Seismic Monitoring of Hydraulic Fracturing Activity in the Wolfcamp Shale of Midland Basin, Texas

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Abstract

Hydraulic fracturing involves the injection of large volumes of fluid, typically water, into the reservoir rock to increase fluid pressure in the pore spaces and alter the stress condition of the rock significantly. The sudden change in the stress condition creates new fractures in the rock and/or stimulates slip along the pre-existing fractures. Creating new fractures and/or inducing slip along pre-existing fractures, markedly increases in the interconnectivity of pore spaces and enhances the flow of oil and gas within the stimulated volume. The spatial distribution of microseismic earthquakes generated during hydraulic fracturing is traditionally used as a proxy for the stimulated reservoir volume (SRV). An accurate SRV estimate is a useful tool that can help industry optimize their stimulation treatment plans thereby increasing the efficiency of hydrocarbon production. However, a simple energy balance calculation suggests that the combined energy released from all microseismic earthquakes during hydraulic fracturing is a small portion of the total input energy supplied to the reservoir rock in the form of injected fluid. The difference in the total input and output energy suggests that alternate mechanism(s) of reservoir rock deformation need to be considered to get a more accurate estimate of the total reservoir volume stimulated by hydraulic fracturing. Recent studies of hydraulic fracturing in the Barnett Shale, Marcellus Shale, Eagle Ford Shale and Montney Shale found evidence of low-frequency events, with drastically different seismic signature (frequency, amplitude, time duration) than traditional microseismic earthquakes. These low frequency (1-80 Hz) earthquakes are proposed to be associated with either the jerky opening or slow rate of slip along pre-existing fractures that are unfavorably oriented in the ambient stress field. The low-frequency events can release as much as 1000 times the energy of an average microseismic earthquake.

We identified multiple long period long duration (LPLD) earthquakes in the surface seismic data recorded during the hydraulic fracturing of two Middle Wolfcamp Shale wells in Reagan County, TX. LPLD events identified in this study show a dominant P-wave signal that persists for 5-10 seconds, significantly longer than traditional microseismic events. We also noticed finite decay in seismic amplitude across the surface-monitoring array suggesting a non-regional or local source of deformation for the LPLD event origin. We aim to compare our surface seismic observations of LPLD with seismic data from two 24-tool borehole arrays that were deployed in the vertical section of two nearby treatment wells. The comparison between surface- and borehole-acquired data will help determine the relative effectiveness of surface seismic monitoring. Borehole monitoring is expected to detect more LPLD events due to the proximity of sensors to suspected LPLD event sources and because downhole seismic data is less contaminated with surface noise.

Introduction

The injection of more than a million gallons of fluid during hydraulic fracturing is now a routine operation to enhance permeability and production from unconventional reservoirs such as shale gas, shale oil, and tight gas and oil. When the injection pressure exceeds the combination of tensile strength of the reservoir rock and the ambient compressional stress, the reservoir rock undergoes a complex fracturing process. The geomechanical changes brought about by high-pressure, high-volume fluid injection are believed to be responsible for the creation of a complex network of newly formed tensile fractures and/or the induction of pure shear slip along preexisting fractures in the unconventional reservoir. Together, these deformation processes increase the permeability of the reservoir rock and improve the efficiency of hydrocarbon recovery. Numerous, small-magnitude earthquakes (microseismic events) are generated by this complex deformation process (Warpinski et al., 2004). The spatial distribution of microearthquakes is sometimes used as a proxy to estimate the stimulated reservoir volume that is anticipated to be contributing in the overall oil and gas productivity. Due to the large uncertainty in the location of microseismic events and their incomplete detection by the monitoring array, the use of microseismicity as a mapping tool for stimulated reservoir volume is a highly questionable concept (Wilson et al., 2016 and Sicking et al., 2013, respectively).

Knowledge of a shale reservoir's geomechanical response to hydraulic fracturing is important for predicting reservoir drainage volume and hydrocarbon recovery. This understanding can also be used to optimize hydraulic fracturing by informing the selection of stage length, the number of perforation clusters, and the composition, rate, and volume of injected fluids. Likewise, knowing the response of depleted wells to hydraulic fracturing is important for predicting the incremental increase in oil and gas production that might be expected from refracturing. However, a clear understanding of the geomechanical response of unconventional reservoir is lacking even after the multi-decade-long operational history of high-rate hydraulic fracturing (Zorn et al., 2017a, 2017b, 2019). For the stimulation of shale reservoirs, the concept of only brittle rock failure and the resulting microseismicity has been severely questioned by recent research efforts that identified a deficit in the energy budget when only brittle failure mechanisms (microseismicity) are considered. These studies suggest that additional deformation mechanisms are needed to balance the energy budget (Boroumand and Eaton, 2012; Kumar et al., 2018b). Recent studies in the Barnett Shale suggest that the slow-slip deformation and the ensuing long-period long-duration (LPLD) events could contribute to hydraulic stimulation in unconventional reservoirs (Das and Zoback, 2011; Zoback et al., 2012). Compared to microseismic earthquakes that are commonly observed during hydraulic fracturing, LPLD events are found to have low seismic amplitude with emergent waveform characteristics (unclear phase arrivals) and a dominant concentration of energy in the 0.8-80 Hz frequency range (Das and Zoback, 2011; Kumar et al., 2016a, 2016b; Hu et al., 2017). LPLD events were also noted during the fracture stimulation of horizontal wells in the Marcellus Shale in Pennsylvania and West Virginia and in the Wolfcamp Shale in the Permian Basin, Texas (Kumar et al., 2017a, 2017c, 2018b).

