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Detection of the Long Period Long Duration (LPLD) Events in Time- and Frequency-Domain

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Abstract

Long Period Long Duration (LPLD) signals are unusual seismic events that can be observed during hydraulic fracturing. These events are very similar in appearance to tectonic tremors sequences, which were first observed in subduction zones. Their nature is not well known. LPLD might be related to the productivity of the reservoir. Different methods of the LPLD events' detection recorded during hydraulic fracturing are presented. The author applied two methods for LPLD detection – Butterworth filtering and Continuous Wavelet Transform (CWT). Additionally, a new approach to LPLD events detection – instantaneous seismic attributes – was used, common in a classical seismic interpretation but not in microseismic monitoring.

Key words: Long Period Long Duration (LPLD), microseismicity, microseismic monitoring, hydraulic fracturing, shale gas.

1. INTRODUCTION

The acronym LPLD comes from Long Period Long Duration events, which means that they last more than 10 s (from 10 to 100 s). LPLDs have significantly longer durations than microseismic events (usually from 0.1 to 1 s). Their frequency bandwidth is 10 to 80 Hz, but can be specified as lower than

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80 Hz, due to the fact that it is hardly possible to obtain any information from frequencies below 10 Hz (geophones with natural frequency of 10-15 Hz are usually used). LPLD events were registered during hydraulic stimulation in various geological settings, and it is possible that the formation properties have a role to play in the frequency content of these signals (Das and Zoback 2013). According to previous studies dedicated to these unusual seismic signals (Das and Zoback 2011, 2013), they are similar in appearance to tectonic tremor sequences. Tremor sequences were first observed at active volcanoes and reflect the internal dynamics of the volcanic system (Chouet 1996). Long-period signals and tremors have the same temporal and spectral components, differing only in duration of events (Chouet 1996). The possible source of this kind of tremors is flow-inducted oscillation in channels transporting magmatic fluid. Nonvolcanic seismic tremors with long-duration seismic signals with no clear *P* or *S* waves were also observed in subduction zones. Their occurrence associated with subduction in southwest Japan as well as their potential shear slip mechanism have been particularly widely described (Obara 2002, Shelly *et al*. 2006, Nadeau and Guilhem 2009). Low-frequency earthquakes (long-period events) occur not only around active volcanoes, but also in different tectonic contexts compared with subduction zones near active fault systems. Nonvolcanic tremor sequences were observed after two strong earthquakes on the Cholame segment of the San Andreas Fault and near Monarch Peak, Lonoak, California (Nadeau and Guilhem 2009). Considering the long duration and the mobility of tremor activity, the generation of tremors may be related to the movement of fluid in the subduction zones (Obara 2002). Another possibility is that tremor is generated directly by slow shear slip on the plane interface, and under this hypothesis, tremor is the weak seismological signature of slip that is otherwise too slow to generate detectable seismic waves (Shelly *et al.* 2006).

The example of LPLD events, recorded during hydraulic fracturing is shown in Fig. 1 (Das and Zoback 2011); the data come from the fracturing experiment which took place in Barnett Shale reservoir. The events themselves are complex but coherent, which means that their appearance is visible from trace to trace (they are recorded by closely located receivers in monitoring wells), but they also show inner diversity (complexity). The fundamental criterion for classification is that *P* and *S* arrivals cannot be resolved. Sometimes small micro-seismicity (classical microseismic events) occurs within LPLD sequences, but whether they are causal or coincidental is not known. Originally, microtremors or simply tremors were observed in subduction zones and on the slopes of volcanoes. Their source was not defined and many hypotheses were proposed. LPLD events are similar to those signals from subduction zones but their frequency range is different. Micro-

