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Seismic Monitoring of Hydraulic Fracturing Activity at the Marcellus Shale Energy and Environment Laboratory (MSEEL) Site, West Virginia

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Summary

Hydraulic fracturing is a well-established completion technique to extract significant volumes of natural gas from organic-rich shale, which would otherwise behave as impermeable formations. Diffusion of water outward from the newly created hydraulic fractures into the reservoir helps reactivate the preexisting faults and initiates shear failure on complex network of preexisting planes of weaknesses. Microseismic events recorded on downhole arrays are a manifestation of associated shear failure along both preexisting and newly created fractures. Some of the recent studies focused on energy balance calculations suggest that the cumulative moment of microearthquakes is a small portion of the moment release expected for the amount of fluid injected into the formation. This suggests some other sources of deformation in the reservoir rock, contemporaneous with microseismic activity that need to be considered to get a balance in the energy budget during hydraulic fracturing process. Recent findings on long period, long duration tremors suggest that "slow slip emission" along weaknesses that are misaligned with respect to the present day stress field is likely the dominant mechanism of deformation and plays a crucial role in reservoir stimulation. In Monongalia County, Morgantown, we carried out surface seismic monitoring of the hydraulic fracturing operation at an active well pad with five seismometers. Upon investigating the waveforms from surface monitoring, we identified 89 high-amplitude, impulsive events and 436 long period, long duration (LPLD) events, with highly emergent waveform characteristics. The time of occurrence of these observed LPLD events have no temporal correlation with the events reported in the regional earthquake catalogs and data from CEUSN stations, suggesting that these LPLDs are not weakened records of regional earthquakes. We observed a significant concentration of energy in the 0.8-3 Hz frequency range for these observed LPLD events. During various stages of hydraulic fracturing, LPLD events were found to occur most frequently when the pumping pressure and rate were at maximum values. As the main purpose of hydraulic fracturing operation is to stimulate oil and gas production from the less permeable reservoir, we compared the relative production contribution per stage to the frequency of occurrence of LPLD events. We found good correlation between the frequency of LPLD events and production data, highlighting the potential contribution of slow deformation processes and its effectiveness in the reservoir stimulation.

Introduction

Hydraulic fracturing of organic-rich shale and tight gas reservoirs is routinely performed to enhance the secondary permeability of the reservoir and increase access to trapped hydrocarbon resources. Application of this engineering technology involves the injection of millions of gallons of water at high pressure to establish a complex network of permeable fracture pathways that enhances hydrocarbon production from an otherwise low-permeability reservoir.

Productivity enhancement and reservoir stimulation is generally thought to be associated with the reactivation of pre-existing fractures, with minor contribution from creation of new hydraulic fractures (Moos et al., 2011; Das & Zoback, 2013). The deformation along pre-existing fractures and the opening of new fractures is likely recorded as microseismic events during hydraulic fracturing treatment. The distribution of microseismic events is most commonly used as a proxy to calculate the stimulated reservoir volume (SRV). For the most part, this correlation is still unsettled in the literature, with evidence both in support of and against the practice (Wilson et al., 2016 and Sicking et al., 2013).

Although the history of hydraulic fracturing treatment dates back to as early as the 1940's (Montgomery & Smith, 2010), the nature of subsurface deformation during hydrofracturing is still unclear. The response of a shale reservoir to hydraulic stimulation has been reported to be extremely variable among different fracturing sites. A simple energy balance calculation suggests that the cumulative moment of micro-earthquakes is a small portion of the moment release expected for the amount of fluid injected into the formation (Warpinski et al., 2012). This energy deficit suggests that other sources of deformation may play a dominant role during hydraulic stimulation. In a recent study of hydraulic fracturing in the Barnett Shale, Das and Zoback (2011) found evidence of low-frequency events (seismic frequencies ranging between 10 and 80 Hz) that persist for a long time period (between 10 to 100 seconds in duration). The LPLD events are low in displacement amplitude, with a mostly emergent arrival that makes phase picking very difficult (Das & Zoback, 2011; Eaton et al., 2013). Two probable mechanisms have been suggested by Das and Zoback (2011) and Zoback et al. (2012) for the occurrence of LPLD events associated with hydrofracturing. These include: (1) high clay content (>30%) at a local scale, which increases shale ductility and promotes slow slip failure along fractures with a stable deformation rate; (2) slip along pre-existing fractures that are unfavorably oriented in the ambient stress field and deform in LPLD events. Waveform analyses by Das and Zoback (2013) indicate deformation along a relatively larger fracture in the case of LPLD events, relative to brittle microseismic event failures, with LPLD events releasing as much as 1000 times the energy of an average microseismic event.

With these considerations about slow slip deformation and their probable role in reservoir stimulation, we have analyzed surface seismic data collected from Monongalia County in West Virginia (Figure 1). We examined the spectral characteristics of the recorded waveforms to accurately record and analyze the characteristics of energy release at low seismic frequencies (0.8-3 Hz) and clearly identify the presence of LPLD slow slip events associated with hydrofracturing. Our spectrogram analyses show bursts of seismic energy in the 0.8-3 Hz frequency range for several discrete arrivals. Waveform characteristics of these low frequency arrivals are similar to tectonic tremors and LPLD events previously reported from the subduction zone environments and hydraulic fracturing operation in the Barnett Shale in Texas respectively (Shelly et al., 2006; Das & Zoback, 2011) and likely indicate the existence of slow deformation processes during hydraulic fracturing.

Data and Method

We used surface seismic network of five broadband seismometers (Nanometrics-Trillium Compact Posthole) to collect data during the hydraulic fracturing of two horizontal Marcellus wells in Monongalia County, West Virginia (Figure 1). We deployed the seismometers within 2 miles of the treatment well pad, with the nearest station (FRAC1) within 700 feet of the well pad. The approximate range of recording frequency for the broadband seismometer is 0.05-100 Hz, with a low noise floor, and it is highly sensitive to detect earthquakes from both local and regional seismicity. We optimized the geometry of the seismic network by placing seismometers around the northwest trending laterals (Figure 1). Of the two laterals (MIP 3H and MIP 5H), well 5H was hydraulically fractured during October 28 – November 5, 2015 and well 3H during November 6 – 15, 2015. We present our analysis of observed data from three months of recording between September to November 2015 in the current study.

