1. Introduction

On May 4, 2001, central Arkansas experienced an M=4.4 earthquake followed by a surprisingly large number of small earthquakes. We recorded about 2500 above the ambient noise level on a continuously recording broadband seismograph deployed in the epicentral area for about 2 months.

The location of the mainshock from regional networks, and the locations of aftershocks from our portable network coincide with the location of a remarkable swarm of earthquakes that took place in the early 1980s. The 1980s sequence produced 30,000 earthquakes in a 3-year period. In 1987 a 40-seismograph campaign in the same area for 4 months recorded only 12 earthquakes. Documented seismicity within the swarm region preceding the 1982 events is almost non-existent. There are some felt-reports indicating that same area experienced earthquakes in 1962-63 (McFarland, 2001).

The area of the swarm is located in the Arkoma Basin, an intraplate setting north of the frontal Ouachita transition zone (Figure 1). The earthquake area lies tectonically and geologically outside of the Reelfoot rift and the New Madrid Seismic Zone (Figure 2) but it is close enough that a common seismogenic mechanism cannot be ruled out. However, I will demonstrate that the Enola zone, where the sequences took place, exhibits a very specific and localized set of conditions that distinguishes it mechanically as well as spatially from the New Madrid Seismic Zone.

An earthquake swarm sequence does not follow a scheme where the mainshock is followed by smaller aftershocks. All the earthquakes in a swarm sequence tend to be of similar size. Swarms also may have seismically quiescent periods before waking up and producing numerous earthquakes. They usually occupy a small crustal volume. Earthquake swarms are frequently related to volcanic regions and sea-floor spreading zones (Sykes, 1970) but they can take place in tectonically different environments like the east Arkoma basin considered here.