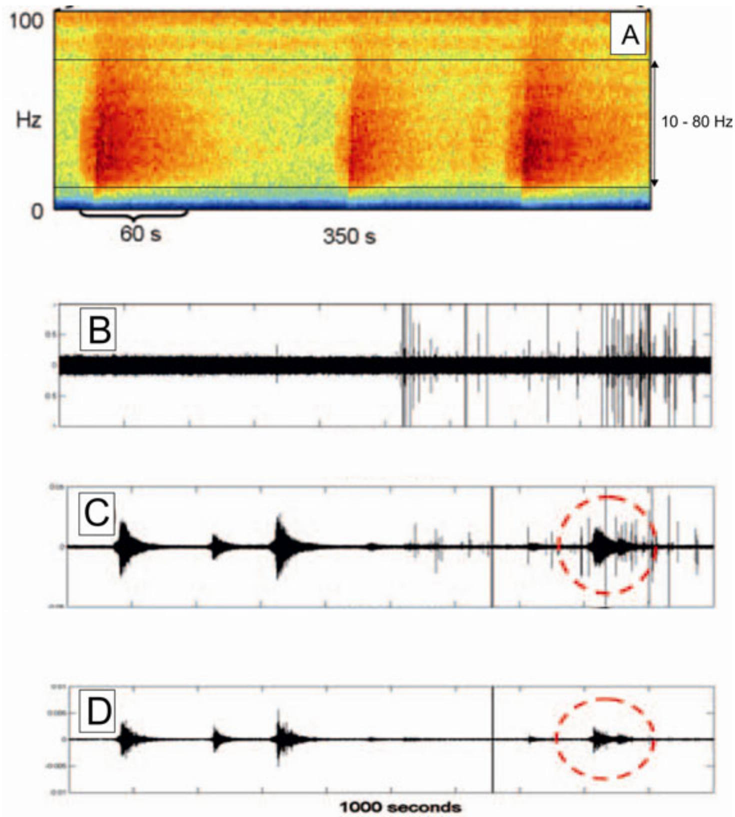

Fig. 1. (A) LPLD events observed below 100 Hz with the extended time scale, (B) original seismogram from stage 8 of simulfrac experiment, (C) signal after band-pass filtering from 10-80 Hz, and (D) signal obtained after wavelet decomposition and reconstruction. Red dotted circles in (C) and (D) show the difference between two methods (Das and Zoback 2011).

tremors are defined for low frequencies – to 10 Hz, whereas a much higher range is characteristic of LPLD events. The amplitudes of microtremors are very similar, displacements are in order of 10^{-4} to 10^{-2} mm (Okada 2003). Although they are very weak, they represent a source of noise for researchers earthquake seismology (Okada 2003). The most significant similarity is that both LPLDs and microtremors occur in swarm-like groups and are coherent (Das and Zoback 2011).

During stimulation of tight hydrocarbons through hydraulic fracturing, it is assumed that the volume of the reservoir corresponds with the volume where microseismicity occurs. Nowadays, microseismic monitoring in order to investigate deformations inside the reservoir records microearthquakes that are related mostly to the brittle failure (Tary and van der Baan 2012). However, a comparison of orders of magnitude of the energy injected into the system with the energy recorded during microseismic monitoring does not account (Maxwell *et al.* 2009). Therefore, not the whole energy produced during hydraulic fracturing causes microseismic events. We can make an assumption, which is intuitive, that part of this energy is involved in different "activity of the reservoir". LPLD events can be understood as representation of another, very interesting process which is present during the stimulation of the shale or tight gas reservoirs.

One of the possible explanations of the LPLD events source is a reactivation of pre-existing faults (shear events), which have been formed naturally in the shale gas reservoirs. The main aim of hydraulic fracturing is to stimulate the productivity of the reservoir enhancing the permeability and creating additional flow paths for hydrocarbons. We cannot tell whether these flow paths are new tensile fractures created during hydraulic fracturing or reactivated, pre-existing features. It is commonly believed that new fractures are the main channels for reservoir fluids, but another hypothesis which is connected with pre-existing faults is also possible. Supposing that the productivity of the reservoir is at least partially correlated with the shearing on pre-existing features, and if the LPLD microseismic events are linked to this phenomenon, they will require further analysis.

The first step, which is the subject of this article, is to detect LPLD events and separate them from other microseismic signals. Once LPLD events are distinguished, a further analysis will be possible.