We applied instrument response corrections to the raw amplitude counts recorded by our surface seismometers to obtain the actual measure of ground motion in nm/s at each site. For a preliminary search of low-frequency signals, we calculated the power spectral density for 10 consecutive windows of 1 hour each, before and after the start of hydraulic fracturing. We compared the power spectral density of the 10-hour windows before and during fluid injection for both stimulation phases (October and November 2015) as shown in Figures 2a and 2b. In an exhaustive search for long duration events, we filtered the seismic waveform in multiple different frequency range of 1-30Hz, 1-5 Hz and 0.8-3 Hz to remove the masking effect of high frequency signal and manually inspected the filtered data. We observed the best coherent signals between stations in the 0.8-3Hz-frequency range. We initially identified 535

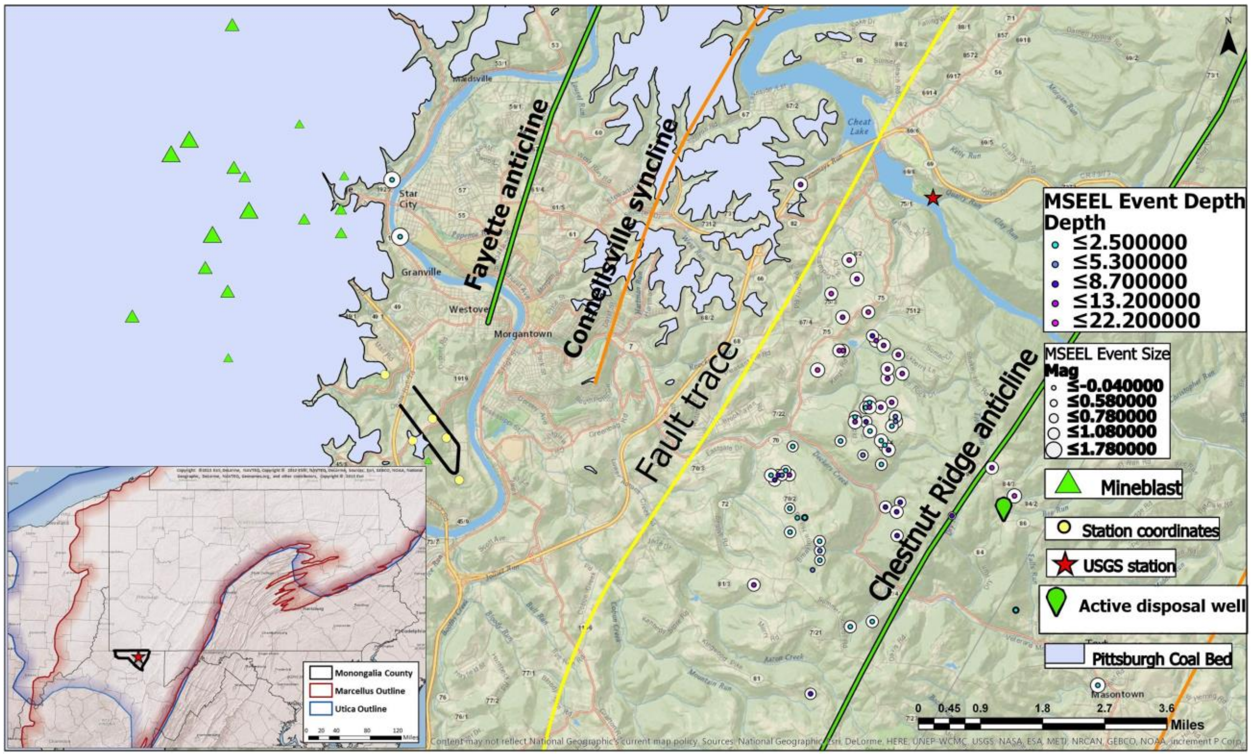

Figure1. Map showing the location of two horizontal wells (solid black lines) in Monongalia County, with a small inset in the bottom left showing the study area and outline of Marcellus shale in West Virginia. Open circles represent the earthquake locations and the green triangles are mining or construction blasts located in the current study. Shaded grey area represents the outline of mined portion of the Pittsburgh Coalbed in Monongalia County, West Virginia.

discrete events, with waveform characteristics typical of an LPLD event, as discussed in Das and Zoback (2013). Each of these events is approximately 40-50 seconds in duration, with no impulsive phase arrival and waveforms dominantly composed of S-wave signal. This larger contribution of energy from the S wave arrival is similar to the waveform characteristics of previously reported long duration seismic tremor in the subduction zone environment and LPLD events from the Barnett Shale, respectively (Shelly et al., 2006; Das & Zoback, 2013).

In our analyses of long duration signal, it is imperative to rule out the possibility of mispicking regional or global earthquakes as potential LPLD events. Regional earthquakes could be a potential pitfall for the identification of LPLD events due to their overlapping frequency content and similar waveform characteristics, as pointed in recent studies (Caffagni et al., 2015; Zecevic et al., 2016). We carefully examined the USGS earthquake catalog for reported seismicity during the time period of observed LPLD events and found temporal overlap with some small magnitude regional events within 1000 km radius of our study area (Figure 3). We checked the arrival time of individual LPLD events and did not find any temporal overlap with the expected arrival time of these small magnitude regional events within 1000 km radius. We also compared the temporal records of our observed LPLD events with the events reported in a larger search radius of 2000 km in the Advanced National Seismic System [ANSS] composite catalog. From our list of 535 events, we found temporal overlap with 22 events reported in the ANSS catalogs. This suggests that either the 513 events are small magnitude regional events below the detection threshold of standard catalogs or they are local events in close proximity to our seismic network. To rule out the possibility of mis-picking small magnitude regional events as local earthquakes, we examined the waveform data from two stations of the nearby Central and Eastern US network (CEUSN), less than 70 miles from our study area (red pyramids, Figure 4). Of 513 non-catalog events, we found temporal correlation with 77 events in the CEUSN. We calculate the spectrogram of the north-south component signal for our final list of 436 unique LPLDs that are missing from both regional catalogs and nearby stations of the USArray.

