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The Processing Procedure for the Interpretation of Microseismic Signal Acquired from a Surface Array During Hydraulic Fracturing in Pomerania Region in Poland.

Michał Antoszkiewicz[1], Mateusz Kmieć[1], Paweł Szewczuk[1], Marek Szkodo[1], Robert Jankowski[2]

[1]*Faculty of Mechanical Engineering, Gdańsk University of Technology, Gdańsk, Poland*

[2]*Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, Gdańsk, Poland.*

michal.antoszkiewicz@pg.gda.pl

Abstract

Hydraulic fracturing is a procedure of injecting high pressure fluid into the wellbore in order to break shell rock and facilitate gas flow. It is a very costly procedure and, if not conducted properly, it may lead to environmental pollution. To avoid costs associated with pumping fluid outside the perspective (gas rich) zone and improve one's knowledge about the reservoir rock, microseismic monitoring can be applied. The method involves recording seismic waves, which are induced by fractured rock, by an array of sensors distributed in a wellbore nearby or on the surface. Combining geological and geophysical knowledge of region with signal processing computer techniques, one can locate induced fractures allowing for real-time process monitoring and rock properties evaluation. In Poland perspective shell formation is located very deep, i.e. about 4km from the surface. Additionally overlaying rock formations strongly attenuate and disperse seismic waves. Therefore, signal recorded by a surface array of sensors is very weak. Signal from a seismic event can be orders of magnitude lower than noise. To recover signal connected with fractured rock one needs to use numerical methods utilizing coherence of signals. An example of such a computer procedure is presented in this paper.

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Keywords: microseismic monitoring, surface array, stacking algorithm

1 Introduction

Hydraulic fracturing is one of the key procedures in search for shale gas. It involves high pressure fluid injection, which breaks impermeable rock formation and allows gas to flow to the wellbore (King, 2012; Montgomery et al., 2010). The procedure is very costly, as it involves usage of high pressure high

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flow rate pumps. Therefore, it is of great interest to develop a reliable method for monitoring of fractures propagation in reservoir rock. Such methods would prevent from fracturing outside the perspective region, which leads to unnecessary costs and may lead to ground water pollution (Arthur et al., 2008; Osborn, Vengosh, Warner, & Jackson, 2011). One of the methods, providing deep insight into fracturing process is microseismic monitoring (Calvez et al., 2007). It utilizes an array of seismic sensors (geophones/hydrophones) that record ground vibrations induced by fractured rock formations. The sensors can be placed in a nearby wellbore or on the surface (Eisner et al., 2010). The signals are recorded during and after hydraulic fracturing process. The recorded data is processed for seismic event detection and localization.

The most basic procedure for seismic signal interpretation requires manual picking of wave arrivals on individual recordings. After precise measurement of wave arrival times, one can use Geiger's method to locate events (Geiger, 1912). To account for sensor measurement uncertainty, probabilistic methods might be used (Lomax, Virieux, & Volant, 2000). When one uses multiple recorders, uncertainty of location, caused by first arrival picks errors and inaccurate velocity model, can be reduced by methods based on signals cross-correlation, double differencing or joint hypocenter determination (Frohlich, 1979; Waldhauser & Ellsworth, 2000).

For automatic and real time applications, seismic signal should by picked in individual traces by appropriate algorithm. One of the most basic solution to that is usage of STA/LTA (Short Time Average/Long Time Average). It consists of computing ratio of short time signal average to long time signal average and applying threshold (Allen, 1978). Different approaches utilize envelope function (Baer & Kradolfer, 1987),detection of abrupt changes in signal parameters e.g. (Coppens, 1985; Sabbione & Velis, 2010) and wavelets (Rodriguez, 2011).

Microseismic events are usually orders of magnitude weaker than earthquakes that destroy buildings (Falborski & Jankowski, 2013; Jankowski, 2015; Jankowski & Mahmoud, 2015, 2016; Naderpour, Barros, Khatami, & Jankowski, 2016). Additionally gas perspective shale formation in Poland is located at the depth of about 4 km and overlaid with highly attenuating layers. This renders huge problems in distinguishing seismic signal from noise on a single record as usually signal to noise ratio is smaller than 1.

