis and Frohlich

(1993) shows that the Guy-Greenbrier swarm is most closely associated to an induced event, while the Enola swarm most closely correlates with a natural event.

SUGGESTED FUTURE WORK

1. Additional elevation points to be surveyed
2. Additional seismic, especially 3D seismic data will be useful in determining the subsurface influence to the earthquake activities
3. Continues monitoring of the benchmarks, and earthquake activities for a consistent five to ten year cycles.
4. Make comparisons of the Enola and Greenbrier swarms to other areas with possibility for earthquakes.

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VIII. APPENDIX

YYYY	# of EQs
1981	0
1982	211
1983	16
1984	8
1985	29
1986	19
1987	13
1988	8
1989	3
1990	6
1991	0
1992	1
1993	0
1994	0
1995	0
1996	0
1997	0
1998	0
1999	0
2000	0
2001	6
2002	0
2003	2
2004	0
2005	1
2006	2
2007	0
2008	0
2009	8
2010	671
2011	702
2012	13
2013	2
2014	4

A1: Yearly earthquakes recorded in Faulkner County. Data obtained from AGS