We also compared the time of occurrence of LPLD events with the pumping pressure records to check for any first order correlation with pressure variation. As pointed by Zoback et al. (2012), long period events are likely

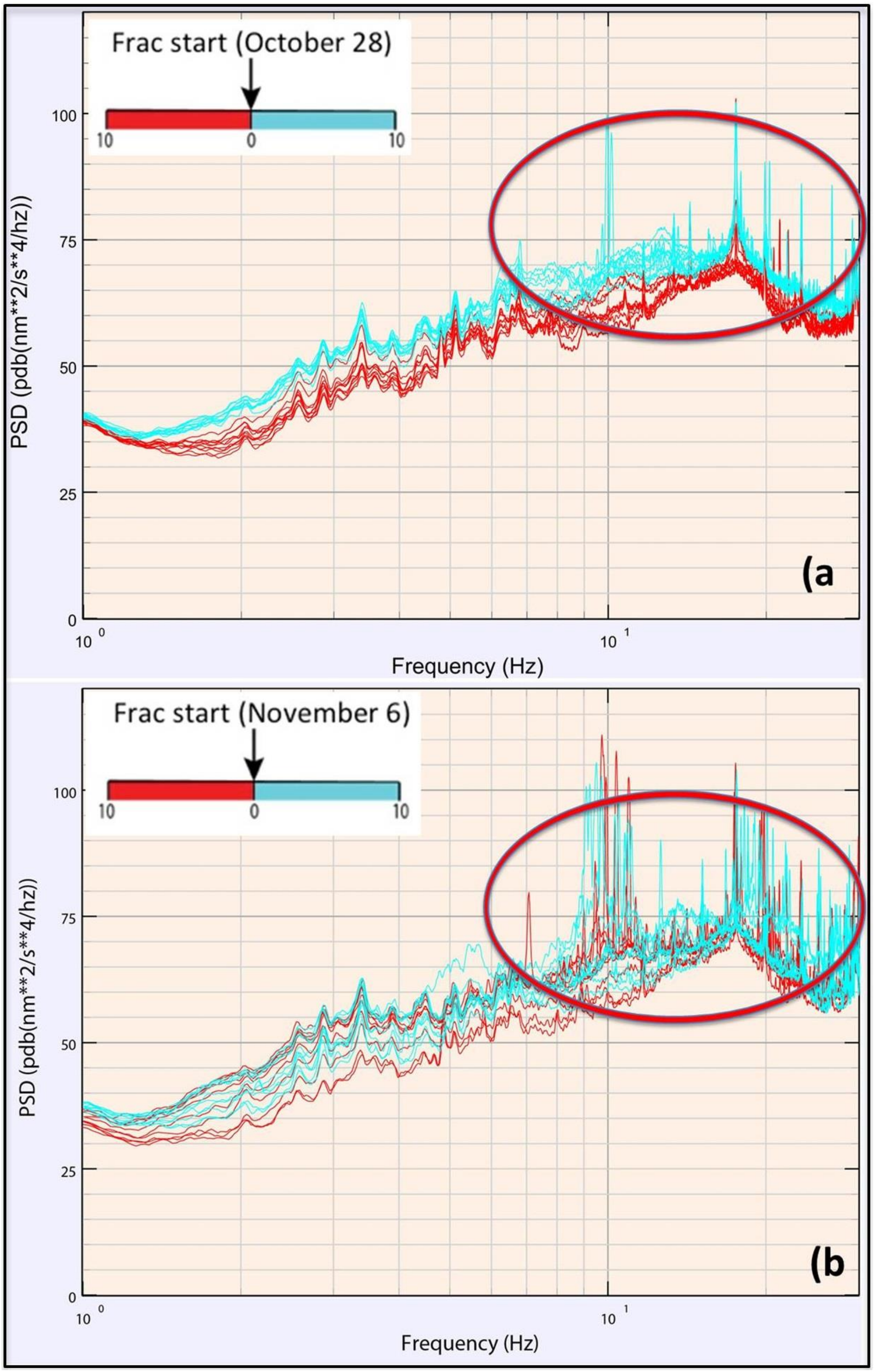

Figure2. Spectral variation of power before (red) and after (cyan) fracturing started on (a) October 28, 2015 for well 5H and (b) November 6, 2015 for well 3H

associated with shear deformation along the preexisting fractures of relatively larger size and contribute more significantly to the stimulated reservoir volume (SRV) than its conventional estimate based on the microseismicity alone. The oil and gas production from unconventional reservoir is assumed to be inherently related to the SRV due to hydraulic fracturing (Warpinski et al., 2012). We compared the time of occurrence of long period events observed during the hydraulic fracturing of well 3H with the stage-by-stage production data to highlight their contribution in reservoir productivity.

While searching for long duration events, we found some high amplitude discrete seismic arrivals with strongly impulsive waveform characteristics. Some of the impulsive events have waveform characteristics similar to a mine blast (these events displayed a pseudo-isotropic pressure pulse), with insignificant energy contribution from S-wave arrivals. We are able to pick P and S-arrivals for all other impulsive events on both the vertical and horizontal components. We used the single-station location procedure in SEISAN (Havskov & Ottemoller, 1999) to locate a final list of 89 impulsive events, including 21 probable mine blasts. We also estimated their moment magnitude by utilizing the spectral parameters of displacement spectra in SEISAN.