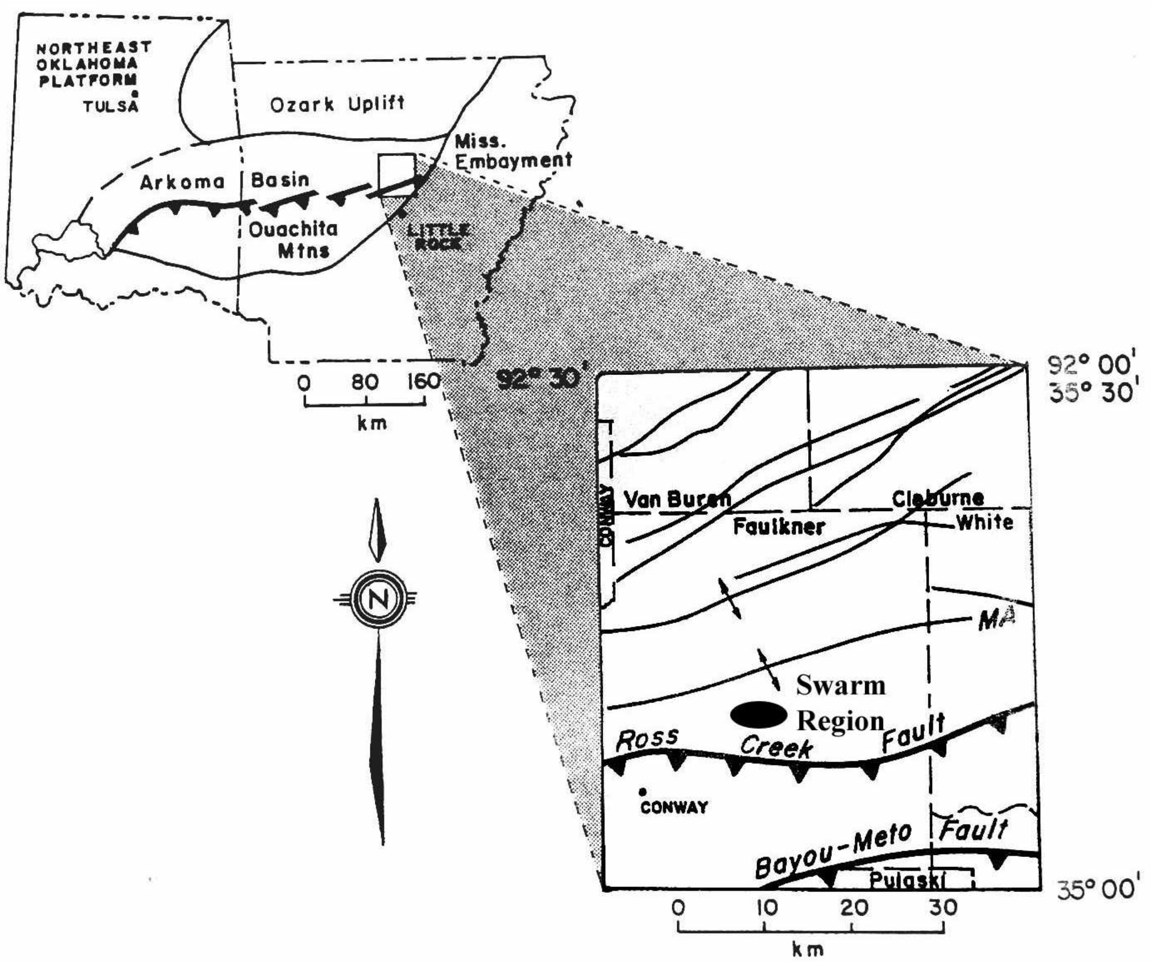

Figure 1. The swarm area (dark ellipse) in the Eastern Arkoma basin north of Little Rock, AR. Unlabeled thin lines in the inset map are normal faults. Thrust faults have symbols on the hanging wall. MA = Morrilton anticline. Modified from VanArsdale (1990).

Based on apparent changes in the v_p/v_s ratio within a day and the large number of earthquakes in a small volume Chiu et al. (1984) proposed that the rock in the Enola area is highly fractured. Interpretation of seismic reflection data taken over the Enola area reveals a fractured medium restricted only to the hypocentral volume (Schweig et al., 1991).

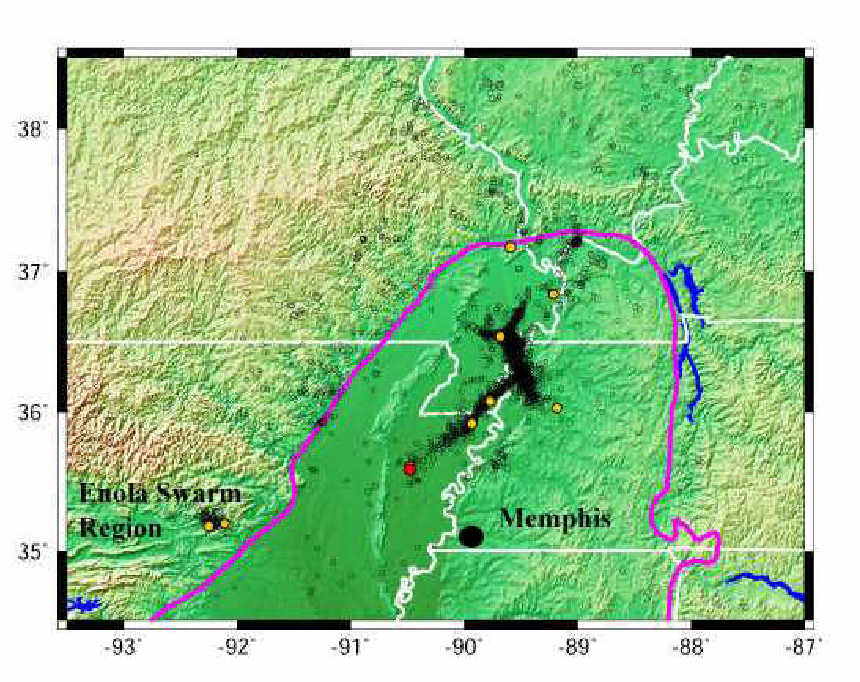

Figure 2. The Mississippi Embayment map. The purple line marks the edge of the embayment. Circles represent earthquake magnitudes recorded on CERI networks up to 1996. The red circles are magnitudes ≥ 5, yellow 4 ≤ M < 5, and open black circles show earthquakes of magnitude < 4. The Enola swarm region is some 200 km southwest from the New Madrid Seismic Zone (majority of seismicity – black circles).

Moreover, application of the joint hypocentral determination (JHD) technique (Pujol et al., 1989) suggested up to 15% lower seismic velocities in the hypocentral volume then in the surrounding rocks.

A series of ENE trending folds characterizes structure in the greater Enola swarm region (Figure 3). The area is dominated by east-west trending folds and faults caused by north-south compression (VanArsdale and Schweig, 1990). However, the principal compression axis of the present day stress field is thought to be oriented ~ ENE (Zoback and Zoback, 1980). South-dipping normal faults structurally dominate north of the swarm area. South of the swarm, however, thrust faults dominate, forming a fold-and-thrust belt.