Such circumstances call for undertaking special numerical approach that would benefit from signal coherence. Those algorithms are mostly based on Kirchoff migration (Baker, Granat, & Clayton, 2005; Gray & May, 1994). The principle of operation of such algorithms is based on stacking of records from multiple receivers. Before stacking, wave travel times from discretized underground to each receiver are computed. This allows for appropriate time-shifting of signals before stacking.

For the data acquired during microseismic monitoring in Poland, diffraction stacking algorithm was used (J. Gajewski, Anikiev, Kashtan, Tessmer, & Vanelle, 2007). The principles of this computer procedure are described further in this paper.

2 Wellbore Location and Monitoring Configuration

Pomerania region in Poland was the region of operation. Horizontal part of the wellbore is at the depth of about 4km. It is drilled through Ordovician strata. It is overlaid with formation problematic from the seismic point of view, i.e. Cenozoic strata with very low wave propagation speeds and high attenuation and anhydrites sand salts which distort and refract seismic signal.

12 thousand geophones were used for the research. Each 12 geophones were connected to one recording line, so that the signals from them were added and recorded as one channel. 25 of such channels were arranged in a 5 by 5 array to form a patch (see Figure 1). Each patch was distributed over the area of 90x95m. 40 of such patches were distributed within 4km radius from the projection of horizontal part of the wellbore. Organizing geophones into channels and channels into patches helps to mitigate surface noise. The locations of the patches were chosen based on the near surface layer

thickness and attenuation factor, avoiding noisy places such as roads, populated places and surrounding of the drilling pad.

There were 11 stages of fracturing in total. Each stage consisted of 6 explosive perforations and a few hours of pumping.

The geophones had a corner frequency of 10Hz. Sampling frequency was set to 500Hz. All channels were constantly recorded during the period of 10 days.

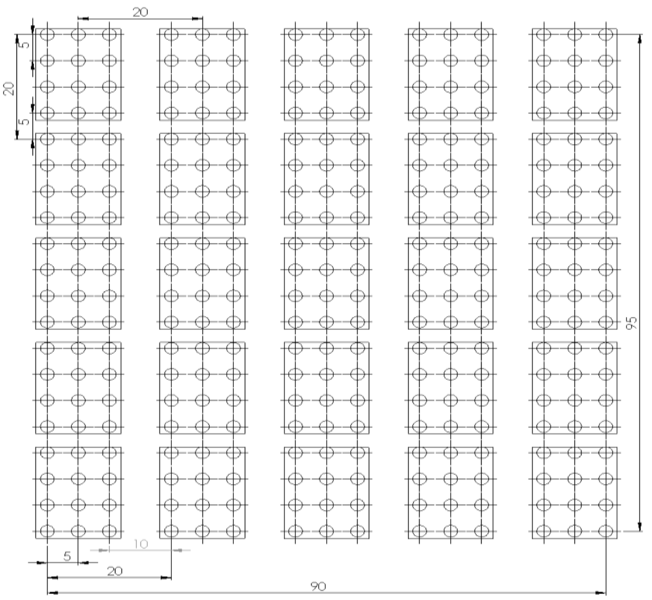

Figure 1: Arrangement of geophones and channels in single patch

3 Signal Analysis Procedure

In the first step, the noise analysis is performed. That was done by computing Root Mean Square (RMS) of signal during different periods of weekdays and on the weekends. Patches with the highest level of noise were not used in the analysis. Signals were filtered with Butterworth bandpass filter from 20 to 40Hz (higher frequencies are strongly attenuated on the way from the event source and therefore are mostly related to noise).

