Seismic monitoring of CO_2-EOR operations in the Texas Panhandle and southern Kansas using surface seismometers

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Summary

Injection of carbon dioxide (CO_2) into depleted oil reservoir is an advantageous tertiary recovery method as it allows for the long-term storage of CO_2 in the empty pore spaces resulting from the removal of in situ pore fluid. Several instances of induced earthquakes have been noticed around enhanced oil recovery (EOR) sites. To mitigate the risk of potential seismic hazards, continuous seismic monitoring of active CO_2-EOR site is of significant importance. To that end, we analyzed surface seismic data recorded at two EOR sites located in the Texas Panhandle and southern Kansas, respectively. We identified 160 discrete seismic events in Farnsworth, Texas and 112 events in Wellington, Kansas that strongly differs from traditional microseismic events. These events are characterized by low frequency content (1-5 Hz) and longer time duration that lasts for 30-60 seconds for data recorded in Farnsworth and several minutes long for Wellington data. We found missing records for these earthquakes from regional earthquake catalogs and data from independent seismic network suggesting a localized source of deformation as the cause of low frequency events observed in this study. We compared the location of low frequency events with the field scale reservoir model for CO_2 plume and pore pressure variation in Farnsworth and found spatial overlap with four events. As majority of the low frequency events are located outside the region encompassing pore pressure changes due to CO2 injection in Farnsworth, we think that they are perhaps related to small scale tectonic deformation or complex subsurface fracturing triggered by other nearby injection activities that are currently functional. We aim to locate low frequency events identified in Wellington, Kansas for further comparison with the reservoir model to check if there are any correlations with CO_2-EOR activity.

Introduction

Optimized recovery of oil from the reservoir rock is major focus of the exploration companies that involves multiple phases namely primary, secondary and tertiary recovery or EOR. Depending upon the properties of oil being explored (heavy oils and tar sands versus light oil), EOR may involve steam injection, chemical flooding and/or injection of miscible carbon dioxide (CO_2). Injecting CO_2 in the reservoir has obvious advantage of reducing the footprint of atmospheric carbon dioxide by storing its significant volumes in the empty pores of reservoir. The CO_2-EOR project in Farnsworth, Texas is a part of nationwide initiative of the U.S. Department of Energy to test the feasibility of long-term storage of anthropogenic CO_2 in the oil reservoir, monitoring the growth of CO_2 plume and evaluating the potential migration of CO_2 out of the reservoir (Balch et al., 2017). The CO_2-EOR project in Wellington, Kansas is comparatively a short-term pilot injection project sponsored by the U.S. Department of Energy that aims at evaluating the possibility of EOR through CO_2 injection in Arbuckle carbonate saline aquifer and potential of transitioning to geologic CO_2 storage through EOR (Holubnyak et al., 2017).

The risk of induced earthquakes with continued injection of large volumes of fluid in the subsurface is a likely phenomenon and myriads of small to moderate size earthquakes have been reported from areas that are proximal to fluid injection activity (Rubinstein & Mahani, 2015). From the perspective of CO_2-EOR operations, with continuous injection of supercritical CO_2 (fluid state of CO_2) in the reservoir, fluid pressure in the pore spaces of the reservoir could likely increase (Gan & Frohlich, 2013, Kumar et al., 2017b). Depending on the scale of subsurface deformation due to pore pressure increase, it could potentially create a chain of earthquakes or it may help in connecting multiple small fractures to create a continuous fracture pathway that would result into a potential leakage of stored CO_2 and a complete failure of the carbon storage program (Kumar et al., 2018a). Therefore, continuous monitoring of CO_2 injection activity at an EOR site using local seismic network is significantly important.

In this study, we present our analysis of surface seismic data recorded at CO_2-EOR sites in Farnsworth, Texas and Wellington, Kansas, respectively (Figure 1). Our preliminary analysis of seismic data recorded in Farnsworth suggests an absence of earthquakes within 90 miles of the injection well (Kumar et al., 2017b). However, during June 2017 to May 2018, we recorded multiple low frequency events of long time duration in Farnsworth that persist for 30-60 seconds (Kumar et al., 2018a).