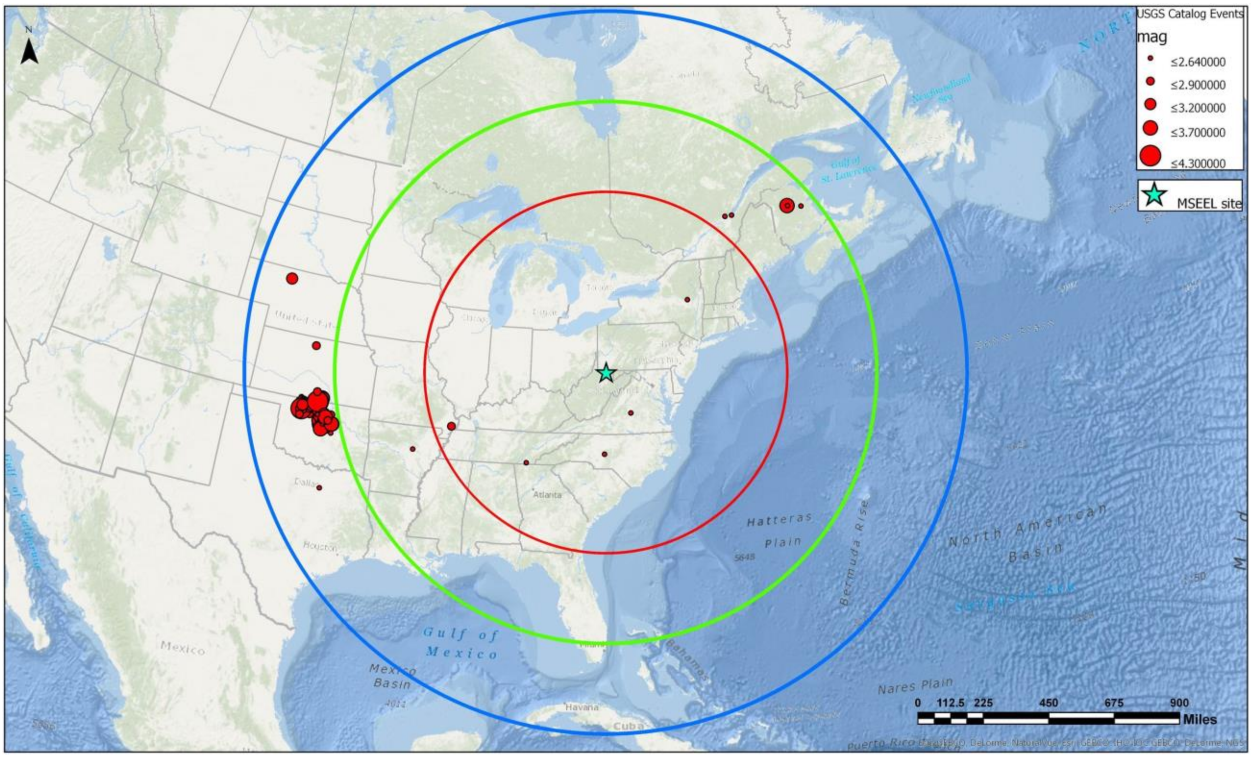

Figure3. Map showing the location of regional events (solid red dots) reported in the USGS catalog during the fracturing of well 5H and 3H. The red, green and blue circles drawn on the map have a radius of 1000 km, 1500 km, and 2000 km respectively

Results and Discussions

The locations of high amplitude impulsive events are shown in Figure 1. We observed two types of impulsive events with differing waveform characteristics. The two groups of events are geographically separated from each other and located on opposite ends of the two horizontal wells. The first group of events, located northwest of the horizontal wells, is composed of sparsely distributed hypocenters with waveform characteristics similar to a mine blast (green triangles in Figure 1). The range of hypocentral depth varies between 0 and 3 km for the first group of events. Review of the USGS record of mined areas for the Pittsburgh coal bed in West Virginia (Fedorko, 1990) shows an excellent spatial correlation between the location of these blast-type events and the southeastern edge of old underground mines in Monongalia County (grey shaded area in Figure 1). This suggests that the impulsive events, having waveform signature similar to pseudo-isotropic pressure pulse, are perhaps related to roof collapse in the old mine or blasts associated with civil construction and other mining activities. Southeast of the horizontal wells, we located a second group of events (open circles in Figure 1) with waveform characteristics similar to a natural earthquake. Events within the second group have hypocentral depth varying in the range of 0 to 22 km, with local magnitude in the range of M_L0 to $M_L1.78$. It forms a linear cluster of events, dominantly oriented north-south, with a minor extension in the northeast-southwest direction. We do not observe any spatial overlap between the location of these normal earthquakes and lateral Marcellus Shale wells. Majority of the events from this distant cluster have less

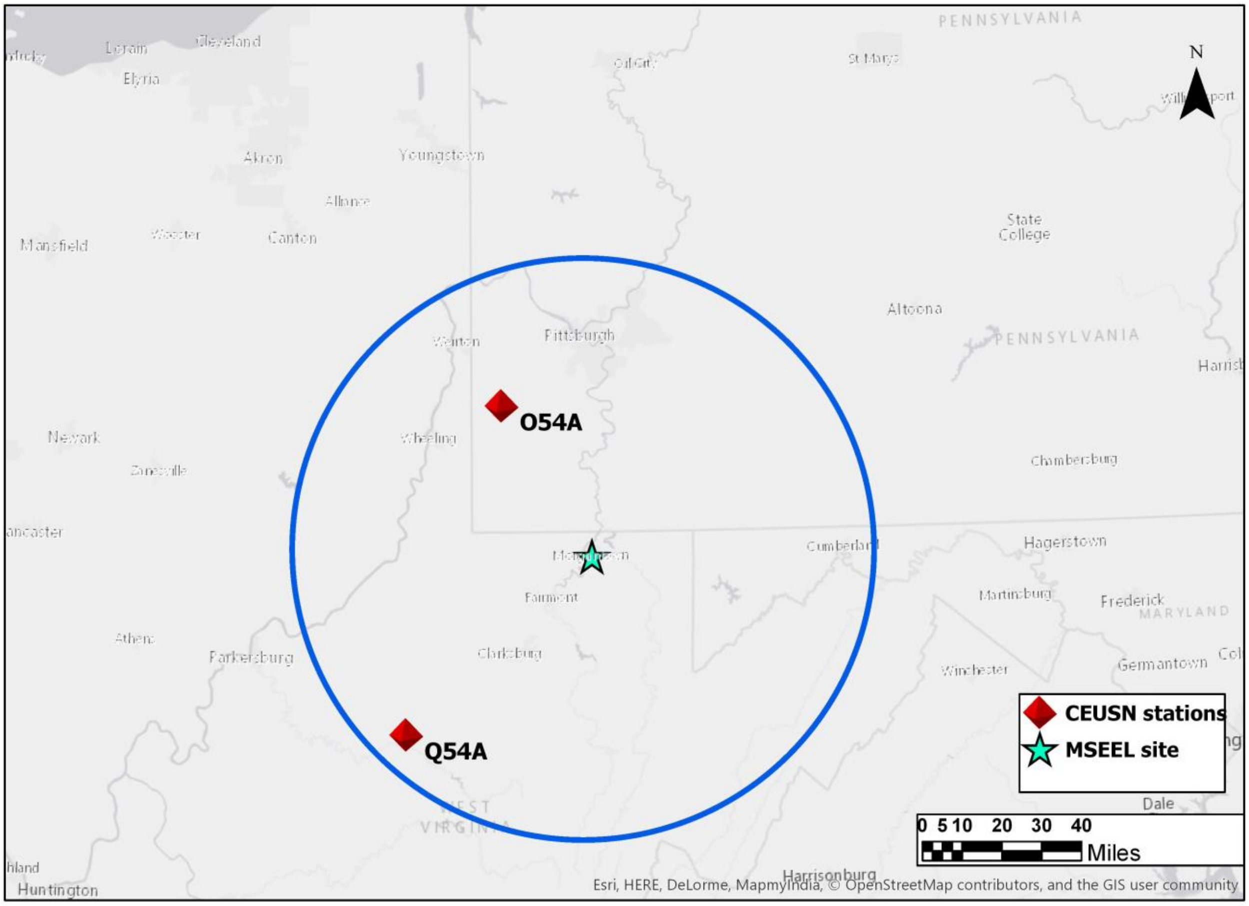

Figure4. Map showing the locations of nearby stations from Central and Eastern United States Network (red pyramids) used for waveform comparison with LPLD events recorded at Monongalia County site (cyan star). The circle (blue) drawn on the map has a radius of 70miles.

