2. Daily Seismicity of the Enola Swarm

The swarm-like seismic history of the Enola region makes an analysis of the temporal behavior of the 2001 sequence a logical step. The question is: Did the most recent seismic episode keep the temporal swarm-like character of the previous swarm?

The 1982 Enola earthquake swarm took place in the same area and started with a few small (magnitude < 2) earthquakes, for about a week, before the largest earthquake ($M = 4.5$) occurred (Johnson 1982). There were more than 30,000 observed earthquakes (none bigger than the one $M = 4.5$) over the next 2 years.

The broadband site (for the 2001 sequence) was almost continuously operational during a 2-month period and seismic records from that site were used to estimate daily seismic rates. There were several episodes of increased seismicity in the background swarm activity (Figure 4). The classic mainshock-aftershock scheme is missing here. These bursts in seismicity might suggest that there was a relatively large earthquake followed by many small ones, followed by a big one again, and so on. The 100 biggest earthquakes mostly took place during periods of the highest seismicity rate.

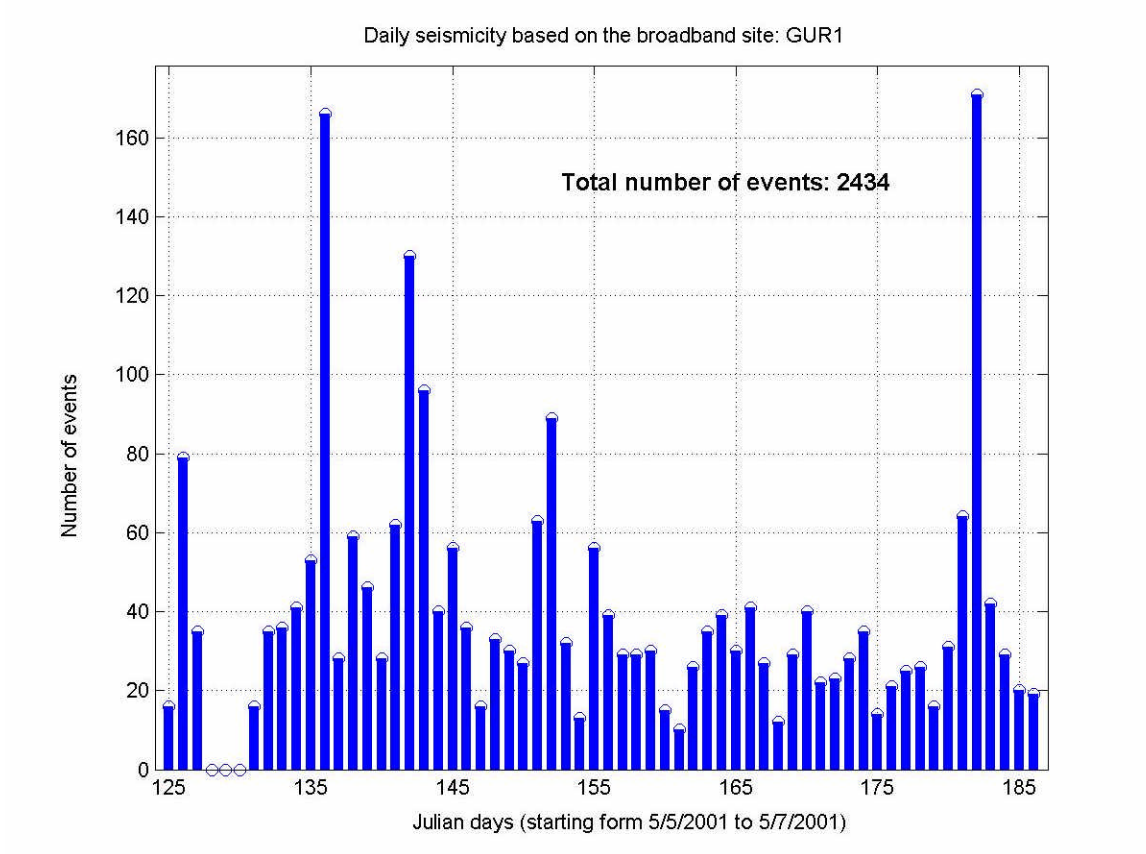

Figure 4. Daily seismicity rates of the Enola 2001 earthquake swarm. The data points missing (days: 128, 129, 130) are due to instrument malfunction. Two biggest peaks (days 136 and 182) closely coincide with the average 41-day period of the 1982 Enola sequence increased seismicity episodes (Figure 5).