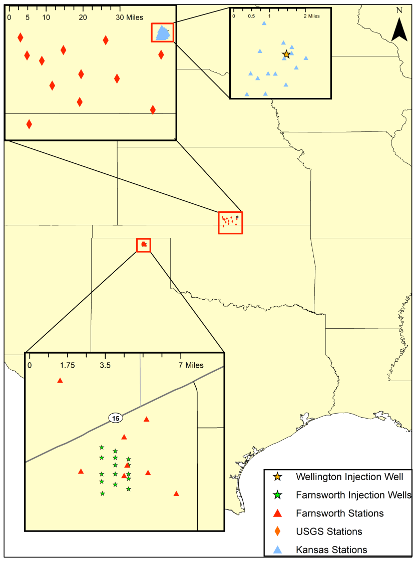

Figure1. Map showing the CO_2-EOR sites and surface seismic networks in Farnsworth, Texas and Wellington, Kansas

We analyzed surface seismic data recorded by local seismic network in Wellington, Kansas and observed numerous low frequency events having waveform characteristics similar to events recorded in Farnsworth, Texas. Although spectral analysis of long-period long-duration (LPLD) events recorded both in Farnsworth and Wellington highlights dominant concentration of energy between 1-5 hertz, event duration time is significantly different at these two sites, with average time span of 4-5 minutes for events recorded in Wellington, Kansas. The location of small number of low frequency events recorded in Farnsworth are observed to be spatially overlapping with reservoir models of CO_2 plume. However, as majority of the low frequency events in Farnsworth are located outside the region encompassing pore pressure changes due to CO_2 injection, we believe that these seismic events are perhaps surface expression of local small-scale tectonic deformation or complex subsurface deformation triggered by other nearby injection activities surrounding the study area. To evaluate the potential impact of small-scale CO_2 injection in Wellington, Kansas, we aim to locate low frequency events recorded during active injection period and check to see if they have any spatial correlation with the modelled extent of CO_2 plume.

Field operations

The CO_2-EOR pilot project in Wellington, Kansas was a short-term tertiary recovery project carried out in Wellington Field in south-central Kansas. The pilot project in Wellington started on January 9, 2016 that lasted until June 21, 2016. As per the report of Kansas Geological Survey, a total of 19,803 metric tons of CO_2 was injected for approximately 175 days in Wellington in the Arbuckle saline aquifer at an average of 120 tonnes per day. The field site for regional carbon sequestration project in Farnsworth is located in the Ochiltree County of Texas Panhandle in the Anadarko Basin. The anthropogenic CO_2 obtained from fertilizer plant in Texas and ethanol plant in Kansas is currently being injected in the Morrow Sandstone in Farnsworth, Texas at 7800-ft-depth (Kumar et al., 2018a).

Data and Method

In this study, we used data collected from the temporary seismic networks deployed at two CO_2-EOR sites in Farnsworth, Texas and Wellington, Kansas respectively. The seismic network in Farnsworth was comprised of eight 3-C broadband seismometers around the CO_2 injection well 13-10A (Figure 1), recording at 100 samples per second. For Farnsworth, we analyzed seismic data recorded through June 2017 to May 2018. The surface seismic data in Wellington, Kansas was acquired using 15 Sercel L-22 short period seismometers that recorded data at 200 samples per second. The seismometers are optimally placed around the CO_2 injection well in Wellington field to minimize azimuthal gap. The Wellington array was functional throughout the active CO_2 injection period from January to June 2016, as analyzed in the current study.

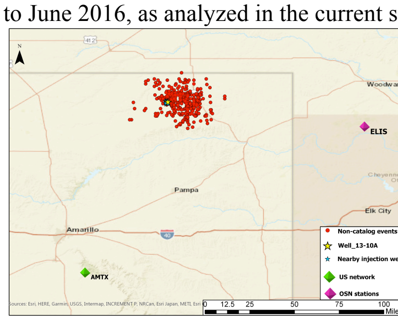

Figure2. Low frequency events detected around CO_2-EOR site in Farnsworth, Texas that are missing from the regional earthquake catalog. Distant stations from US (green pyramid) and Oklahoma (pink pyramid) seismic networks used to cross validate low frequency events

We focused our analysis on low frequency spectrum of the seismic data to identify long period long duration (LPLD) events potentially linked with non-brittle deformation in the subsurface (Kumar et al., 2017a, 2017c; Ghahfarokhi et al., 2019). After manual inspection of seismic waveform in multiple frequency ranges including 0.8-3 Hz, 1-5 Hz, and 1-30 Hz, we observed myriads of discrete seismic events within 1-5 Hz frequency range for datasets recorded in Farnsworth and Wellington, respectively (Kumar et al., 2017b). These low frequency events are characteristically similar to long period long duration events and seismic tremors previously observed at hydraulic fracturing sites and in the subduction zone environments (Shelly et al., 2007; Das & Zoback, 2011; Kumar et al., 2016a, 2016b, 2018b, 2018c). Although waveform characteristics of low frequency events observed at both field sites are broadly similar (emergent with unclear arrival time of seismic phases), their average time duration differs significantly. The low frequency events recorded in Farnsworth, Texas has average time duration of 30-60 seconds that extends to 2-3 minutes for events recorded in Wellington, Kansas.

