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Spatio-temporal evolution of frequency-magnitude distribution and seismogenic index during initiation of induced seismicity at Guy-Greenbrier, Arkansas

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ABSTRACT

In this study, we carry out detailed analyses of the spatio-temporal variations of seismic *b*-value during the onset of the potentially induced-earthquake sequence between Guy and Greenbrier, Arkansas, to investigate correlations with pore-pressure change. The range of *b*-values suggests that the seismicity in the Guy-Greenbrier area is mostly a result of the activation of pre-existing faults. The spatial distribution of *b*-value correlates with modeled pore-pressure changes. In the northern segment of the fault, *b*-value increases with depth due to large pore-pressure changes and opening of new fractures in the deeper part and stress relaxation in the shallower parts. Whereas, in the southern segment, the shallower part shows higher *b*-values due to higher pore-pressure fluctuations but the deeper part in the crystalline basement has low *b*-value due to higher confining stress. The correlation between the temporal variation of *b*-value and hypocentral depth explains a previously observed temporal drop of *b*-value. This suggests that temporal variations should be interpreted along with the spatial variations. Estimation of the seismogenic indices for the Guy-Greenbrier fault is provided. Our analysis suggests that monitoring changes in *b*-value and seismogenic indices during an injection period might be used to avoid the occurrence of significant events if injection volume is reduced at critical times.

1. Introduction

The relationship between the frequency of occurrence and magnitude of earthquakes (frequency-magnitude distribution or FMD) for a given population of earthquakes is described by: $\log_{10}N(M) = a - bM$ (Gutenberg and Richter, 1944), in which N is the cumulative number of earthquakes having magnitudes equal to and larger than M, and a and b are constants. The relative size distribution of earthquakes denoted by the *b*-value is a widely reported seismicity parameter that is essential for seismic hazard analysis.

The *b*-value measures differences in the relative proportion of small and large earthquakes. High *b*-values in a volume indicate smaller rupture sizes compared to a volume with low *b*-values. Its inverse relation to the effective stress has been investigated and reported in many studies (e.g., Scholz, 1968; Wyss, 1973; Urbancic et al., 1992; Wiemer et al., 1998; Zang et al., 1998; McGarr, 1999; Wiemer and Katsumata, 1999; Lei, 2003; Schorlemmer et al., 2004; Schorlemmer and Wiemer, 2005; Khan and Chakraborty, 2007; El-Isa and Eaton, 2014). On the other hand, it has a direct relation to thermal gradient (e.g. Warren and Latham, 1970), pore pressure (e.g. Lockner and Byrlee, 1991; Power et al., 1995; Wyss et al., 1997; Wiemer and McNutt, 1997; Wiemer et al., 1998; Jolly and McNutt, 1999; Murru et al., 1999; Sanchez et al., 2004; Bridges and Gao, 2006; Farrell et al., 2009; van Stiphout et al., 2009; Bachmann et al., 2012), and material heterogeneity (e.g. Mogi, 1962).

Observations in tectonic areas show that when large volumes are sampled, the *b*-value is close to the constant value of 1.0 (Frohlich and Davis, 1993; Kagan, 1999). However, at both local and regional scales *b*-values can vary between 0.8–1.2 (e.g. Schorlemmer et al., 2005; Kamer and Hiemer, 2015) depending on the rupture mechanism and get as high as 3.0 (e.g. Wiemer and Wyss, 1997; McNutt, 2005) for earthquake swarms. Hence, swarm-like behavior of induced seismicity (Skoumal et al., 2015), suggests that the *b*-value can be used as a potential discriminatory parameter for induced earthquakes. This hypothesis has been supported by observation of higher *b*-values compared to tectonic

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events in several induced seismicity cases (e.g. Fletcher and Sykes, 1977; Rutledge et al., 2004; Maxwell et al., 2009; Vermylen and Zoback, 2011; Zhou et al., 2013; Guest et al., 2014). However, in several other cases, estimated *b*-values for the induced seismicity are quite close to those for the tectonic seismicity (e.g. Holland, 2013; Friberg et al., 2014; Skoumal et al., 2015). This motivates further investigation of FMD characteristics of induced earthquakes.

Human activities, especially wastewater injection into subsurface rocks, are thought to be the main cause of elevated seismic activity in the central United States since ~2009 raising serious concerns regarding elevated seismic hazards in this region (Ellsworth, 2013; Frohlich and Brunt, 2013; Kim, 2013; Keranen et al., 2013, 2014; Barnhart et al., 2014; Rubinstein and Mahani, 2015). A well-documented case of seismic activity potentially induced by wastewater injection was an intense sequence of earthquake swarms that occurred near the towns of Guy and Greenbrier, Arkansas (Fig. 1), between August 2010 and June 2011 (Horton, 2012a,b; Llenos and Michael, 2013; Huang and Beroza, 2015; Ogwari et al., 2016; Huang et al., 2016; Ogwari and Horton, 2016; Dempsey et al., 2016). The earthquakes started within a few weeks after beginning of injection at nearby wells (less than 6 km away), and after a period of intense activity, gradually stopped within a three-month period following injection termination.