The 1982 sequence also exhibited periods of increased seismicity (Figure 5). This period of ~ 40 days seems to be a common attribute for both sequences. The shared periodicity may reveal an essential similarity of the driving forces of the both swarms.

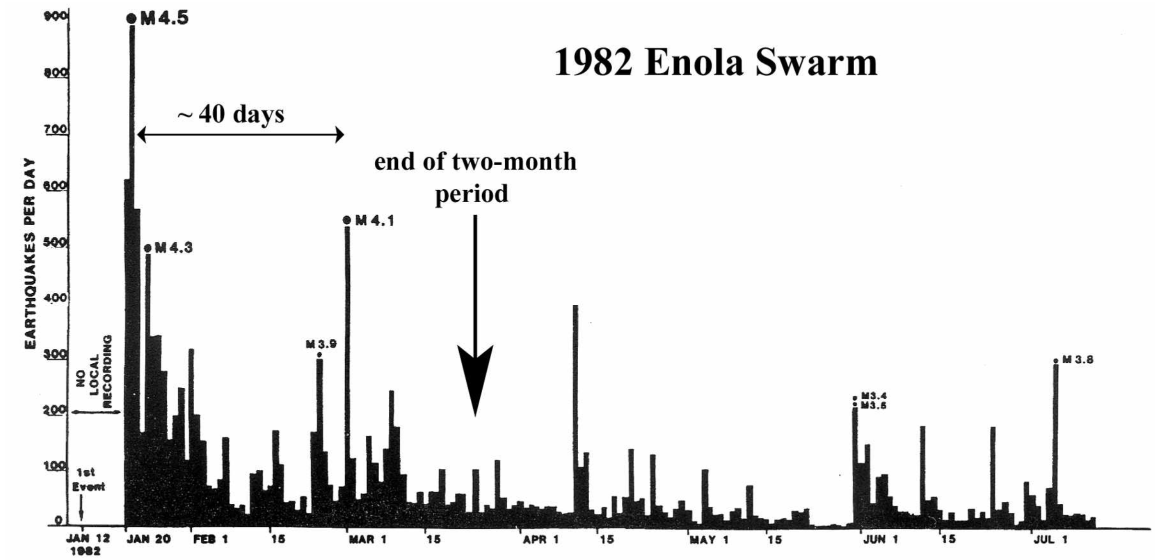

Figure 5. 1982 Enola swarm seismicity rate (modified from Johnson, 1982). The vertical arrow ends the first two months of the record. Horizontal arrow depicts the approximate 40-day period of seismicity rate increase.

Figure 4 is missing events for three days shortly after the deployment of the broadband instrument. Could these days conceal another spike in daily seismicity rates rejecting the hypothesis of the 40-day periodicity? I analyzed seismicity rates based on several accelerographs but even though I did not observe a consistent spike in seismicity rates for the days mentioned it is still unclear whether the rates were close to the first “spike” (Julian day 136).

The overall lack of a well-defined Omori decay (so characteristic for a typical mainshock-numerous aftershock scheme) supports the swarm attribute for both sequences.

Figure 6 shows recorded seismicity for an episode of increased seismicity (Julian day 143). The entire record is ~ 10 min long and reveals at least 8 small and one larger earthquake. Seismic activity on this record illustrates the swarm character of the 2001 sequence.