2. METHODS

The goal in microseismic data processing, in general, is to increase signal to noise ratio. There are many ways to achieve this, and one of them is analyzing the signal in joint time-frequency domain. The frequency domain is a good environment for signal analysis. The representation of time series in the frequency domain often illustrates many features difficult to visualize in the time domain. The manner in which the time series is mapped into the frequency domain determines the amount of new information that can be obtained (Chakraborty and Okaya 1995). The change of domains is possible through Fourier Transform. Apart from the basic Fourier Transform (performed with Fast Fourier algorithm), the decomposition of signal into its frequency components is possible with the use of different decomposition algorithms (Castagna *et al*. 2002, Castagna and Sun 2006, Kumar and Foufoula-Georgiou 1997, Chakraborty and Okaya 1995). Continuous Wavelet Transform is based on the concept of time-scale analysis and has two advantages over the others. Firstly, it keeps good resolution for high and low frequencies because the length of the window depends on the frequency of the original signal. Secondly, frequency is proportional to scale (Castagna and Sun 2006) which means it contains the same information and its results can be freely comparable with common spectral analysis.

Downhole recorded microseismic data were pre-processed and a band-pass filter was applied. After filtering, three procedures were applied separately (each on the previously filtered data set). The first was instantaneous frequency (IF) which is related to the centroid of the power spectrum of the seismic wavelet (Taner 1992). The algorithm is based on the classical method presented in 1979 (Taner *et al.* 1979). The program can be found at: www.seismicunix.com/w/Suattribute. IF indicates where the "center of mass" of the spectrum is. IF illustrates lateral continuity of a waveform character and is independent of amplitude (Chung 1994). This property of IF is useful for LPLD detection in microseismic data. The output is a scalar value, so its results can be easily interpreted. Applying IF had mainly experimental value. This particular attribute was used, because instantaneous frequency should reveal changes in frequency, especially its increases. Also, the application of IF is straightforward and is not time-consuming.

Second and third procedures involved using CWT. In SeismicUnix this procedure can be performed in more than one way (Stockwell 2008). Two different approaches were used. CWT is especially useful for time series which are considered to be non-stationary. Non-stationarity means that all their parameters, including frequency, vary with time. Because of that fact, seismograms whose spectral content vary significantly with time required not-standard methods of decomposition. CWT provides such a method (Chakraborty and Okaya 1995, Castagna and Sun 2006). The mathematical formula for CWT is shown in the following equation:

$$C(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} f(t)\varphi\left(\frac{t-b}{a}\right)dt\ .$$

The output C is a wavelet coefficient which is a function of scale (a) and translation (b). Translation can be understood as a position in time, changing from $t=0$ to the end of the seismogram. $f(t)$ is the original seismic trace and $\varphi(t)$ is the so-called "mother wavelet", which can be understood as a second signal of different parameters (for instance, Ricker wavelet, Haar wavelet, *etc.*). Frequency is reversed to the scale: low scale a ("shrinked" wavelets) means compressed wavelets, hence, able to reveal rapidly changing details (high frequencies); high scale a means stretched wavelets, able to show slowly changing course features (low frequencies).

A choice of wavelet seems to be of paramount importance. Morlet wavelet is very popular for CWT because it is very similar to a seismic trace (Tary and van der Baan 2012), but other types are also used. In SeismicUnix only three wavelets are defined: 2nd derivative of Gaussian function, 4th and 6th (which are commonly called "Mexican hat", "Witch's hat", and "Wizard's hat"). For computation "Mexican hat wavelet" was applied.

The first approach of applying CWT was based on the following parameters:

- wavelet type: "Mexican hat",
- number of decomposition levels: 201 (changing from –1 to 1 with step 0.01),
- filter base: 10.

The second approach:

- wavelet type: "Mexican hat",
- number of decomposition levels: 20 (changing from –1 to 1 with step 0.1),
- filter base: 2 (so-called "diadic scalling").

3. STUDY AREA

The data set consists of borehole data. Seismic monitoring was conducted in Barnett Shale reservoir in Texas; it was a different stimulation than that analyzed by Das and Zoback (2011, 2013). During the analysis, data from one stage of fracturing were closely studied and the procedure described earlier was applied to the whole record (approximately 5 hours of recording).