well-constrained hypocentral depth with large mean depth error (~25 km) that can be attributed to wide azimuthal gap (~360°, angle between two straight lines connecting an earthquake location with the two adjacent seismic stations in the network). This linear cluster apparently coincides with the western flank of Chestnut Ridge anticline, the westernmost ridge in the Appalachian Plateau Physiographic Province (Figure 1). We also found a class II injection well along the eastern edge of this earthquake cluster that is actively being used for commercial brine disposal at ~8000 ft (green place mark, Figure1). As widely evidenced in Central Oklahoma, the saltwater disposal could potentially increase the level of background seismicity (Walsh and Zoback, 2015). Considering the large error in hypocentral depth, it is difficult to quantify the exact nature of subsurface deformation related to this distant earthquake cluster. It is possible that the shallow events within this cluster are related to the subsurface variation in pore pressure resulting from brine disposal and deeper events are perhaps related to the tectonic deformation in the lower crust under this portion of the Central Appalachians.

During hydraulic fracturing, we observed a significant increase in the power spectral density between 7 and 30 Hz, with a larger number of peaks as compared to the pre-fracture time interval (Figure 2). The difference in spectral peaks before and during the hydraulic fracturing is significant at three seismometer locations (FRAC1, FRAC2 and FRAC4) for both laterals (wells 5H and 3H). We observed a subtle difference in power spectral peaks for FRAC5 that can be attributed to greater loss of energy due to its distal location from the two horizontal Marcellus Shale wells. At FRAC3, data recording was discontinuous due to solar charging shortcomings and we are unable to calculate power spectra at the time when fracturing started. The increase in power spectral peaks during stimulation indicates a significant contribution of energy from the low frequency (<30 Hz) signal.

Our detailed analyses of the LPLD events and their spectrograms show abrupt flares of energy in the seismic frequency range between ~0.8 to 3 Hz, with occasional spikes up to 4 Hz (Figure 5). Although our spectrograms for the LPLD events are similar to those discussed by Das and Zoback (2011), spectral content is significantly different with lower dominant frequencies. This difference in spectral content is perhaps related to the different positioning of the recording system between ours and previous studies. We used data from surface seismometers for spectral analyses as opposed to borehole geophones used by Das and Zoback (2011). Seismic waves attenuate as they propagate through the earth, with larger attenuation for higher frequencies due to the inherent high-cut/low-pass filtering property of the earth. As the borehole geophones are likely to be closer to the origin point of LPLD seismicity in the subsurface, attenuation of higher frequencies will be less significant due to a shorter travel path. For the surface seismometers, higher frequencies will be comparatively more attenuated due to a longer travel path and the seismic signal will be left with dominantly lower frequencies. Of the 436 LPLD events, 55% (242 events) of the LPLD events were identified during the stimulation of well 5H and 45% (194 events) during the hydraulic fracturing of well 3H. Although there are no obvious differences in the hydraulic treatment strategies between well 5H and 3H to account for the difference in observed LPLD counts, one possibility is the difference in the number of stimulation stages between well 5H and 3H. Well 5H was stimulated over more stages than well 3H (30 versus 28 stages), which would create an elevated fluid pressure condition in the reservoir for a longer period of time and perhaps be responsible for the increased LPLD count during the treatment of well 5H. Another possibility is the closer proximity of seismometers (FRAC2 and FRAC4) to well 5H, leading to improved detection for small magnitude LPLD events.