In this study, we present our analysis of surface seismic data recorded at a hydraulic fracturing site in the Wolfcamp Shale within the Midland Basin, Texas (Kumar et al., 2018c). We observed multiple low frequency (long period) earthquakes of relatively long-time duration (compared to microseismic events) during the hydraulic fracturing of the two Middle Wolfcamp wells. These events are 5-10 seconds long and are characterized by low frequencies of 10-60 Hz. Waveform characteristics of these LPLD events are highly emergent (unclear phase arrivals) and similar to LPLD events observed earlier in the Barnett Shale, the Marcellus Shale and the Eagle Ford Shale (Das and Zoback, 2011; Kumar et al., 2017a; Hu et al., 2017). We observed one fundamental difference between LPLD events observed in the current study and the events previously observed in the Barnett Shale and the Marcellus Shale -the LPLD events observed in this study have dominant concentrations of energy in the form of P-wave, which is similar to LPLD events observed in the Eagle Ford Shale (Hu et al., 2017), but different from LPLD events observed in the Barnett Shale and the Marcellus Shale that were dominantly composed of S-wave energy (Das and Zoback, 2011; Kumar et al., 2017a). This concentration of energy in different forms of seismic phases could likely be linked to different source characteristics of LPLD events observed in their respective regions. We performed cross correlation of the waveform envelope to locate a subset of LPLD events, selected for having a high signal coherency across the monitoring array.

Data and Methods

In this study, we used data collected from a surface seismic network deployed at a hydraulic fracturing test site (HFTS) in Reagan County, Texas in the Midland Basin (Figure 1). The HFTS is a controlled field-based site for hydraulic fracturing research intended to improve the characterization of an unconventional shale reservoir and to maximize production efficiency of horizontal shale wells (Ciezobka et al., 2018). As part of this field project, 11 horizontal wells were drilled, targeting the Middle and Upper Wolfcamp formations at approximately 8000-ft. depth. The 11 horizontal wells were drilled from north to south, roughly perpendicular to the orientation of the maximum horizontal compressive stress (Sh_{max}). The drilling program was optimally designed to better understand the interaction of intra and inter-well stresses and their effect on hydrocarbon productivity. The surface seismic data was collected during hydraulic fracturing of two Middle Wolfcamp wells (4SM and 5SM) using two arrays of 3C geophones, each consisting of 24 GS-One 3C geophones, spaced 220-ft.-apart. The geometry of the monitoring arrays was an elongated cross, having 20 geophones along longer arm, aligned parallel to the magnetic north-south direction (353.5° azimuth); the remaining 4 geophones were deployed orthogonally along the shorter arm (Figure 1). The length of the extended lateral sections of wells 4SM and 5SM are 10, 261 ft. and 10, 213 ft., respectively. Using conventional plug and perf operations, wells 4SM and 5SM were zipper fracked during December 9 – 21, 2015.