Next step was related to the velocity model building. For the precise seismic location, one needs a good velocity model, ideally obtained by 3D seismic method. In the case of our research, we only had 1D velocity profile obtained by seismic well logging. Velocity profile relates pressure wave velocity to depth. As the log lacked the data for near surface and for depth higher than 3700m, it was linearly extrapolated in both directions.

Next the subsurface was discretized with model grid step 25m. The size of discretized subsurface was 321x281x209 nodes. From those nodes, a subvolume was chosen, in which events are expected (around horizontal part of the wellbore). The size of this subvolume was 101x101x53 nodes (image points). Having velocity profile and spatial location of each receiver, pressure wave travel times were computed from each discrete underground location in the subvolume to each receiver.

Then, for each discrete source location in the subvolue (image point), records from all receivers were shifted in time accordingly to travel times computed in previous step and stacked (eq. 1)

$$S(x, y, z, t) = \sum_{R} A(t + t_P^R(x, y, z)), \qquad (1)$$

where S is the computed stack value for the image point (x,y,z) and origin time t, A is the recorded seismogram, $t_P^R(x, y, z)$ is the computed P-wave travel time from the source point (x,y,z) to the receiver R on the surface. For a fixed origin time t, we call this function: image function.

In the simplest case, one can add shifted signals. Some researcher suggest stacking of signal absolute values to prevent canceling out of signals with different phase, as in SSA algorithm (Kao & Shan, 2004). Others use signal envelopes stacking (Gharti, Oye, Roth, & Kühn, 2010), semblance stacking (Neidell & Taner, 1971) or STALTA stacking (Grigoli, Cesca, Vassallo, & Dahm, 2013).

The stack was created for every possible source point from discretized subsurface. For each time step t, a maximum stack value over x,y and z were found. Maximum stack was searched for events by STA/LTA algorithm with defined threshold to find event origin time, t*. When event was detected in time, the image function for all considered source points was computed by taking absolute value of the function from eq. 1 with t=t*. The event location has coordinates (x*,y*,z*) for which image function reaches its maximum value.

To further improve localization of seismic events one needs to calibrate wave velocity model. In order to do that, an event with a known location and large magnitude is needed. For this purpose explosive perforation was chosen, that could be easily distinguished on most of the records. The event corresponding to perforation was detected 1.15 deeper then it occurred. After multiplying velocity profile by 1.15, the event was detected at the right depth. More information on that algorithm can be found in (Anikiev, Valenta, Staněk, & Eisner, 2014; O. Zhebel & Eisner, 2012; Oksana Zhebel & Eisner, 2015)

4 Implementation

The algorithm was implemented in MATLAB. The stacking procedure is computationally intensive, as it requires adding 1000 records separately for every image point (540653 nodes). Therefore the stacking procedure was run in parallel on a computer cluster using 12-core Intel® Xeon® E5 processors. The algorithm scales well with the number of used cores. Computation of stack for one minute rocord (30k samples x 1000 channels) for one image point with usage of one core takes about 0.23 s. Therefore algorithm can be run in real-time by 2100 cores.

5 Results

Full seismic processing was applied only to time sections, in which downhole seismic array detected events with the highest magnitude. Calibration of the velocity model was performed with utilization of perforation shots that were recorded during periods of low noise.

The numerical results of the stacking procedure are shown in Figure 2 for an event with relatively high magnitude. First plot shows maximal value of the stack function over all image points, second plot is a result of STA/LTA filtering of the above signal and the last one shows the corresponding semblance value. Figure 3 shows image function of detected event for time, which had the highest maximum stack value. A probability density function of event location was estimated from image function (Figure 4).

6 events were detected in total from the surface array monitoring. Comparison of locations of events from downhole and surface monitoring can be seen in Figure 6 and 7.