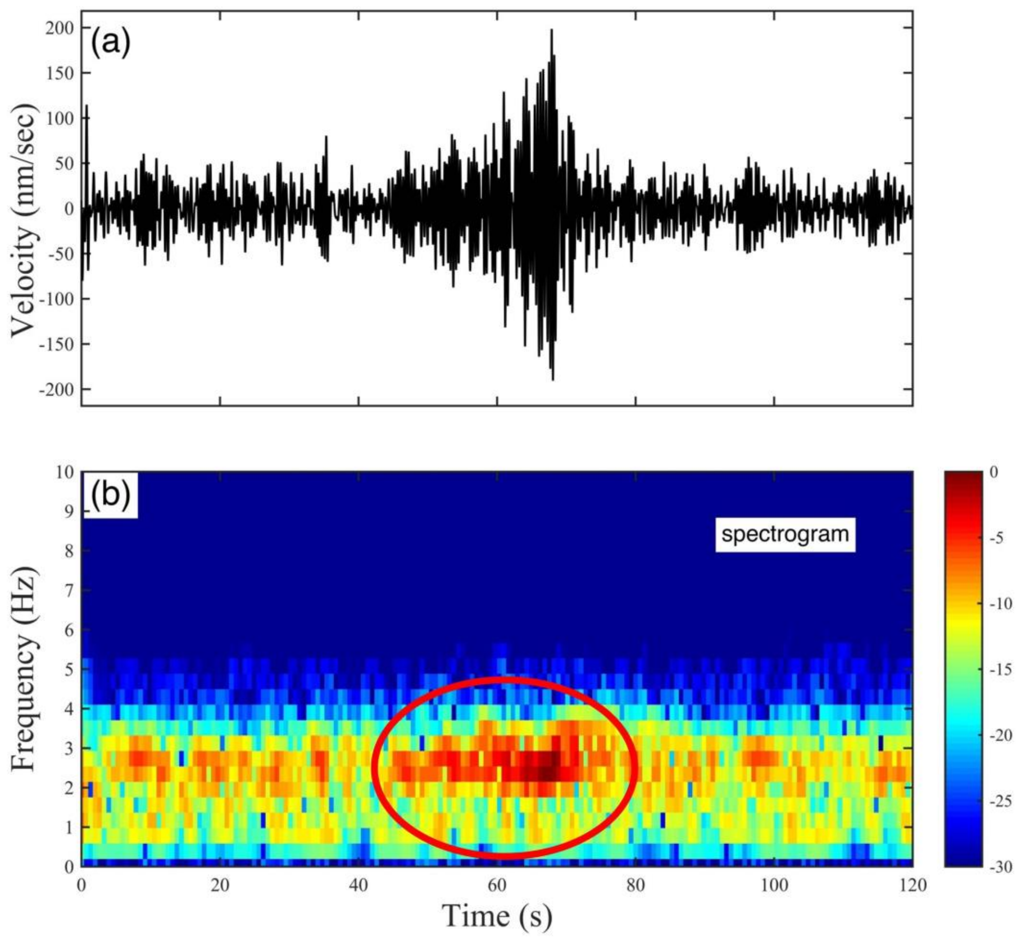

Figure5. Stacked waveform (panel-a) and spectrogram (panel-b) of a long duration event identified during November stimulation period of well 3H. Color scale shows amplitude in decibel, with warmer colors corresponds to higher amplitude and vice-versa.

As mentioned in the previous section, we made diligent efforts of checking standard earthquake catalogs and data from nearby stations of CEUSN to avoid misinterpreting any small to large magnitude regional events as potential LPLD events. From our final list of 436 LPLD events, we carefully selected some high quality LPLD events with high signal to noise ratio and analyzed 2-minute long records of CEUSN data spanning the arrival times of these selected LPLD events. We found no indication of small magnitude events during the relevant time intervals at both stations (O54A and Q54A) from CEUSN (Figure 6). The seismic waveforms recorded at both CEUSN stations appear to contain a uniform record of background noise, without any noticeable change in the amplitude level or frequency content with time. The direct comparison of seismic waveforms of individual LPLD events to the CEUSN data also highlights the static amplitude level at both CEUSN stations with no signs of regional phase arrival before and after the origin time of LPLD events (Figure 7). The absence of LPLD record from the CEUSN data is an important observation that likely suggests a local source of deformation for the causality of LPLD signal rather than small magnitude regional earthquakes not listed in the standard catalogs.

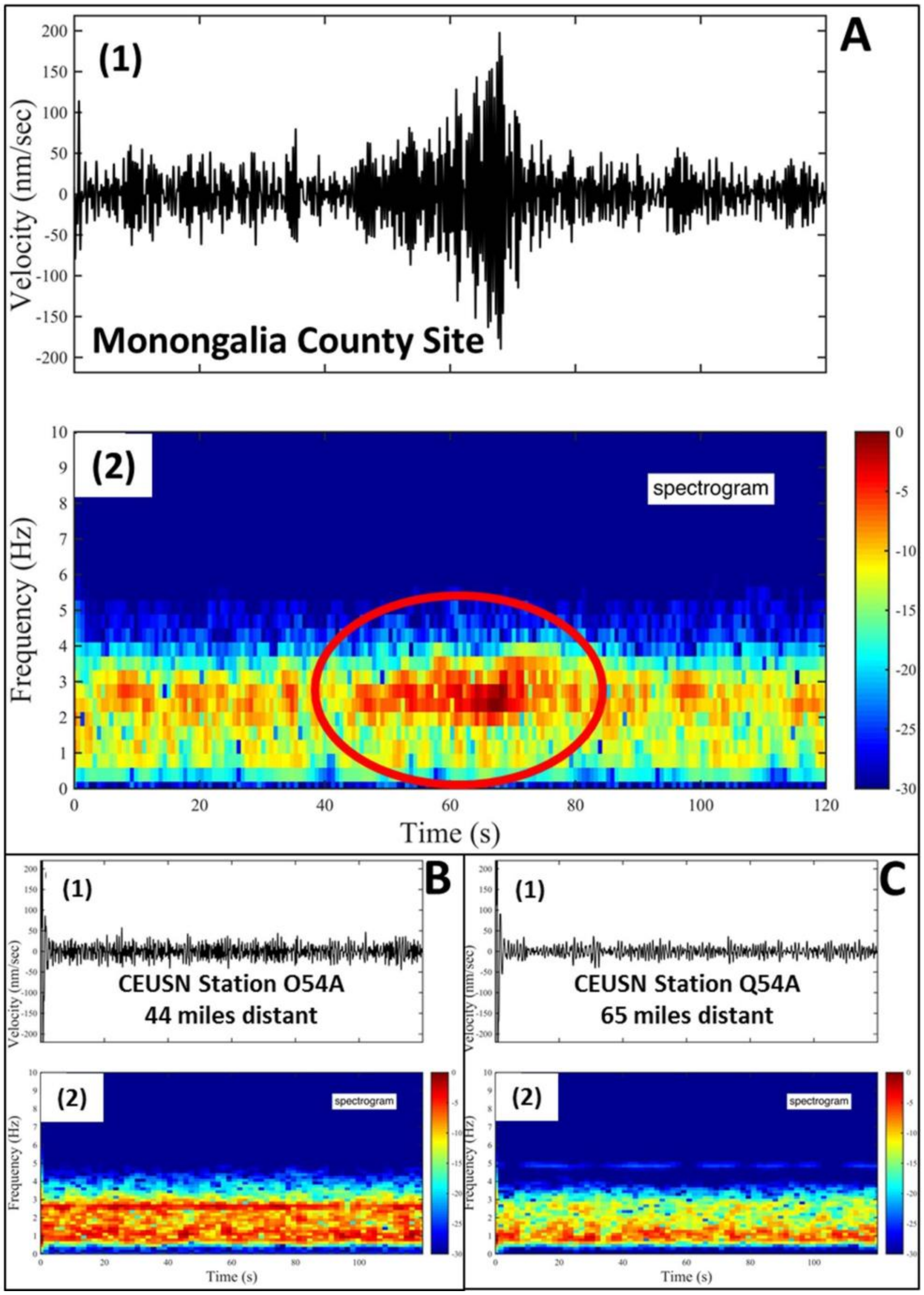

Figure6. Stacked seismic traces (panel 1) and spectrogram plots (panel 2) of (A) a long duration event recorded at MSEEL site from treatment well 3H (B-C) Central and Eastern United States Network (CEUSN) data recorded at O54A and Q54A respectively for similar timeframe as used for panel A