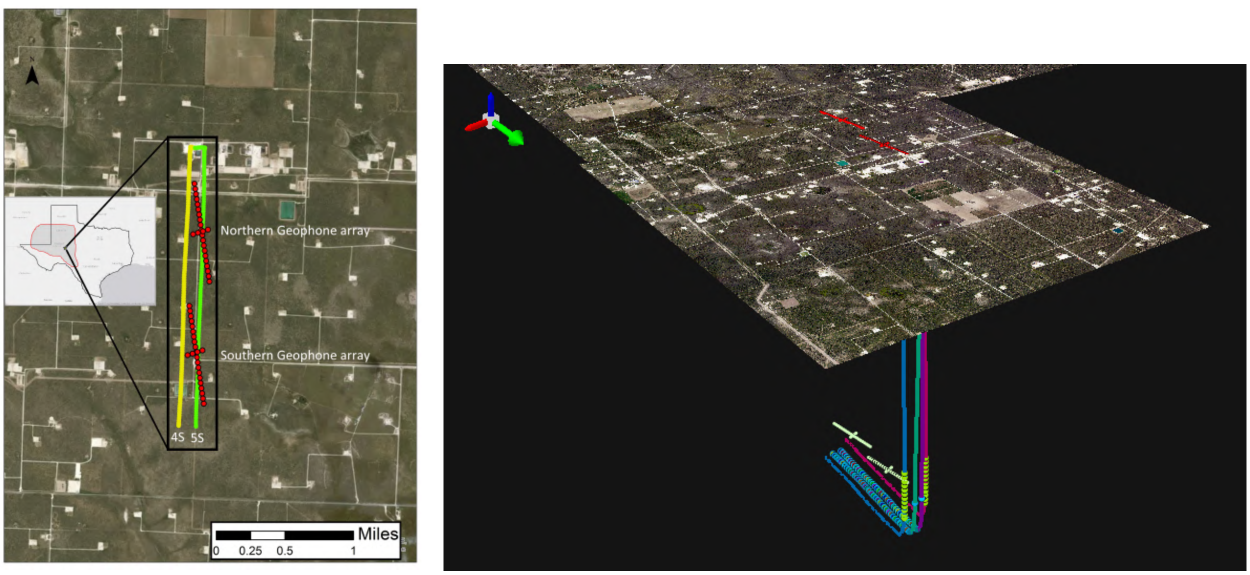

Figure1. Map showing the location of HFTS project in the Midland Basin, Texas. Surface treatment wells 4SM and 5SM are shown in map view (left panel, yellow and green lines) and in 3-D perspective view (right panel). Two observation wells (either side of the two treatment wells in the middle) with downhole monitoring arrays are also shown in the 3-D view. Data used in the current study was acquired using a surface array of 48 geophones, shown as red crosses overlying the surface footprints of well 5SM (labeled 5S on left panel).

We analyzed the low frequency spectrum of the seismic data collected during the hydraulic fracturing of wells 4SM and 5SM to identify LPLD events that might be linked with non-brittle deformation in the reservoir caused by high-pressure, high-rate fluid injection (Kumar et al., 2017a, 2017c; Ghahfarokhi et al., 2019). The first step was to manually scan the data in multiple frequency ranges to identify individual low frequency events. Surface seismic data were filtered in five frequency ranges, including 10-15 Hz, 10-20 Hz, 10-40 Hz, 10-60Hz, and 10-80 Hz, and the filtered waveforms were manually inspected. We observed that the majority of the low frequency events with clear coherent arrivals occurred within the 10-60 Hz frequency range. Due to the non-linear frequency response of surface geophones, we were not able to inspect the seismic waveform for the presence of LPLD events below 10 Hz. We identified 242 individual low frequency events during the first 9 days (December 9-17, 2015) of hydraulic fracturing. The majority of observed low frequency events are 5-10 seconds long, which is significantly longer than the event duration of microseismic earthquakes normally recorded during hydraulic fracturing (Figure 2). We analyzed all three components of recorded seismic data and observed a larger concentration of seismic energy on the vertical component (compared to horizontal components), which is similar to the LPLD events previously observed during hydraulic fracturing of the Eagle Ford Shale in NE Mexico (Hu et al., 2017).