The target formation of the reservoir stimulation was Cline formation (the Lower Wolfcamp formation) in the Midland Basin. The Midland Basin is one of three sub-basins in the Permian Basin along with the Delaware and the Central Basin Platform. The lower Wolfcamp is of Pennsylvanian-aged (upper Carboniferous) organic rich shale with interbedded silt and sand. There is no direct information about natural fractures in the Lower Wolfcamp Formation, but we do have some information about fractures in the Spraberry which overlays the Wolfcamp Formation. The fractures of NE-SW directions were found in cores in the Spraberry Formation. The horizontal cores from sandstone-siltstone reservoirs in this formation have documented two systems of dramatically different yet dynamically compatible natural fractures (Lorenz *et al*. 2002).

Northeastward-directed Laramide compressive stress has been suggested to be the source of much, if not all, of the minimal, post-Permian structural deformation and fracturing in the Permian basin. The present-day stresses, significant in terms of fracture conductivity, are still generally aligned with this trend (Lorenz *et al*. 2002). It is possible that these fractures also exist in the Wolfcamp formation, but is not guaranteed. Moreover, the examination of vertical cores suggest that natural fractures in the Spraberry Formation are commonly extended by hydraulic processes associated with drilling and coring, obscuring the differentiation between natural and inducted fracture and complicating fracture interpretations (Lorenz *et al*. 2002).

4. RESULTS

In the data set from one stage of downhole monitoring, 5 LPLD-like events were interpreted. The author presents two of them. The results are shown in Figs. 2 and 3. On the left hand side at the top (Fig. 2A), there is one file after filtering. The file consists of 43 traces; their numbers are displayed on the horizontal scale. The first trace is the calibration trace, then 42 traces follow. Geophones which were used for the recording were 3 components (3C) with a nominal frequency of 15 Hz. As a result, every three traces is a record from one geophone only (vertical component and two horizontal components). In the middle (Fig. 2B), there is a single trace, number 29, which is vertical. On the right hand side at the top (Fig. 2C) there is corresponding instantaneous frequency applied to the file from the left. In Fig. 2D a decomposed signal is visible. It is a decomposition of 29th trace after applying the first approach. Each trace in Fig. 2D is one level of decomposition (so one frequency from the whole spectrum). The left hand side corresponds to lower scales and keeps information about high frequency content, whereas the right hand side about low frequencies. The area of interest is marked with the purple arrow (Fig. 2A and B). The length of this event is approximately 100 s and is visible after filtering as well as after applying IF and CWT. IF shows stronger pattern across the array, even for areas where filtering alone seems to have weaker results. CWT helps to investigate how amplitudes vary with frequency and time. It is also a good tool for determining coherency. The second approach of CWT (Fig. 2E), with the use of dyadic scaling, shows similar results. Moreover, it helps to check the level of inner complexity and variability of an LPLD signal. This property of CWT is very helpful in determining whether the signal can be named as an LPLD event by checking if *P* and *S* arrivals can or cannot be resolved. Figures 2A-E show that it is impossible to separate *P* and *S* arrivals, so the signal is most likely to be classified as an LPLD event. Comparing this signal to the signals recorded during hydraulic fracturing it has extraordinary duration and is quite unique.

In Figure 3 another LPLD-like event is presented. A typical pattern is visible after filtering (Fig. 3A), IF (Fig. 3C), and CWT (Fig. 3D and E). For decomposition also 29th trace was used. In this case, also two approaches of CWT are presented – one with 201 levels of decomposition (Fig. 3D) and the other with dyadic scaling and 20 levels of decomposition (Fig. 3E). The difference between these two approaches lies in the level of details that can be revealed. The decomposition with 201 levels provides more details, and more features that are present in the signal. The event presented in Fig. 3 lasts for approximately 20-30 s; it is much shorter than the one presented in