Faults at depth are expressed at the surface by many anticlines. These faults were formed during middle and late Pennsylvanian time. Thrust faulting is thought to be the last tectonism in the area overprinting the preexisting normal faults (VanArsdale and Schweig, 1990). Within the swarm area Paleozoic sandstones and carbonates occur to a depth of ~ 5 km where the Precambrian basement starts (Schweig et al., 1991).

About 80 m.y. ago Arkansas was a volcanically active region because of the passage of the Bermuda hotspot (Cox and VanArsdale, 2002). However, there are no indications that both Enola sequences are due to episodes of igneous activity even though the 1982 sequence shared attributes with swarm-like seismicity of a volcanic origin in Matsushiro, Japan (Johnston, 1982).

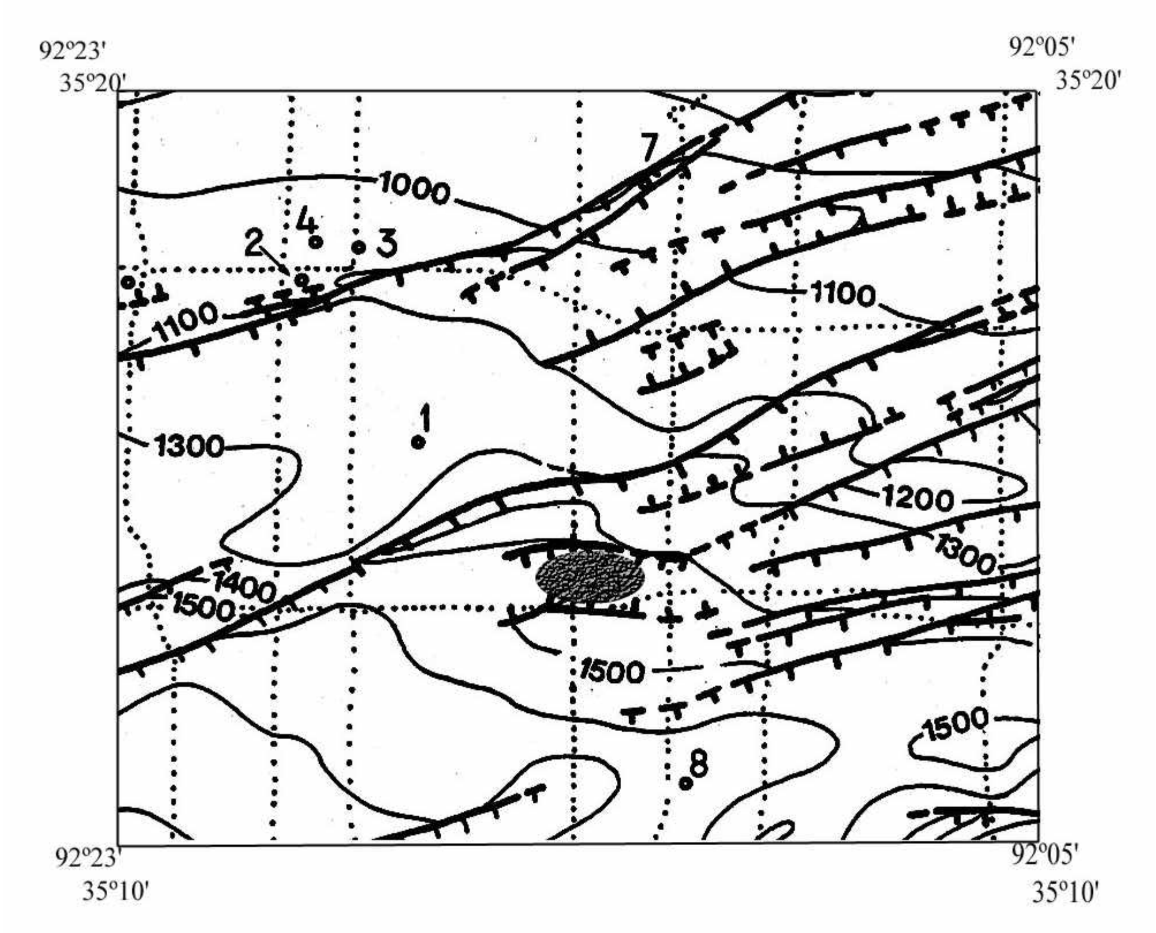

Figure 3. Numerous faults around the swarm area (dark ellipse). Bold lines are normal faults, teeth on downthrown side. Dotted lines are seismic reflection lines. Modified from VanArsdale (1990).