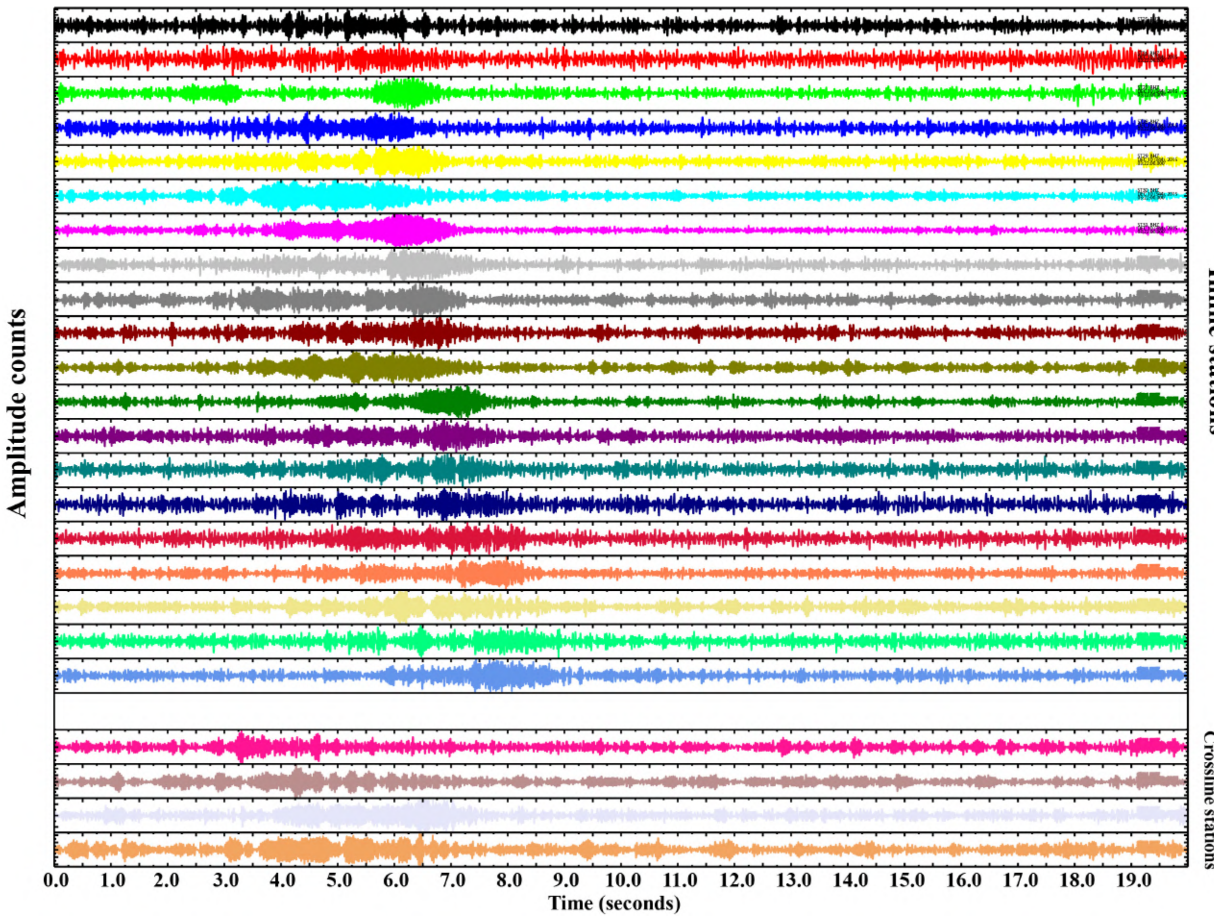

Figure2. Filtered (10-40 Hz) waveform of a long period long duration event recorded by the surface array. Finite temporal moveout across the surface array suggests local (closer to the monitoring array and treatment wells) source of deformation.

Recent studies (Caffagni et al., 2015; Zecevic et al., 2016; Kumar et al., 2017b, 2018a) have highlighted the critical issue of regional seismicity being a potential pitfall for identifying and characterizing LPLD events. To rule out the possibility of misinterpreting regional earthquakes as local LPLD events, we carefully examined the earthquake catalog of United States Geological Survey (USGS) and extracted the observed times of known regional events. 166 regional earthquakes were recorded during the first 9 days of hydraulic fracturing; their observed arrival times were carefully examined for temporal overlap with observed LPLD events (Figure 3). 28 LPLD events were found to have occurred within the six-minute time window from the origin time of catalog events; these events were excluded from further analysis. As pointed out by Zecevic et al. (2016b), it is prudent to investigate data recorded at other nearby independent seismic networks for additional observations. One broadband seismic station from the United States National Seismographic network (USNSN) is within a 120-mile radius of the test site, and was operational during the 9 days of hydraulic fracturing (Figure 4). We extracted four-minute-long records of seismic data from USNSN database, spanning the arrival times of 214 LPLD events (242 observed LPLD events minus 28 LPLD events that temporally coincided with regional events in the USGS earthquake catalog), and compared the seismic data recorded by the USNSN station during these intervals with the spectrogram of corresponding LPLD events. 30 LPLD events were found to coincide with events recorded by the USNSN station; these events were excluded from further study.

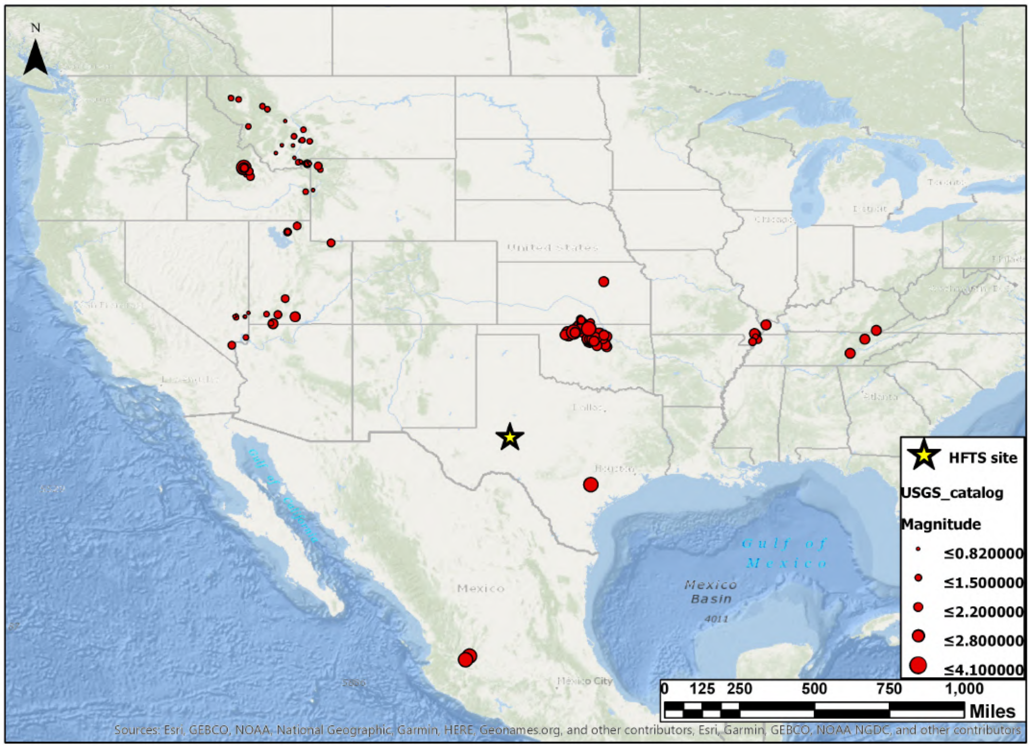

Figure3. Map showing the location of regional events listed in the USGS earthquake catalog that were recorded during first nine days of hydraulic fracturing.