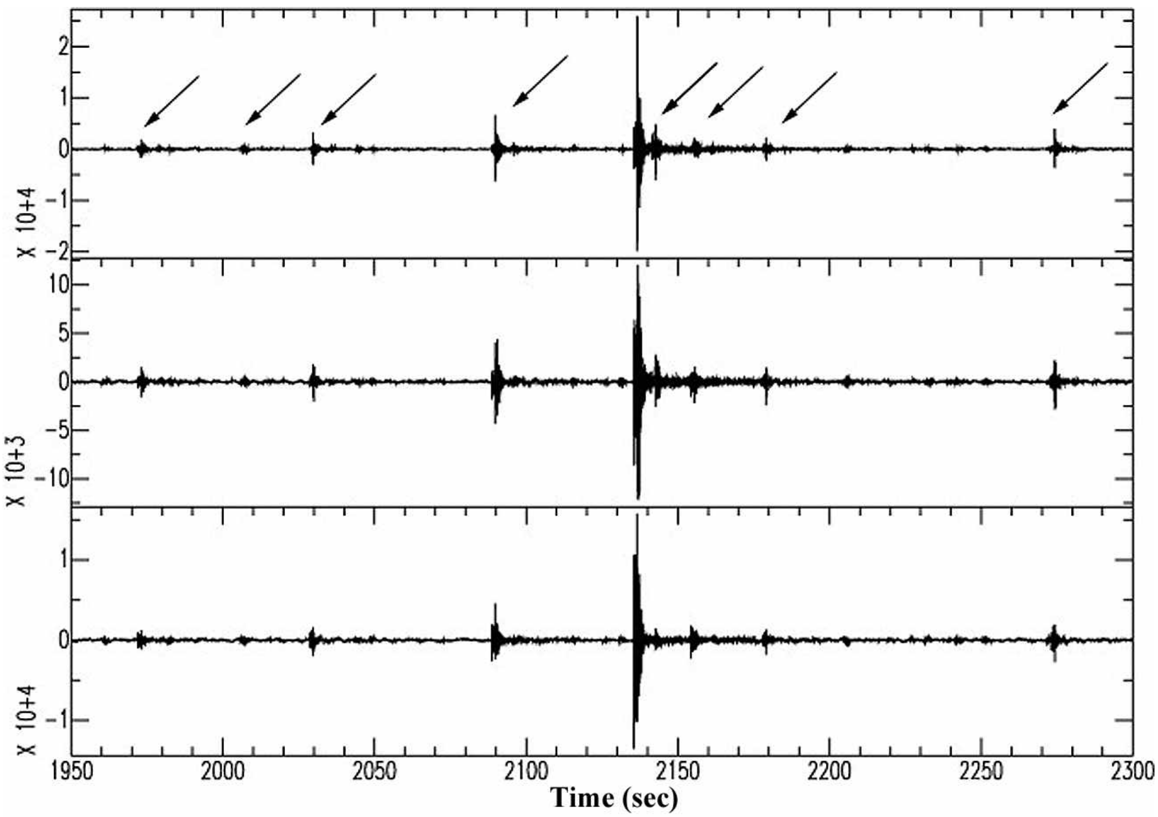

Figure 6. Example of earthquake activity on the three-component (from top: East, North, Vertical) broadband seismograph: GUR site. The sequence was recorded on Julian day 143, on the third biggest peak in daily seismicity (see Figure 4). The components were band pass filtered with corner frequencies 0.1-10 Hz. Multiple arrows point out numerous earthquakes. Horizontal scale in seconds, vertical in counts.

To analyze the daily seismicity behavior of the 2001 sequence I wrote a couple of scripts using MatLab (see Appendix A).

2.1. Earthquake Size Distribution

The size distribution of earthquakes has been studied since the early days of modern seismology. Gutenberg and Richter introduced the magnitude – frequency relationship in the form of a power-law (Gutenberg and Richter, 1944):

$$\log n(M) = a - bM \qquad (1)$$

Where $n(M)$ is the number of earthquakes with magnitude $\geq M$.

The b value usually stays close to unity, regardless of the area of seismicity or its temporal changes. It has been also noticed that slight deviations from the value of one might show a particular characteristic of the investigated seismic region (Sykes, 1970).

Some of these characteristics that correlate with the b-value are (Utsu, 1999): specific tectonic zones, degree of fracturing, material properties, degree of stress concentration (spatial variations), stress level changes, pore-fluid pressure, and fracture growth condition (temporal variations).

B-values of greater than one are observed in swarm sequences along the mid-Atlantic ridge and fracture zones (Sykes, 1970) and indicate a relatively higher percentage of smaller earthquakes. In laboratory studies of microfracturing, stress inhomogeneities related to concentrated sources are known to be correlated with b–values higher than one and to swarm-like sequences (Scholz, 1968).