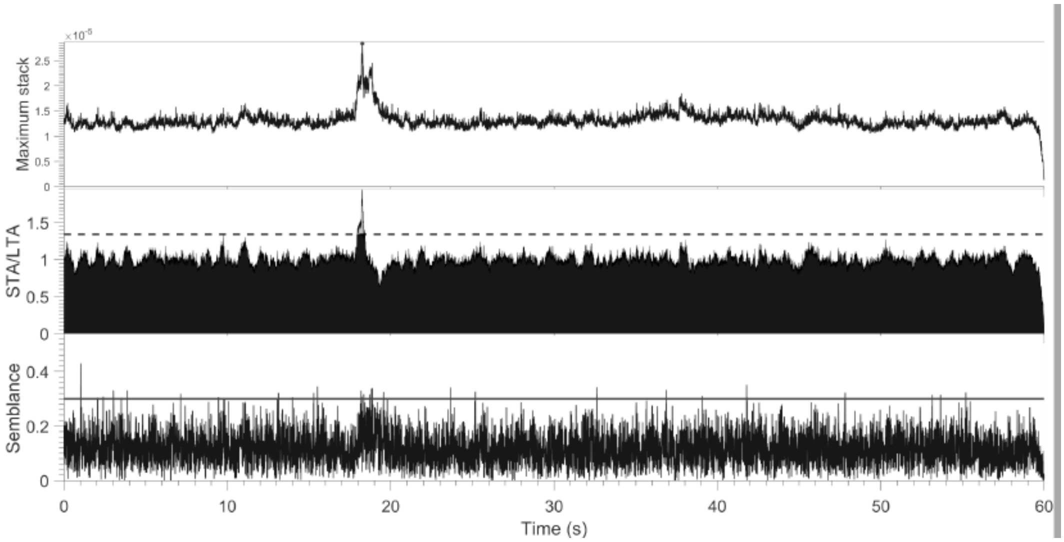

Figure 2: Stacking results

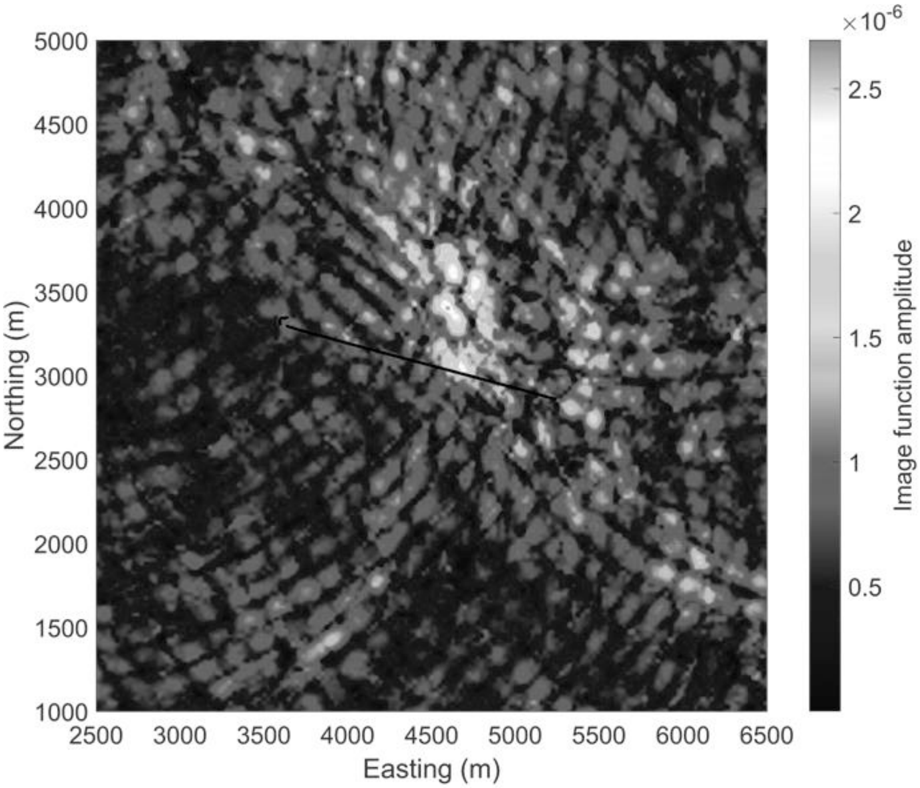

Figure 3: Spatial image funcion of detected event. Horizontal view. Black line is a trajectory of the horizontal part of the wellbore