Both brittle and non-brittle deformation contribute to the permeability increase in shale reservoirs that have been hydraulically fractured. Whether brittle or non-brittle deformation predominates depends on the geomechanical properties of the reservoir. Traditional microseismic monitoring is appropriate for brittle reservoir rock, including most limestone, sandstone, and siltstone but not for the more ductile shale that contains varying amounts of clay minerals. However, shale reservoirs include both brittle and non-brittle rock, and microseismic does not account for the non-brittle deformation that occurs during hydraulic fracturing, which could be important to hydrocarbon production. An understanding of non-brittle deformation is needed to optimize the fracture stimulation of shale reservoirs, and a study of LPLD occurrence is indicated. To understand the linkage between LPLD occurrence and non-brittle deformation, it is necessary to obtain robust locations for LPLD events. The seismic waveform characteristics of LPLD events are highly emergent, similar to non-volcanic seismic tremors observed in the subduction zone environment (Obara 2002; Shelly et al., 2006). Due to unclear phase arrivals, the conventional earthquake location algorithm that heavily depends on phase arrival time information is not very useful to determine LPLD location. We used a more advanced approach of waveform envelope cross correlation (Obara 2002; Hu et al., 2017) to obtain relative arrival times of envelope across the seismic network and further utilized the spatial distribution of the arrival time to determine the location of certain selected (high quality signal) LPLD events.

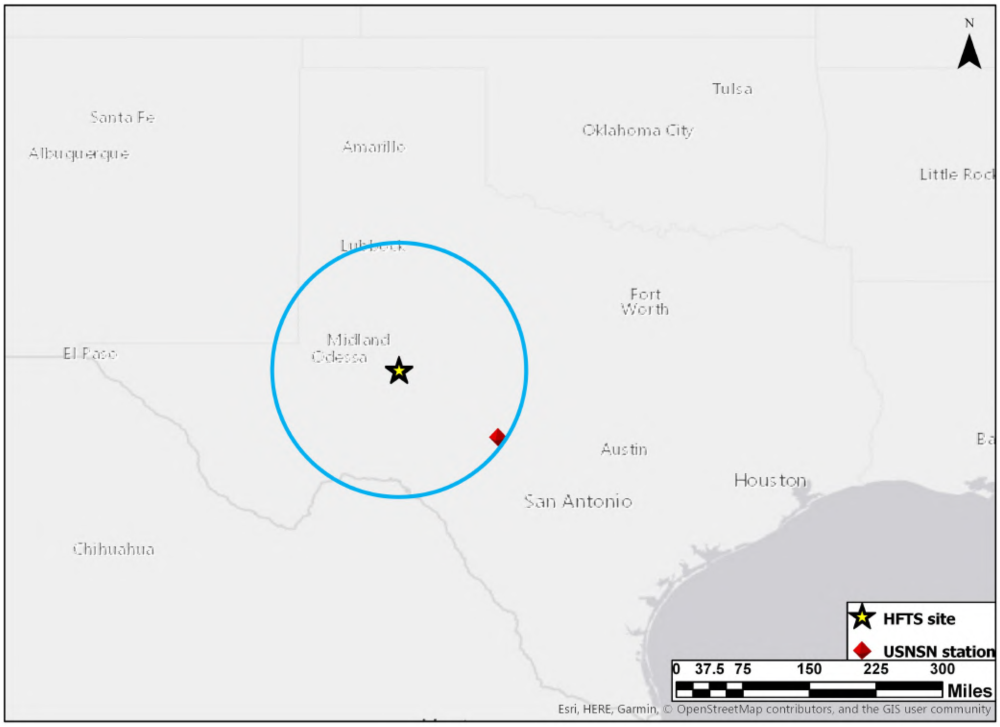

Figure4. Map showing the location of a nearby station from an independent seismic network (United States National Seismographic Network) that was used to differentiate LPLD events recorded in the current study with the small magnitude regional events not listed in the national earthquake catalog. Circle drawn in the map has radius of 120 miles.

Results and Discussions

Stimulating oil and gas production from unconventional reservoirs that are characteristically low permeability (<0.1 millidarcy) formations requires extensive fracturing of rock volume to improve the hydraulic conductivity. Starting in 1947 in the Hugoton field, Kansas (Palisch et al., 2009), hydraulic fracturing has been used to create a network of conductive fractures in unconventional reservoirs (shale and tight formations e.g. sandstones and limestones) that greatly increased U.S. oil production. However, insuring nation's energy security needs further development of our current understanding of the reservoir's geomechanical response to hydraulic stimulation. This improved understanding can help to perform more targeted fracturing and unlock larger percentages of oil and natural gas that are left unproduced otherwise. Additionally, such fundamental understanding of rock's geomechanical response would be applicable to other subsurface operations, such as exploration of geothermal energy, geologic storage of CO_2, and disposal of radioactive waste. Until recently, brittle deformation and ensuing microseismicity was considered to be totally representative of reservoir deformation processes caused by hydraulic fracturing. However, in last few years, several instances of LPLD events likely associated with contemporaneous non-brittle deformation of unconventional reservoir have been reported during hydraulic fracturing (Das & Zoback, 2011; Kumar et al., 2017a, 2017c; Ghahfarokhi et al., 2019).