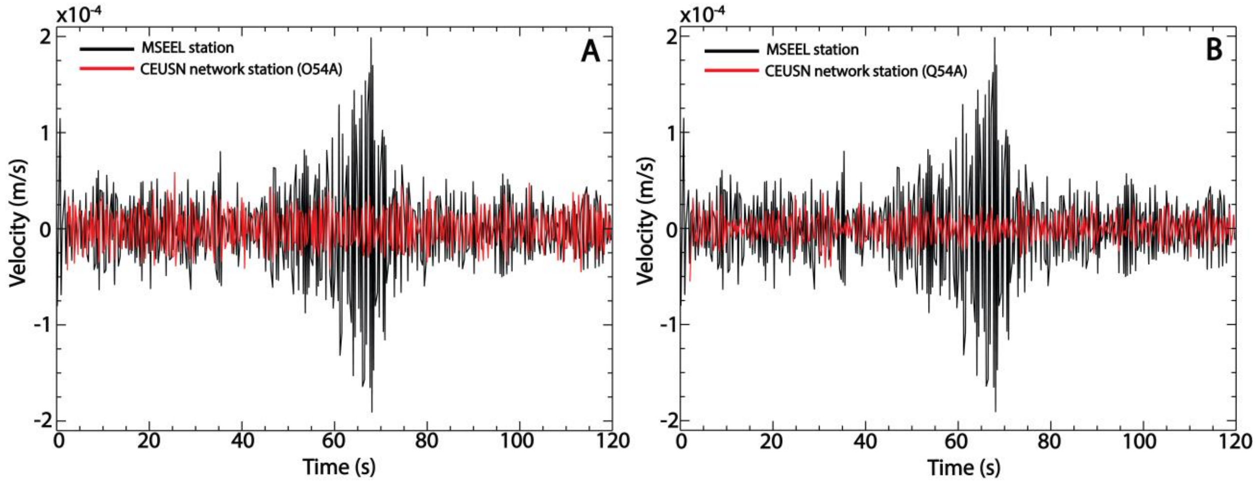

Figure7. Stacked seismic traces showing the waveform comparison of a LPLD event recorded at MSEEL site (black trace) and CEUSN data (red trace) (A) at O54A station (B) at Q54A station. This is the same LPLD event as shown in Figure 6 (A). The timeframe for both MSEEL stations and CEUSN stations is same

Our attempt of finding a temporal correlation, if any, between the time of occurrence of LPLD events and variation in the pumping parameters reveals that LPLD events mainly occur during the pad and proppant phases of pumping, when pumping pressure and pumping rate are plateaued at their maximum (Figure 8). This is similar to the previous observation of Das and Zoback (2011) for the hydraulic fracturing of Barnett Shale and associated LPLD events. As suggested by Das and Zoback (2011) and Zoback et al. (2012), LPLD events during hydraulic fracturing are triggered by shear deformation along sub-optimally oriented natural fractures by an exceptional increase in pore pressure. Our observed correlation between the time of occurrence of majority of LPLD events and increased pumping pressure and rate is therefore logical given that the maximum pore-pressure perturbation is likely to correlate with the maximum pressure and rate.

How to maximize the effects of reservoir stimulation for better access to hydrocarbons is still a looming question even after 80 years of operational history of hydraulic fracturing technology. This is in most part related to the complexity of the geomechanical response of the reservoir during hydraulic fracturing, to which a clear understanding is still lacking. This incomplete realization of reservoir response adversely affects the recovery efficiency of oil and gas from the unconventional shale reservoirs. A recent study by Boroumand and Eaton (2012) that focuses on the energy budget estimate during hydraulic fracturing, clearly highlights the energy deficiency based on the microseismicity alone. This also suggests that the expected production of oil and gas and SRV estimate, based on the microseismicity alone, is perhaps an underestimate. To reduce the gap in the energy budget or estimated production, other deformation mechanisms (non-brittle deformation) need to be taken into account. We attempt to highlight the contribution of non-brittle deformation and associated LPLD events to reservoir productivity by comparing the production contribution per stage from well 3H to the observed frequency of LPLD events during hydraulic fracturing, as discussed in the method section. There are several cycles of high and low production that indicate a significant variation in the overall production of 28 different stages for well 3H (Figure 9). We observe correlation between the stage-by-stage gas production and the frequency of LPLD events recorded during stimulation. We do notice some mismatch between peaks in production and peaks in the LPLD count, likely due to uncertainty in the location of LPLD events. Though the LPLD may have occurred during a particular stage, the actual stimulated volume of rock may be closer to an adjacent stage. This correlation between the occurrence of LPLD activity and production data strongly suggest a significant contribution from non-brittle deformation in the SRV, which ultimately correlates with early-life gas production. We can use this correlation between production data and surface seismic observation to make better completion strategies and stimulation designs for other prospective projects in future.