Horton (2012a,b) reported approximately 1000 events with $M_D > 2.0$ recorded by local and regional stations in the area. The relocated hypocenters illuminated the previously unknown ~13 km long Guy-Greenbrier fault. Llenos and Michael (2013) examined the seismicity rate changes in the area and based on stochastic epidemic-type aftershock sequence (ETAS) modeling and statistical tests showed that the earthquake rate change is man-made. Huang and Beroza (2015) detected more than 460,000 events with $Mc \sim -1.0$ between July 2010 and October 2011 using single-station template matching, and they analyzed the temporal variation of *b*-value during the sequence. In their study, it was observed that the earthquakes deviate from the linear Gutenberg–Richter distribution and are characterized by low *b*-values (0.85) and a convex-type distribution during the injection period. Ogwari et al. (2016) studied the spatial and temporal evolution of the seismicity during the first three and half months following the beginning of the injection (July 7, 2010) at nearby wells. They detected and located more than 17,000 events with $M_L > -0.67$ using ten local stations deployed during this time period. They obtained a *b*-value of 1.1 for the entire catalog with a range from b = 1.4 in the northern segment connecting the fault to well #1 and b = 0.78 for earthquakes deeper than 5 km in the southern segment. Huang et al. (2016) estimated the stress drops of 25 events to be between 1.02 MPa to 42.50 MPa with a median

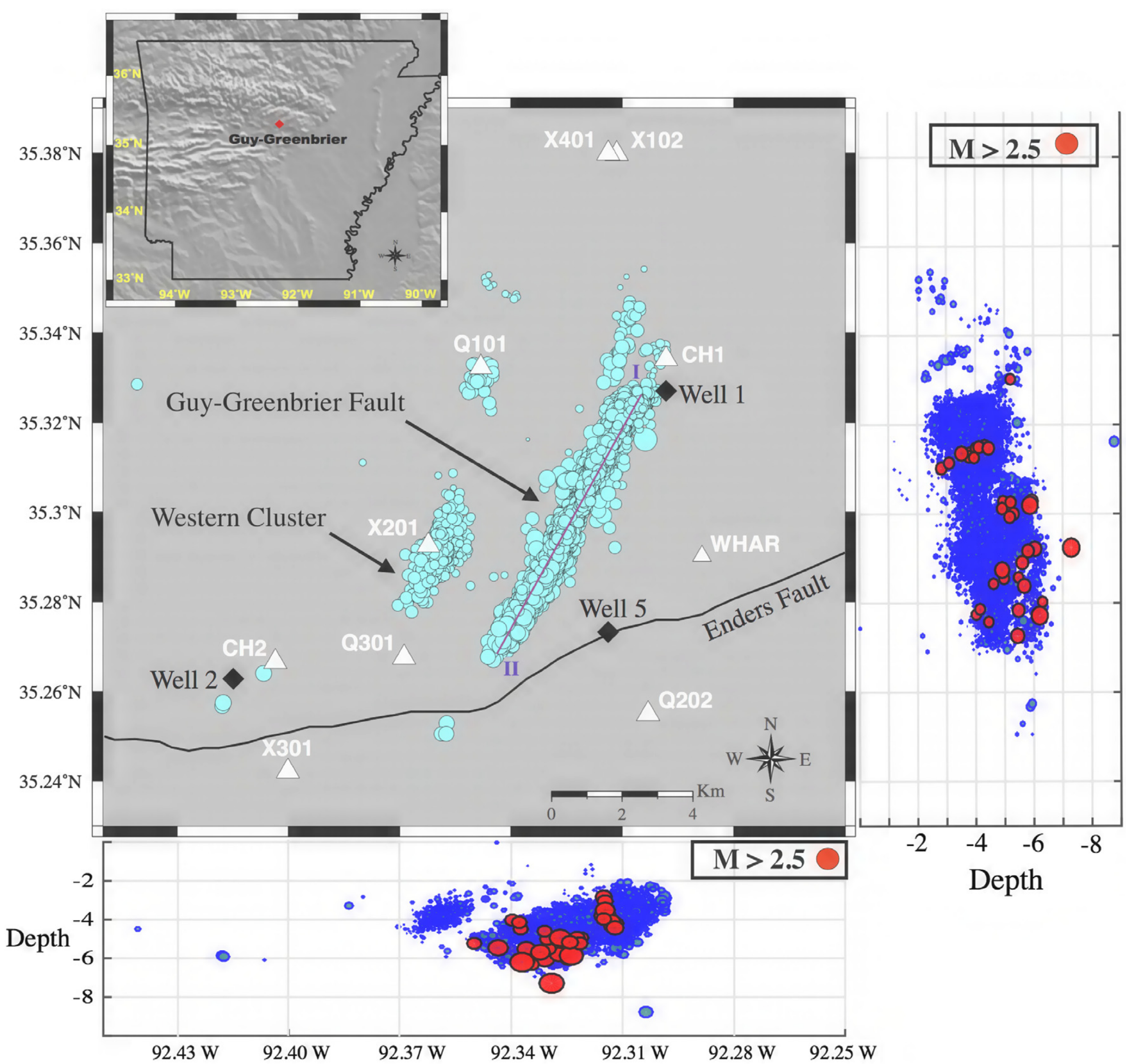

Fig. 1. Epicentral and cross-sectional distributions of seismicity in the study area (between 7 July and 20 October 2010). Marker sizes are scaled to event sizes. Seismic stations are shown by white triangles and black diamonds are disposal wells. The Enders fault is shown by a solid black line.