In the current study, we identified multiple low frequency events of long-time duration during the hydraulic fracturing of the two horizontal Middle Wolfcamp Shale wells in the Midland Basin in Reagan County, Texas. These low frequency events have dominant concentration of energy in the 10-60 Hz frequency range with average duration of 5 seconds (Figure 2). We observed significant similarities in the waveform characteristics (amplitude, frequency content, and clarity of seismic phase arrivals) between LPLD events observed in the current study and previously reported LPLD events in the Barnett Shale, the

Marcellus Shale, and the Eagle Ford Shale (Das & Zoback, 2011; Kumar et al., 2017a, 2017c; Hu et al., 2017). We observed a slight difference in the time period of LPLD events compared to other hydraulic fracturing sites, which is likely related to site specific differences in rock's geomechanical properties (brittleness, compressibility, etc.), lithology, ambient stress condition, and difference in hydraulic treatment strategies (pumping pressure, rate, fluid content, etc.).

Our final list of LPLD events are local events that were recorded by the surface geophone arrays at the test site, but not recorded by the USGS seismic network or by one station from an independent seismic network (USNSN) that was 120 miles from the HFTS. Figures 5 and 6 compares waveforms and spectrograms for coeval data recorded at our local station and from the independent network station 120 miles away. We observed discrete seismic signal at our local station both in time and frequency domain (Figure 5, panel a and b) compared to background noise recorded at the USNSN station (Figure 6, panel a and b) in the same time window. The USNSN station (Figure 4) is too far from our study site to be able to record events related to hydraulic fracturing, but close enough to be able to record small-magnitude unknown regional events surrounding our study area. We believe that if the LPLD events are genetically linked to small-scale rock deformation triggered by hydraulic fracturing then there should be no corresponding record of such local deformation and associated LPLD events at distant (or regional) stations. Therefore, the absence of LPLD events in the USNSN data suggests a localized source of slow-slip as the cause of LPLD signals rather than small magnitude regional earthquakes not listed in the standard catalogs.

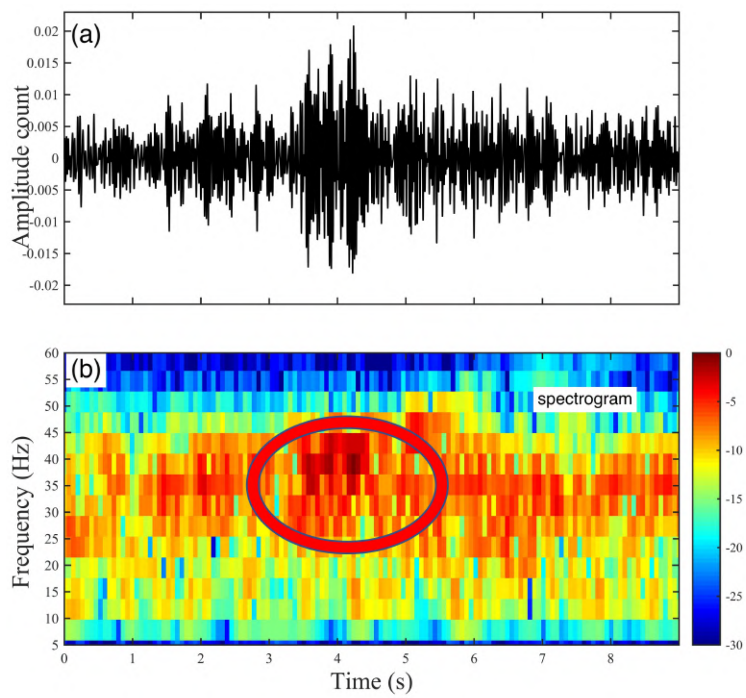

Figure5. Stacked waveform (panel a) and spectrogram (panel b) of the LPLD event shown in Figure 2.

We observed larger concentration of seismic energy on the vertical component of 3C geophones for LPLD events recorded in the current study (Figure 7). As vertical component seismogram is dominantly composed of P waves, LPLD events recorded during hydraulic fracturing of the two Middle Wolfcamp Shale wells are similar to volcanic tremors and previously reported LPLD events from the Eagle Ford Shale in NE Mexico that are also observed to have clear P wave signal (McNutt, 1992; Hu et al., 2017). The similarity in waveforms is perhaps linked to similar source characteristics, suggesting that the observed LPLD events are generated in response to tensile opening of cracks triggered by high-pressure fluid injection during hydraulic fracturing and the subsequent resonance of fluid in those cracks is partly responsible for long duration signal of the observed LPLD events (Aki et al., 1977, Chouet 1988, Hu et al., 2017).