We utilized advanced approach of waveform envelope cross correlation (WECC) to automatically detect low frequency events and finding their location using travel time lag across the seismic network (Wech & Creager 2008, Chao et al., 2017). We processed surface seismic data from Farnsworth using WECC technique and auto-detected more than 700 events during June 2017 to May 2018. To rule out the possibility of misidentifying any regional earthquake of tectonic origin as local event, we compared the observed arrival time of auto-detected events with the known regional events listed in the USGS earthquake catalog. We removed all of the commonly recorded events from our list and used remaining 563 events for further analysis of Farnsworth data. For Wellington, Kansas, we detected 433 low frequency events through manual inspection of the filtered data. Of these 433 events, 321 events are found to be temporally overlapping with regional events reported in the earthquake catalog and were subsequently removed from further analysis. We aim to use WECC technique in coming months to locate remaining 112 events recorded in Wellington, Kansas.

Furthermore, we examined seismic data recorded at nearest stations (Figure 2) from two independent seismic networks (United States National Seismic Network (USNSN) and Oklahoma Seismic Network (OSN)) around the time windows spanning observed arrival time of 563 non-catalog events recorded in Farnsworth, Texas. We found common temporal records of roughly 72% of the non-catalog events at the nearby stations and further removed them from our analysis. This common recording of non-catalog events by independent seismic network at distant location (>100 miles from CO_2 injection site in Farnsworth) suggests that they are not of local origin rather linked to regional deformation activities and likely smaller than the recording threshold of regional earthquake catalog. We performed similar analysis for low frequency events recorded in Wellington, Kansas and calculate the spectrogram and power spectral density of uniquely recorded events at both sites. Additionally, we had the opportunity to compare the location of low frequency events and reservoir model of CO_2 plume and pore pressure variation for CO_2-EOR project in Farnsworth, Texas. This comparison allowed us to explore the likelihood of geomechanical correlation between ongoing CO_2 injection and triggering of low frequency earthquakes in Farnsworth.

Results and Discussions

Oil reservoirs worldwide are known to have limited productivity through conventional recovery methods. More than 60% of the original-oil-in-place (OOIP) remain unrecovered in reservoirs either due to strong capillary forces or high viscosity. Enhanced oil recovery (EOR) methods can help recover significant portions of oil-in-place (OIP) that are left unrecovered after primary and secondary recovery, ranging from 45% OIP to 100% OIP. Injection of significant volumes of compressed CO_2 into an oil reservoir is a popular EOR practice that results into improved flow behavior of trapped oil due to mixing of CO_2 and resulting expansion of oil. During EOR, more than one-third of injected CO_2 stays in the reservoir that leads to geologic storage of greenhouse gas and help reduce the environmental impact of anthropogenic CO_2.

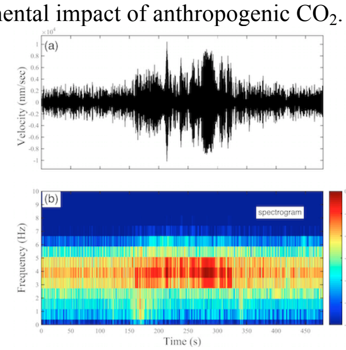

Figure3. Stacked waveform (panel a) and spectrogram (panel b) of a LPLD event recorded at CO_2-EOR site in Wellington, Kansas

As CO_2 is injected into an oil reservoir, resulting change in pore pressure over extended period of EOR operation may stem into reducing the effective normal stress and unlocking the preexisting faults and fractures. Depending on the scale and slip rate of fault rupture, triggering of small to moderate size earthquakes in the vicinity of CO_2-EOR operation is not unlikely (Nicholson and Wesson, 1992). This is evident from previous instances of induced seismicity reported around multiple EOR sites in Colorado and Texas (Raleigh et al., 1976; Gan & Frohlich, 2013). In the current study, we identified 160 low frequency seismic events recorded during June 2017 to May 2018 at CO_2-EOR site in Farnsworth, Texas. These events are uniquely recorded by local surface seismic network (Figure 2). At CO_2-EOR site in Wellington, Kansas, we identified 112 low frequency seismic events of similar waveform characteristics recorded during active injection period starting from January 9 to June 21, 2016.