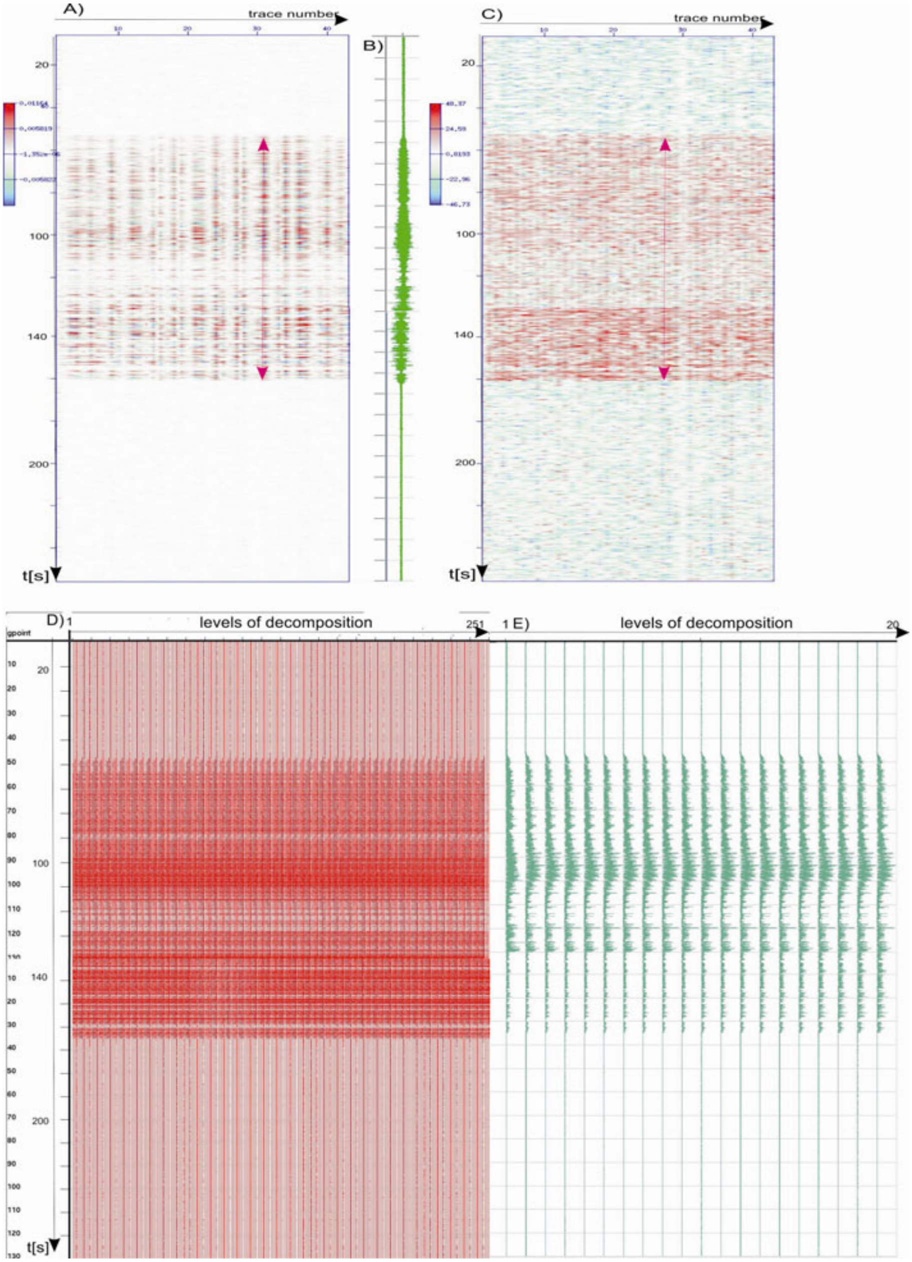

Fig. 2: (A) File after Butterworth band-pass filtering (filter parameters: (11|16|76|79)), (B) 29th trace (vertical component after the same filtering), (C) file after applying instantaneous frequency, (D) 1st approach of CWT, and (E) 2nd approach of CWT. The LPLD event is marked with the purple arrow – (A) and (C).