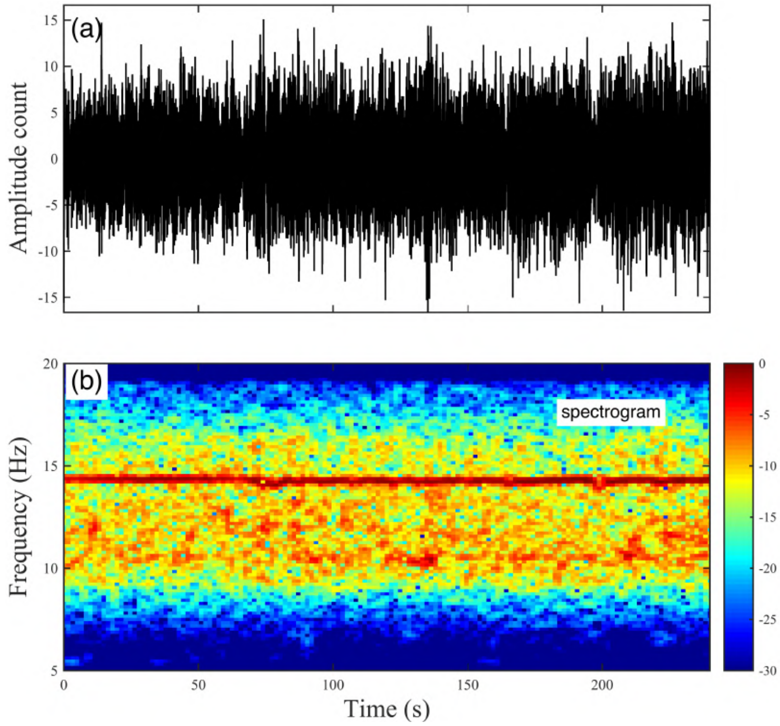

Figure6. Filtered waveform (panel a) and spectrogram (panel b) of the data recorded at nearby station of the United States Seismographic Network (USNSN) in the same time window as LPLD event recorded in the current study and shown in Figure 5.

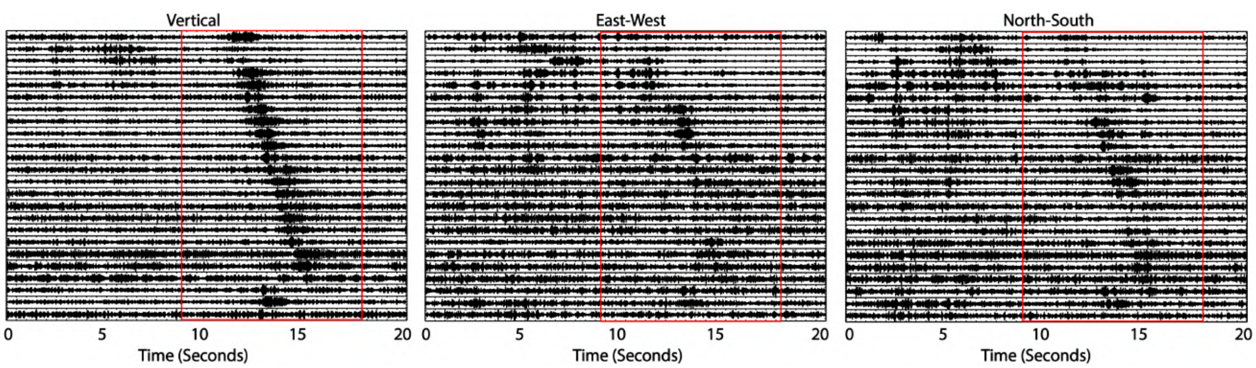

Figure7. Filtered waveform (10-40 Hz) of a LPLD event recorded on three different components of surface geophones. A higher concentration of seismic energy is observed on the vertical component when compared to two horizontal components (east-west and north-south).

We determined the location of 25 high quality LPLD events using the advanced technique of cross correlating a seismic waveform envelope across the monitoring network. The majority of the LPLD events are located between two treatment wells 4SM and 5SM (Figure 8, left and bottom right panels). As shown in the map view, the epicenters of LPLD events are closely (within few feet) distributed along the long arm of the monitoring array (Figure 8, left panel). This preferential distribution of epicenters seems to be the result of systematic bias in the location of LPLD events. Bondar et al. (2004) and Alessandro & Anna (2016) have discussed the affect of station coverage (the distribution of monitoring stations around the epicenter) and the azimuthal gap on the quality of the earthquake location. For better location accuracy, monitoring stations should be uniformly distributed around the epicenter. As the majority of the geophones are preferentially distributed along magnetic north-south direction, leaving a large gap in station coverage in other directions, the location algorithm is biased accordingly and perhaps the main reason for the preferential distribution of LPLD epicenters.