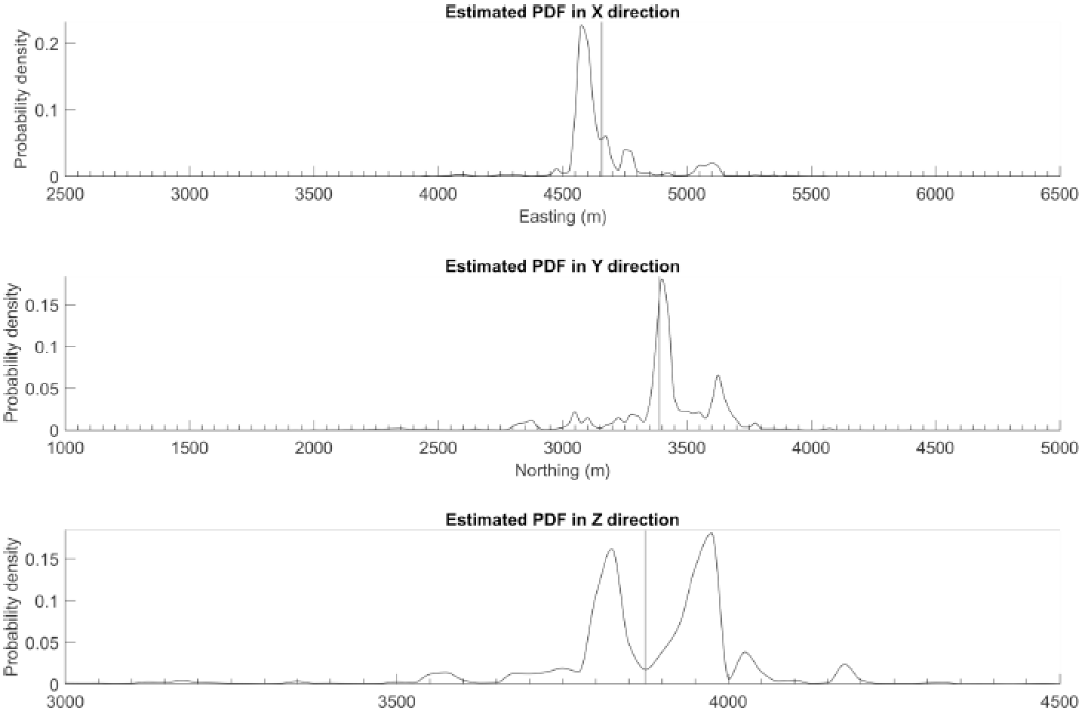

Figure 4: Probability density funciton of event location.