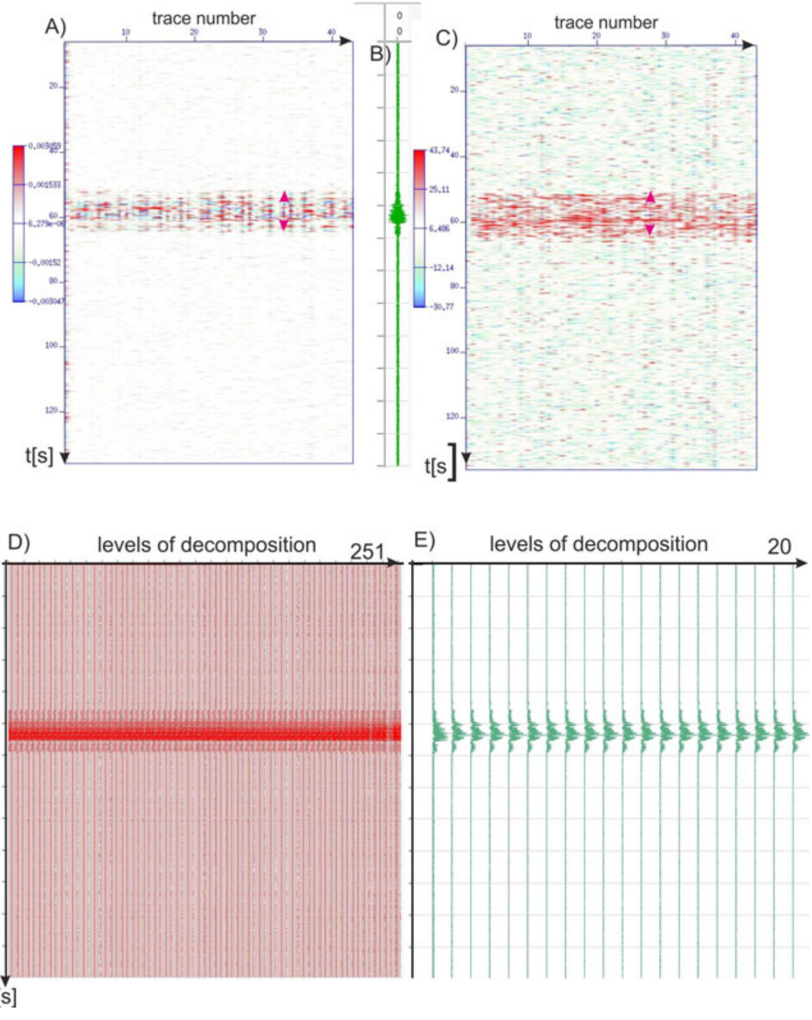

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Fig. 2. It is visible clearly by applying Butterworth filtering; however, its beginning and end can be estimated more precisely for sections after instantaneous frequency and spectral decomposition. The event is coherent across the array and similar pattern is recorded on every trace. CWT is also a good tool for searching microseismic events. After applying CWT, the microseismic events are also visible as straight lines across the array.

5. DISCUSSION

An approach which was originally proposed by Das and Zoback (2011) was applied to the data but with one significant change. Only forward continuous wavelet transform was used, and no reconstruction of the signal was made. This method makes it possible to look carefully on the signal within an LPLD sequence. This approach seems to be valuable, especially if it is not fully understood how the mechanism of LPLD works and what the main source of these events is. CWT reveals many features, which are not necessarily visible in the time domain. Analyzing trace by trace after decomposition makes it possible to determine lateral variability of the event and its coherency. According to the author's opinion, forward CWT gives more information about the character of the event (compare Figs. 1D, 2D-E, and 3D-E). Moreover, by applying CWT it was possible to separate LPLD-like signals from those that at first looked like LPLD but in fact they were not. This was done by indicating *P* and *S* arrivals that were clearly visible after decomposition and not visible on signals after filtering or IF.