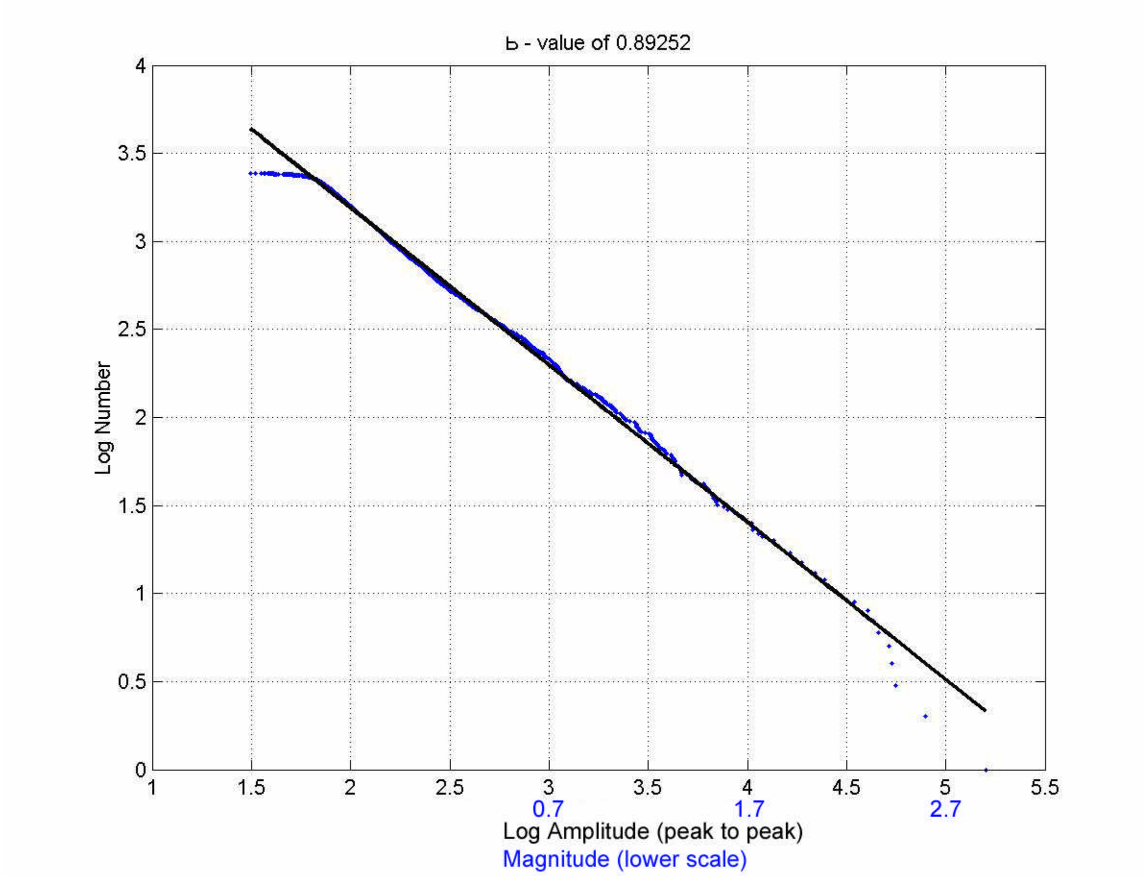

Figure 7. Size distribution of the 2001 sequence. Logarithm of the cumulative number of earthquakes is on the vertical axis. Horizontal axis spans logarithm of earthquake amplitudes and local magnitudes (blue). The amplitudes are given in counts. The black line is the best fit (least squares method) for the relationship. Earthquakes less than ~1.6 (log of amplitude) are excluded from the fit because the noise level is at about 40 counts (log of 40 is about 1.6).

The b –value of ~0.9 characterizes the 2001 Enola sequence (Figure 7). The size distribution plot for the 2001 sequence is strongly controlled by the "middle" of the curve. In the range from above the noise level up to the couple of large magnitude events, there are >96 % of the total number of earthquakes. In this percentile, it is impossible not to notice (qualitatively) how well the least squares solution fits the data.

