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Source characterization of moderate induced earthquakes in Oklahoma, USA: A case study of 2013-2016 Cushing earthquake sequence

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The significant increase of seismicity rate in the central and eastern United States since 2009 has drawn wide attention for the potential seismic hazard. Unfortunately, most of moderate earthquakes in this region lack near-fault strong motion records, limiting in-depth studies. The 2016/11/07 M 5.0 Cushing, Oklahoma earthquake and its fore/aftershock sequence, which was monitored by four strong motion stations within 10 km of the mainshock epicenter, is the only exception. According to Oklahoma Geological Survey, no M>1.5 earthquake occurred before 2013 within 5 km of the mainshock epicenter, but 110 foreshocks, including two M>4 events, had occurred before the mainshock initiation. The close-fault records also revealed that M>4 foreshocks and mainshock excited unusually high level of strong ground motion. For example, 2015/10/10 Mw 4.3 Cushing earthquake resulted in peak ground acceleration (PGA) and peak ground velocity (PGV) up to 0.6 g and 8.3 cm/s, respectively. Simply correcting the geometric spreading (1/R, R is hypocenter distance) leads to mean PGA and PGV of 0.2 g and 3.6 cm/s at R=10 km, which are 4-8 times of the average values inferred from NGA-West dataset (Archuleta and Ji, 2016). Here we constrain the slip history of Cushing mainshock and its M>4 foreshocks using strong motion waveforms and compare them with the results of other moderate Oklahoma earthquakes. Our preliminary analysis of the mainshock leads to a preferred model of heterogeneous dextral slip on a vertical fault plane orienting N60oE, with three major rupture stages. The rupture initiated at a depth of 4.1 km, within the "cloud" of foreshocks. The first subevent has a rupture duration of 0.7 s and accounts for 20% of total seismic moment (Mw 4.4). After a delay of ~0.5 s, a slip patch just outside the foreshock "cloud" and 2-3 km away from the hypocenter broke. From 1.2 s to 1.7 s, 45% of total seismic moment (Mw 4.7) was quickly released. The rest of the seismic moment (35%, Mw 4.6) occurred in the shallower depths (<2 km) within the next 1.5 s. The inverted total seismic moment is 2.6x10ˆ16 Nm (Mw 4.9) and the peak slip is about 0.4 m. The total rupture duration of the inverted model is 3.2 s, about twice the typical value of Mw 4.9 earthquakes. The peak static stress drop estimated using the slip model is 10 MPa, but the energy based average stress drop is only 2 MPa, slightly lower than typical tectonic earthquakes. We note that these rupture characteristics are similar to the results of 2011 Mw 5.6 Prague, Oklahoma earthquake (Sun and Hartzell, 2014). Both of them support the hypothesis that unlike the tectonic earthquakes that occur on mature faults and often have single predominant asperity, the induced moderate earthquakes in Oklahoma can be viewed as cascade ruptures on pre-mature fault planes with multiple isolated asperities close to failure. Such a hypothesis supports the argument that the damage from injection-induced earthquakes will be especially concentrated in the immediate epicentral region (Hough, 2014).