The recurrence of swarm-like seismicity near Enola after ~20 year hiatus begs the question of what conditions give rise to this phenomenon. One explanation is that the seismic activity is caused by the regional compressive stress field acting on specific and highly localized source properties, namely cracked rock possibly filled with fluids that are not present outside the strict Enola zone.

In order to test the viability of this claim, I have studied the seismotectonic characteristics of the 2001 Enola swarm. The attributes of the 2001 sequence that I focused on, and the general results may be summarized as follows:

Overall spatial-temporal behavior. The 2001 sequence occupied a small crustal volume, some 10 km^3, where the 1982 sequence also took place. A small crustal volume indicates highly localized seismogenic properties. The earthquakes did not rupture a preexisting mapped fault.

The 2001 sequence produced about 2,500 earthquakes (beside the mainshock) of magnitude $M_L < 3$ over two months. This indicates a swarm-like character. Numerous small size earthquakes suggest specific seismogenic characteristics of the Enola zone. To investigate the seismicity rates I developed a robust phase picker that produces a database with several quality parameters controlling the quality of the earthquake counting algorithm. The 2001 earthquake sequence did not follow a simple mainshock-aftershock scheme. An aftershock decay cannot be observed. The sequence exhibited swarm-like behavior. I obtained daily seismicity rates based on the continuously operating broadband seismograph.

Size distribution of the sequence earthquakes. The b-value of the 2001 sequence differs from b-values calculated for earthquake swarms in volcanic zones and the mid-Atlantic ridge. I determined the size distribution of the 2001 sequence. The slope of the distribution gives the b – value. The seismicity of the sequence migrated in time that could indicate fluid-controlled seismicity. I analyzed the chronology of the earthquake locations. I used published results on rock possibly filled with cracks in the strict Enola earthquake zone. I calculated the local magnitudes of the sequence and estimated the energy release of the mainshock as well as that of the rest of the sequence using the local magnitude scale (Richter, 1958). The energy released during two months of seismicity is not comparable with the energy release of the mainshock. This may suggest that the mainshock played a significant role in triggering the rest of the 2001 Enola seismicity. Swarms are usually characterized by uniformly low energy events closely clustered in space and time without a single mainshock.

Earthquake locations. The 2001 sequence hypocentral structure does not reveal unambiguously identifiable fault planes. I accurately located the earthquakes using manually picked arrival times of P and S waves and a published velocity model based on a seismic reflection line across the earthquake area. Relative arrival times of P and S waves using a waveform cross-correlation technique and a double-difference algorithm were also analyzed.

Focal mechanism distribution. Focal mechanism solutions for the largest earthquakes in the sequence are comparable with the regional stress field. The principal compression axis of the present day stress field is thought to be oriented ~ ENE (Zoback and Zoback, 1980). I calculated accurate focal mechanism solutions based on P, S and SH wave polarities using a grid-search algorithm.

For these analyses I analyzed data from the CERI network of several analog and six digital portable 6-channel (3 accelerometer, 3 short-period seismometer) seismographs that operated in triggered mode and a 3-component broadband instrument for about 2 months. The data were collected bi-weekly. Based on preliminary earthquake locations the network was relocated to better encompass the seismicity area. The STA/LTA ratio for the instruments (Short/Long Time Average) was adjusted to reflect the appropriate threshold where only earthquakes would be recorded. Details on the portable network deployment can be found in Appendix D.

I selected about 100 of the largest and locatable earthquakes recorded by the triggered network. I believe this set is a representative sample of the 2001 sequence and reveals the main features of the sequence, such as the spatial-temporal seismicity pattern and source properties.

I analyze phase arrival times and P and S waveforms to constrain event locations and source parameters. Determination of basic parameters about the faulting is essential in this intraplate region to understand possible seismic zones and regional stress conditions.

At the end I suggest future work (waveform analysis to determine source and propagation properties, finding more locatable earthquakes to refine the location picture, etc.). Some particular questions may be answered by deeper and more detailed analysis of the high-quality and comprehensive seismic data set.