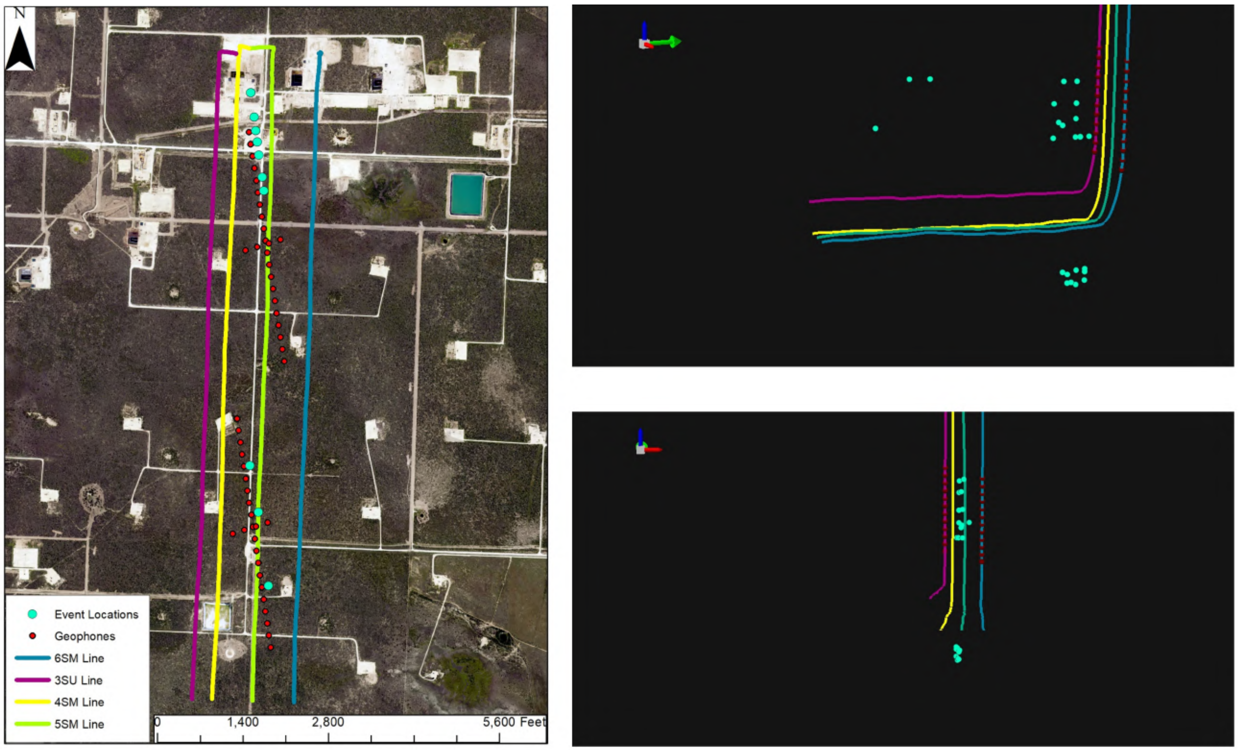

Figure8. Map (left panel) showing the location of selective LPLD events (magenta circles) recorded during fist nine days of fracturing. Depth profile and gun barrel views are shown in the top right and bottom right respectively, with magenta dots representing the depth distribution of LPLD events. Treatment wells 4SM and 5SM are shown as solid yellow and green lines and the observation wells 6SM and 3SU are shown as purple and blue lines, respectively.

We note that the hypocentral depth of LPLD events varies between 6500ft to 8800ft., spanning 1500ft. above to 800ft. below the average treatment depth (Figure 8, right panels). These hypocenters are estimated using a two-layer velocity model, first layer from surface down to 5000-ft. depth and second layer between 5000 to 9000-ft depth. We used a sonic log to estimate the average velocity of 3800 m/s for second layer (5000-9000 ft.). Due to unavailability of sonic record at shallower depth (<5300 ft.), we used perforation shots to obtain average calibrated velocity for the first layer. It is worth noting that use of 1-D velocity model for travel time prediction during location process is an over simplification of the 3-D Earth and further, 1-D velocity model estimated from perforation shot arrivals could be significantly different from the true 1-D velocity model. We think this two-fold simplification in velocity model perhaps bleeds into significant hypocentral error and is the likely reason for the large hypocentral depth range of LPLD events. We aim to relocate these LPLD events using true 1-D velocity model in coming months and that would further help in their accurate geomechanical interpretation.

Conclusions

We analyzed surface seismic data recorded during hydraulic fracturing of the two Middle Wolfcamp Shale wells in the Midland Basin, Texas. We found multiple low-frequency earthquakes of long-time duration (compared to normal microseismic events) that are recorded across the surface-monitoring array with finite temporal moveout. The low-frequency events have dominant concentration of energy in 10-60 Hz frequency range, with average time duration of 4-5 seconds. The majority of LPLD events are uniquely recorded at the local surface array, with no temporal record in the regional earthquake catalog and missing data from a nearby seismic station, suggesting a local source of deformation as their probable cause. We observed dominant concentration of energy on the vertical component of the seismogram for these LPLD events, which is similar to volcanic tremors and LPLD events previously recorded during hydraulic fracturing in the Eagle Ford Shale. Our observations suggest that the LPLD events recorded in the current study are likely generated in response to tensile opening of cracks triggered by high-pressure fluid injection during hydraulic fracturing. The location of selective LPLD events are observed to be closely distributed within few feet of the treatment wells in the horizontal direction, with a large offset in the vertical direction. This could likely be related to systematic error in the hypocentral location of LPLD events perhaps introduced by the inaccurate velocity model used to locate these events. We aim to relocate LPLD events using a true velocity model in the near future to improve their location uncertainty and facilitate better geomechanical interpretation.

Disclaimer

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