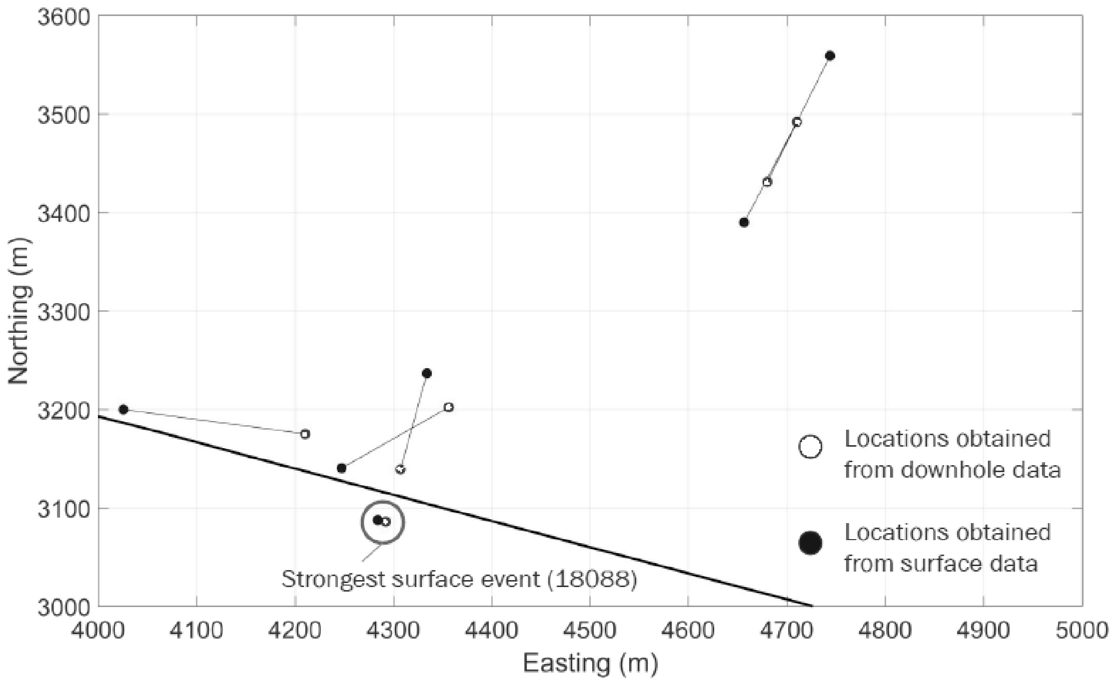

Figure 5: Comparison of 6 synced downhole and surface events (horizontal view)

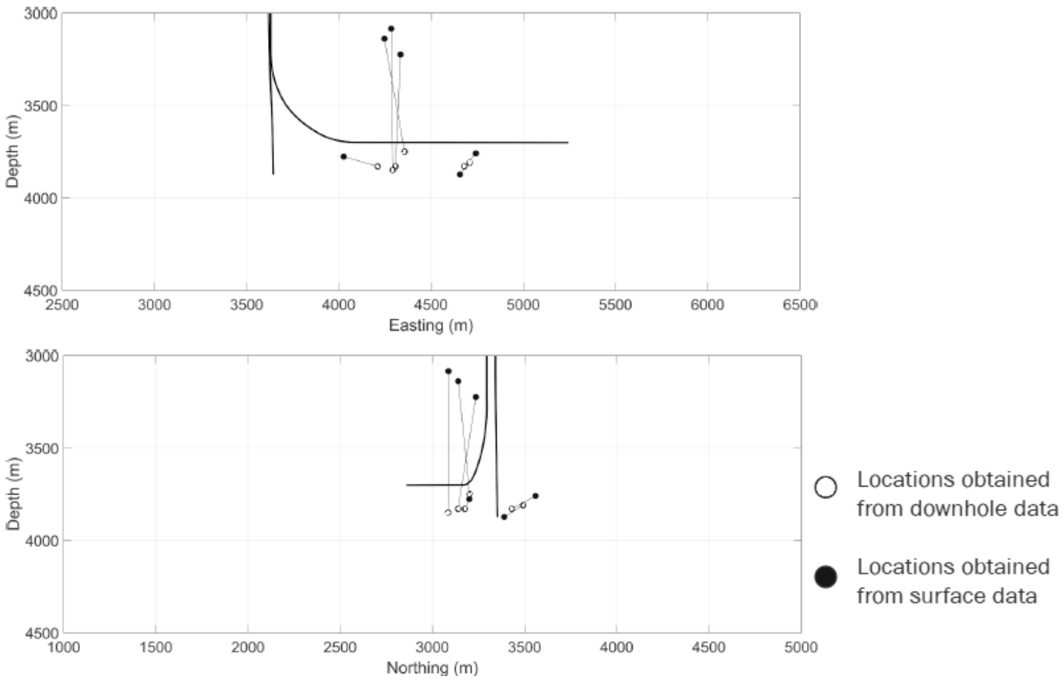

Figure 6: Comparison of 6 synced downhole and surface events (vertical view)

6 Conclusions

In total, 8 events were detected by using the computer algorithm with data obtained from the surface array. 6 detected events has strong correlation with downhole (according to origin times). Comparison of locations shows highest misfit in horizontal direction of around 200 m and 800 m in vertical direction. Horizontal misfit for the strongest event is less than 10m.