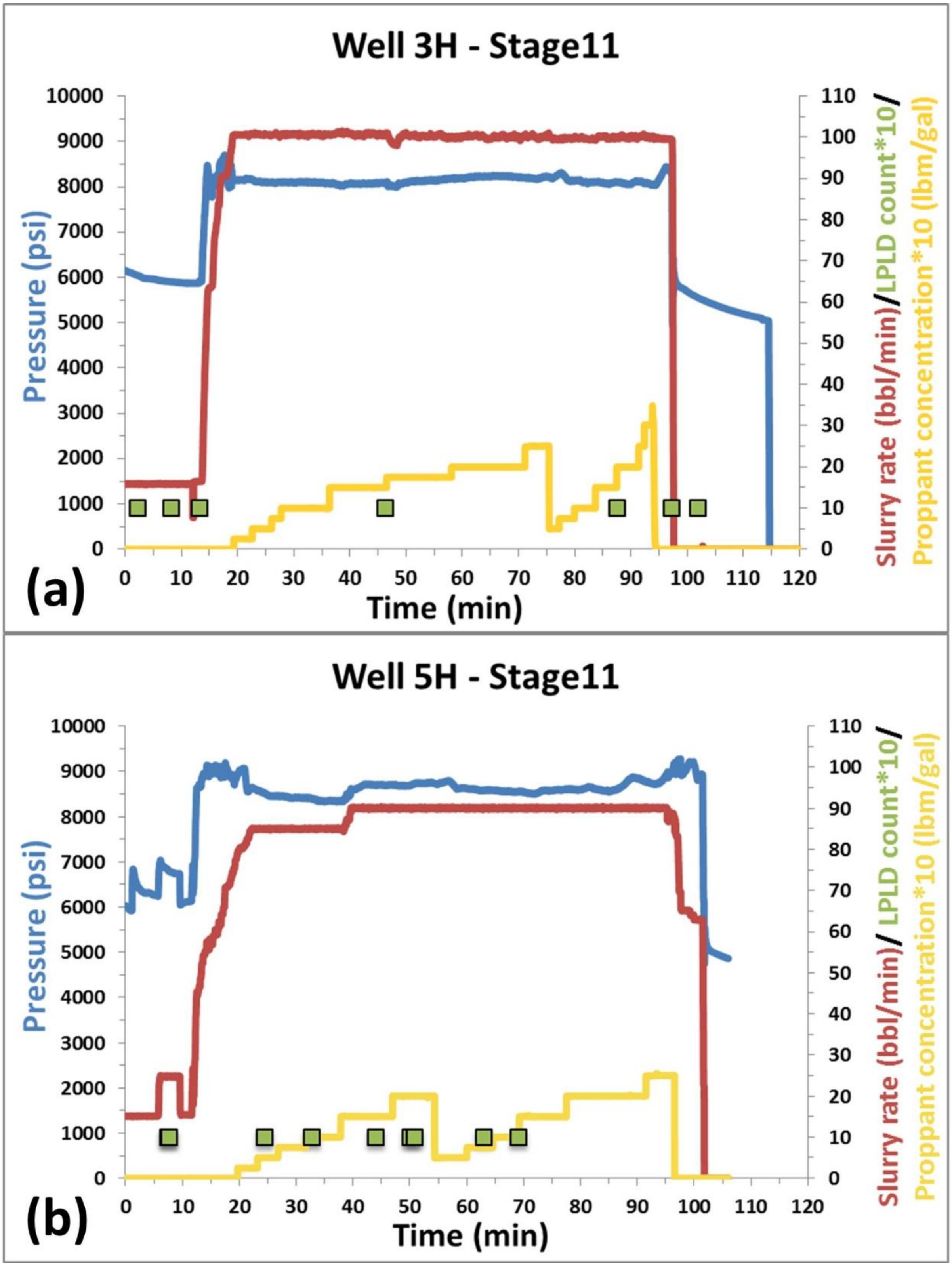

Figure8. Comparison between frequency of occurrence of LPLD events and injection parameters. Long duration events are shown as green rectangles for stage 11 of wells 5H and 3H, with solid lines representing surface pressure recording (blue), slurry rate (red), and proppant concentration (yellow)

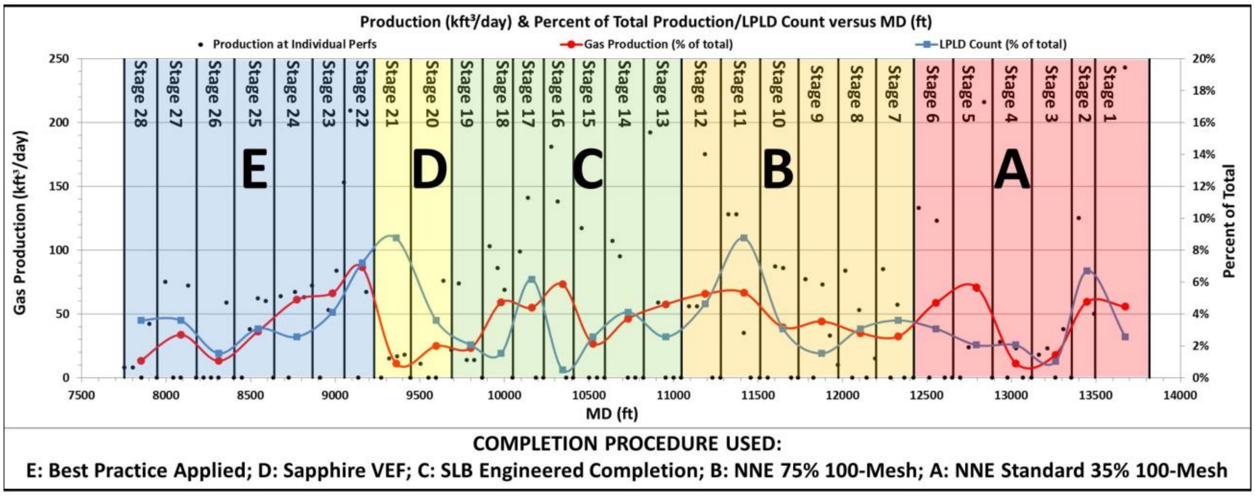

Figure9. Comparison between relative production contributions per stage (red curve) from well 3H to the frequency of occurrence of observed LPLD events (blue curve)

Conclusions

We present new 3-component surface seismic data collected during the hydraulic fracturing of horizontal Marcellus Shale wells in Monongalia County, West Virginia. We observed seismic events with waveform characteristics varying from impulsive to emergent, with high and low frequency content, respectively. We found an excellent spatial correlation between coal mining areas and impulsive events with waveform characteristics similar to a mine blast. These events are likely related to mine roof collapse and other mining related activities in the nearby region. We also noticed a linear cluster of impulsive events in Monongalia County that aligns with the western flank of Chestnut Ridge Anticline and close to an active wastewater disposal well in this proximity. This distant cluster of seismic events is perhaps related to the reactivation of basement faults triggered by disposed fluids and/or small-scale crustal deformation in this tectonically complex portion of the Central Appalachians. Most seismic events exhibit waveform characteristics similar to long period, long duration (LPLD) events previously observed in the Barnett Shale, Texas. These events are characterized by emergent waveforms with no clear arrival of the body wave (P and S) phases. We observed a significant difference in the power spectral peaks before and during hydraulic fracturing. This suggests a significant contribution of energy from the low frequency signal during stimulation. Spectral characteristics of these LPLD events are similar to those observed in Barnett Shale, but differ in terms of frequency content, having lower dominant frequencies. This difference in spectral content is likely due to attenuation of higher frequency component from the seismic signal as it covers a longer travel path to the surface seismometer. During various stages of hydraulic fracturing, LPLD events were found to occur most frequently when the pumping pressure and rate were at maximum values. These observations suggest that long period, long duration events are generated in response to highly elevated fluid pressure. We also noticed a positive correlation between the variations in LPLD counts and the stage-to-stage production for one of the two laterals suggesting a significant contribution from the non-brittle deformation in the reservoir stimulation and early-life gas production.

Disclaimer

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