We examined the spectrogram and power spectral density of these low frequency events and observed significant concentration of seismic energy in the 1-5 Hz frequency range (Figure 3) that last for 30-60 seconds long interval for events recorded in Farnsworth, Texas and 2-3 minutes long for low frequency events recorded in Wellington, Kansas. This difference in event duration time of low frequency earthquakes recorded at two individual CO_2-EOR sites could be related to geological and operational differences and their combined effects on subsurface deformation characteristics at these two field sites.

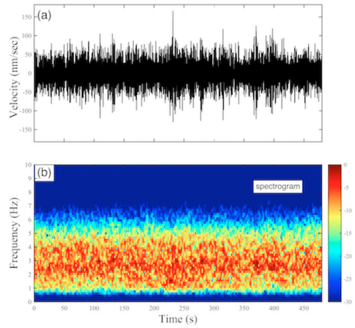

Figure4. Seismic waveform and spectrogram of the data recorded at distant station of US array for the time interval containing low frequency event (as shown in Figure 3) recorded at Wellington seismic network

Earlier, Hu et al. (2017) reported low frequency events from Eagle Ford Shale in NE Mexico having multiple subevents. It is likely that low frequency events recorded in Wellington, Kansas is also composed of multiple subevents of relatively shorter duration, each of which is recorded within few minutes with overlapping onset time that jointly appears to be one extra long low frequency event. We aim to locate these events, following the analysis of Hu et al. (2017), which should allow us to check if the low frequency events of extra long duration recorded in Wellington, Kansas are composed of coherent signals from multiple subevents.

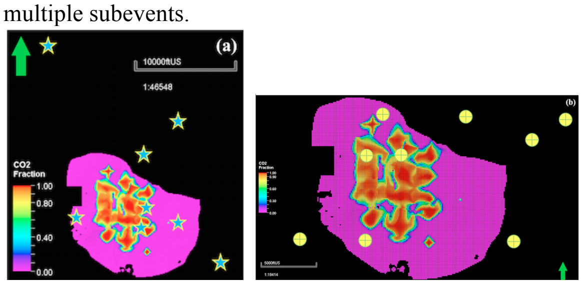

Figure5. Map showing reservoir model for CO_2 plume (warm color) and pore pressure variation (pink shaded region) in Farnsworth, Texas with (a) surface seismic stations on top (magenta stars); (b) spatially overlapping and nearby low-frequency events are shown as crossed circle

Our main aim of seismic monitoring at CO_2-EOR site is to detect any small to large-scale local subsurface deformation and resulting seismicity that could likely be triggered by continued injection of CO_2. To focus on local seismicity, we crosschecked the regional earthquake catalog and seismic data recorded at moderately distant stations from our EOR sites in the Texas Panhandle and southern Kansas. We examined seismic waveforms recorded at distant stations from USNSN and OSN in 4 to 8 minute long time windows spanning the observed time of individual low frequency events recorded by our local seismic network. We did not find any corresponding seismic record at distant stations for our final list of 160 and 112 low frequency events recorded in Farnsworth, Texas and Wellington, Kansas, respectively (Figure 4). This absence of seismic record, both in time and frequency domain, suggests that these low frequency events are not the seismic footprint of regional deformation activities, rather linked to subsurface deformation of more local origin.

We attempt to spatially compare the location of uniquely recorded 160 low frequency events at CO_2-EOR site in Farnsworth, Texas with the reservoir model of CO_2 plume and area encompassing pore pressure changes. The epicenters of low frequency events are randomly distributed within 17 miles of the active injection well. We found spatial overlap between the epicenters of 4 low frequency events and footprints of the CO_2 plume and pore pressure perturbation (Figure 5). As majority of the low frequency events are spatially uncorrelated with the reservoir model, background tectonic deformation or nearby injection activities, currently operational around our study site in Farnsworth, could be responsible for their occurrence. We aim to compare the location of low frequency events recorded in Wellington, Kansas and the local reservoir model in coming months.

Disclaimer

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