The results show that the numerical procedure applied in the study can be an efficient tool in determination of the events. Moreover, surface microseismic has been found to have some potential in Polish geological conditions although the signal to noise ratio was too high to detect reasonable number of events. Also events locations are quite disturbed. Probably using higher number of patches and 3D seismic velocity model would facilitate detection and localization.

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References

Allen, R. V. (1978). Automatic earthquake recognition and timing from single traces. *Bulletin of the Seismological Society of America*, *68*(5), 1521–1532.

Anikiev, D., Valenta, J., Staněk, F., & Eisner, L. (2014). Joint location and source mechanism inversion of microseismic events: Benchmarking on seismicity induced by hydraulic fracturing. *Geophysical Journal International*, *198*(1), 249–258. https://doi.org/10.1093/gji/ggu126

Arthur, A. J. D., Consulting, A. L. L., Bohm, B., Coughlin, B. J., Layne, M., & Ph, D. (2008). Evaluating the Environmental Implications of Hydraulic Fracturing in Shale Gas Reservoirs, (March), 1–21.

Baer, M., & Kradolfer, U. (1987). An automatic phase picker for local and teleseismic events. *Bulletin of the Seismological Society of America*, *77*(4), 1437–1445.

Baker, T., Granat, R., & Clayton, R. W. (2005). Real-time earthquake location using Kirchhoff reconstruction. *Bulletin of the Seismological Society of America*, *95*(2), 699–707. https://doi.org/10.1785/0120040123

Calvez, J. H. L., Craven, M. E., Klem, R. C., Baihly, J. D., Bennett, L. A., & Brook, K. (2007). Real-Time Microseismic Monitoring of Hydraulic Fracture Treatment: A Tool To Improve Completion and Reservoir Management. *SPE Hydraulic Fracturing Technology Conference*, (SPE 106159), 7. https://doi.org/10.2118/106159-MS

Coppens, F. (1985). First Arrival Picking on Common???Offset Trace Collections for Automatic Estimation of Static Corrections. *Geophysical Prospecting*, *33*(8), 1212–1231. https://doi.org/10.1111/j.1365-2478.1985.tb01360.x

Eisner, L., Hulsey, B. J., Duncan, P., Jurick, D., Werner, H., & Keller, W. (2010). Comparison of surface and borehole locations of induced seismicity. *Geophysical Prospecting*, *58*(5), 809–820. https://doi.org/10.1111/j.1365-2478.2010.00867.x

Falborski, T., & Jankowski, R. (2013). Polymeric Bearings – A New Base Isolation System to Reduce Structural Damage during Earthquakes. *Key Engineering Materials*, *569*, 143–150.

Frohlich, C. (1979). An efficient method for joint hypocenter determination for large groups of earthquakes. *Computers and Geosciences*, *5*(3–4), 387–389. https://doi.org/10.1016/0098-3004(79)90034-7

Geiger, L. (1912). Probability method for the determination of earthquake epicenters from the arrival time only. *Bull. St. Louis Univ*, *8*(1), 56–71.