What makes the slope qualitatively steeper is a huge number of small magnitude events as opposed to a few of larger magnitude. It is not clear what the b-value for the 1982 sequence is. The 1982 sequence was abundant in earthquakes of M<4 and limited at the upper end by the M~4.5 event. I cannot determine if the b-value has changed for the past 20 years in the Enola swarm area.

The 6 largest earthquakes deviate from the b-value of ~0.9. As stated before, this part of the distribution influences the slope very little. Nevertheless it seems that the 2001 sequence undershoots at larger “magnitudes”. This might be a direct indicator of source volume properties: Above some “magnitude” the swarm source is not capable of producing larger “magnitude” earthquakes that would follow a power law with the b value of ~0.9 (Singh et al., 1983).

This roll-off effect has been noticed and studied in many other instances. Experimental data show different degrees of discrepancy with a power-law at the lower and higher magnitude ranges (Cosentino et al., 1977; Singh et al., 1983; Wesnousky et al., 1983). Wesnousky et al., (1983) proposed that the power-law distribution does not have to hold for parts of a fault system or for an individual fault based on a study of intraplate seismicity in southwest Japan. The magnitude distribution described by a power-law holds conspicuously better for seismicity on a regional scale. He also stated that the magnitude distribution depends on a combination of slip rates and length of fault segments.

The numerous small magnitude (<4) earthquakes of the 1982-84 sequence (>30,000) and about 2,500 earthquakes for the 2001 sequence (only 2 months of observation) in the area of 5x5 km and depth range of 3-6 km would strongly suggest that the stress levels are very high and the sources concentrated. Yet the calculated b-value is less than that proposed for swarms.

It is not clear whether the b-value of ~0.9 would suggest dropping the "swarm" attribute for 2001 Enola earthquakes but it certainly raises a need to redefine the terminology for Enola-like earthquake sequences.

2.2 An Energy Estimate

In a mainshock-aftershock earthquake sequence the mainshock undoubtedly perturbs the stress field helping the aftershocks to take place. Swarm-like seismicity, I believe, does not rely strongly on one event perturbing enough of the stress field to help the rest of the swarm to occur. If significantly more energy were released by the mainshock than by events of the rest of the sequence, I would interpret this as evidence that the crustal stress changes due to mainshock might be a large influence on occurrence rates for the rest of the sequence.

The energy released by the 2001 sequence, based on the portable network data, is not on the same order of magnitude as the energy released by the mainshock. The energy *E* (in ergs) released by an earthquake, used here, can be estimated from the local magnitude using the formula (Richter, 1958):

$$\log E = 9.9 + 1.9 M_L - 0.024 M_L^2 \qquad (2)$$

Where M_L represents the local magnitude calculated using Richter, (1958):

$$M_L = \log A - \log A_0 \qquad (3)$$

Where *A* is the S wave amplitude of an earthquake in millimeters as it would be recorded by a Wood-Anderson seismograph and A_0 is a reference amplitude used to scale the measured amplitude *A* to 100 km from the earthquake epicenter.

I wrote a SAC script to deconvolve/convolve the data recorded by the broadband instrument (GUR site) to obtain displacement, as a Wood-Anderson seismograph would record it. The S wave amplitudes on the N-S component were used to calculate the amplitudes for the earthquakes.

The largest earthquake observed (beside the mainshock on May 4th) during the two month deployment occurred on May 22, 2001 with magnitude M_L = 2.9 (day 142). This corresponds to about 1.7 x 10^{15} ergs, using (2). The magnitude of the mainshock (recorded by the regional network) was 4.4, corresponding to an energy release of 9.2 x 10^{17} ergs. The cumulative energy of the sequence (excluding the mainshock) equals some 4.7 x 10^{15} ergs, which is ~200 times less than the energy released by the mainshock. Despite the numerous earthquakes in the Enola zone the cumulative energy of the sequence is not comparable with the energy released by the mainshock.

It seems that this discrepancy in energies and in the size distribution sense (the mainshock does not scale with the rest of the 2001 Enola seismicity) may suggest that the mainshock played a significant role in possible triggering of the rest of the 2001 Enola seismicity.