Instantaneous frequency is a common and basic attribute that is used almost in every 2D or 3D seismic interpretation, even though it is not popular among seismologists. Microseismic event detection and location are more close to seismology than to seismics, hence seismic attributes are not the "weapon of choice". Applying IF was treated as kind of experiment, which yielded relatively good results. LPLD-like events are characterized by sudden increase of IF. Hence, the source of LPLD events may be connected with the reactivation of preexisting faults, *i.e.*, many microseismic events (micro-earthquakes) that take place on a fault plane. Nevertheless, IF results are not sufficient to determine the LPLD event mechanism. Their long durations as well as their broadband spectra give reasons to believe that these events are closer to shear events, like tectonic tremors (Shelly *et al.* 2007) than fluid-driven events, like volcanic tremors (Chouet 1996), even though fluids must play a role in their generation. In the overall tectonic context LPLD events and tremors are closely related and very difficult to distinguish one from the other (Chouet 1996). If a given explanation is relevant to LPLD event mechanism, we shall observe an increase in instantaneous frequency. Instantaneous frequency results for this case are considered to be good, but do not give many details about the nature of the LPLD signals. The only information is that a rapid increase in frequency is observed, so the application of IF is limited.

Time-frequency analyses are particularly well-suited for the study of long-duration, non-stationary phenomena that may take place inside the reservoir (Tary and van der Baan 2012). Applying different transforms which make it possible to analyze signal in a time-frequency domain can reveal new phenomena. The one that may also be somehow connected to LPLD events occurrence is resonance. Resonance seems to be almost the basic kind of signal which exist naturally and, moreover, can be created during the process of injecting fluid into the reservoir. Resonance frequencies can be generated by source, path, or receiver effects. Each effect has to be considered separately to determine the origin of particular resonance frequency (Tary and van der Baan 2012). Even though geophones which are used for microseismic monitoring are deployed in a boreholes, the design of a borehole itself and the presence of geophones also produce resonance frequencies (Sun and McMehan 1988, St-Onge and Eaton 2011). Before reaching the receivers, resonance frequencies can also be produced along the raypath (Tary and van der Baan 2012). This is connected, *e.g.*, with interference of waves, multiple wave scattering, influence of the near surface, low velocity layer. Additionally, resonance can be created by fractures and flowing fluid themselves. This resonance is connected with source-side effects. Because the source of LPLD events has not been clearly defined yet, it is possible that they are related to the resonance which is present in the reservoir. However, resonance is not very likely to be the direct source of LPLD events. LPLD events are characterized by broad-band spectra, whereas resonance is usually characterized by narrow-band spectra. It probably indicates that the causal mechanism is different in these two cases; nevertheless, the phenomena may still be related somehow. To test this idea, further analyses of their inner variability have to be applied. As can be seen from the examples, CWT helps to study the LPLD events structure, so it might be a good tool for distinguishing the source of these events.

The integration of microseismic monitoring with seismic data seems to be an overriding matter. Such analyses are not widely used because of high costs, and also because it is not common for gas companies to share their seismic data with a monitoring company (usually not the same). The advancement in seismic analyses, and the usefulness of various seismic attributes, might contribute greatly to the analysis of the signal recorded during hydraulic fracturing. In the case of LPLD events such a concept may be extremely useful, especially if their sources are pre-existing faults. Such a research would be of paramount importance.

6. CONCLUSIONS

Instanteous frequency seams to give reasonable results and its interpretation is straightforward and easy. Additionally, the computation of IF is very quick and the algorithm is well-described (Taner *et al*. 1979).

CWT results are dependent on the number of levels of decomposition. More levels reveal much more details and a more accurate analysis is possible. Microseismic events are visible after decomposition. Run times (computational costs) are extremely time-consuming and computation of CWT requires a lot of memory. The advantage of CWT is also the fact that the robust extraction of the signal of a certain scale (defined frequency) is possible. Moreover, while interpreting results of CWT we can study the whole range of frequencies at the same time.

The results of both, IF and CWT, are consistent and show a similar pattern across the array. Analyzing all traces at the same time gives significant information about the coherency of the signal.

The mechanism of recorded LPLD events is not known. The future work should focus on localizing these signals. Moreover, an attempt to integrate their localizations with seismic data may give valuable information. The author's work was dedicated exclusively to determining the occurrence of LPLD events in a given dataset.

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