Gharti, H. N., Oye, V., Roth, M., & Kühn, D. (2010). Automated microearthquake location using envelope stacking and robust global optimization. *Geophysics*, *75*(4), MA27. https://doi.org/10.1190/1.3432784

Gray, S. H., & May, W. P. (1994). Kirchhoff migration using eikonal equation traveltimes. *Geophysics*, *59*(5), 810–817. https://doi.org/10.1190/1.1443639

Grigoli, F., Cesca, S., Vassallo, M., & Dahm, T. (2013). Automated Seismic Event Location by Travel-Time Stacking: An Application to Mining Induced Seismicity. *Seismological Research Letters*, *84*(4), 666–677. https://doi.org/10.1785/0220120191

J. Gajewski, D., Anikiev, D., Kashtan, B., Tessmer, E., & Vanelle, C. (2007). Source Location by Diffraction Stacking, (June), 5–7. https://doi.org/10.3997/2214-4609.201401879

Jankowski, R. (2015). Pounding Between Superstructure Segments in Multi-Supported Elevated Bridge with Three-Span Continuous Deck Under 3D Non-Uniform Earthquake Excitation. *Journal of Earthquake and Tsunami*, *9*(4), 1550012. https://doi.org/10.1142/S1793431115500128

Jankowski, R., & Mahmoud, S. (2015). *Earthquake-Induced Structural Pounding*. Springer.

Jankowski, R., & Mahmoud, S. (2016). Linking of adjacent three-storey buildings for mitigation of structural pounding during earthquakes. *Bulletin of Earthquake Engineering*, *14*(11), 3075–3097.

Kao, H., & Shan, S. J. (2004). The Source-Scanning Algorithm: Mapping the distribution of seismic sources in time and space. *Geophysical Journal International*, *157*(2), 589–594. https://doi.org/10.1111/j.1365-246X.2004.02276.x

King, G. E. (2012). Hydraulic Fracturing 101: What Every Representative, Environmentalist, Regulator, Reporter, Investor, University Researcher, Neighbor and Engineer Should Know About Estimating Frac Risk and Improving Frac Performance in Unconventional Gas and Oil Wells. S. *Proceedings of the SPE Hydraulic Fracturing Technology Conference*, 80 pp. https://doi.org/10.2118/152596-MS

Lomax, A., Virieux, J., & Volant, P. (2000). Probabilistic earthquake location in 3D and layered models. *Advances in Seismic Event*.

Montgomery, C. T., Smith, M. B., Technologies, N. S. I., Fracturing, H., Cooke, C. E., Dollarhide, F. E., … Poollen, H. K. Van. (2010). Hydraulic Fracturing - History of an enduring Technology. *Journal of Petroleum Technology*, (December), 26–41. https://doi.org/10.2118/1210-0026-JPT

Naderpour, H., Barros, R. C., Khatami, S. M., & Jankowski, R. (2016). Numerical study on pounding between two adjacent buildings under earthquake excitation. *Shock and Vibration*, *2016*.

Neidell, N. S., & Taner, M. T. (1971). Semblance and other coherency measures for multichannel data. *Geophysics*, *36*(3), 482–497.

Osborn, S. G., Vengosh, A., Warner, N. R., & Jackson, R. B. (2011). Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(20), 8172–6. https://doi.org/10.1073/pnas.1100682108

Rodriguez, I. (2011). Automatic Time-picking of Microseismic Data Combining STA/LTA and the Stationary Discrete Wavelet Transform. *CSPG CSEG CWLS Convention, Convention Abstracts*, (1), 2–5.

Sabbione, J. I., & Velis, D. (2010). Automatic first-breaks picking: New strategies and algorithms. *Geophysics*, *75*(4), V67–V76. https://doi.org/10.1190/1.3463703

Waldhauser, F., & Ellsworth, W. L. (2000). A Double-difference Earthquake location algorithm: Method and application to the Northern Hayward Fault, California. *Bulletin of the Seismological Society of America*, *90*(6), 1353–1368. https://doi.org/10.1785/0120000006

Zhebel, O., & Eisner, L. (2012). Simultaneous microseismic event localization and source mechanism determination . SEG Las Vegas 2012 Annual Meeting Simultaneous microseismic event localization and source mechanism determination . SEG Las Vegas 2012 Annual Meeting, 1–5.

Zhebel, O., & Eisner, L. (2015). Simultaneous microseismic event localization and source mechanism determination. *Geophysics*, *80*(1), KS1-KS9. https://doi.org/10.1190/geo2014-0055.1