Calculation of Focal mechanism for Composite Microseismic Events

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Summary

It is often difficult to obtain a reliable single-event source mechanism with a sparse surface array, mainly due to the typically low signal/noise ratio and poor azimuthal coverage. In this study, we propose an inversion procedure to estimate the focal mechanism of composite microseismic events - i.e., a set of events interpreted to share a common focal mechanism - recorded using a sparse surface network. Our method uses polarities of P-wave first motion together with Sh/P amplitude ratios. Sensitivity analysis using synthetic data indicates that reliable focal solutions can be obtained if both the amplification factor on Sh/P ratio is within the range of 0.2 ~ 7, and > 50% polarities are correctly picked. We apply our approach to a set of 13 microseismic events recorded during hydraulic-fracture stimulation of the Marcellus Shale formation in West Virginia and Pennsylvania, USA. Similar to previous studies of this area, we obtain a focal mechanism comprised of northwest or northeast trending strike-slip faulting accompanied by a minor thrust-faulting component.

Introduction

Microseismic focal mechanisms can provide various kinds of information such as the faulting type, source rupture process and stress state (Michael, 1987; Hicks et al., 2000; Eaton and Mahani, 2015). In general, the accuracy of focal solutions is greatly affected by the azimuthal coverage of the stations as well as the signal/noise ratio (S/N). Under a surface monitoring network with unfavorable azimuth coverage, various types of data can be combined to overcome this limitation (Fojtíková and Zahradník, 2014; Vavryčuk and Kim, 2014). For areas with frequently repeating earthquake swarms, aftershock sequences or microseismic clusters, under a sparse surface array, a common focal mechanism can be resolved by using the P-wave polarities or S/P amplitude ratios of the multiple events with the assumption that the all the events within the cluster have the similar or identical source mechanism (Got et al., 1994; Sato, et al., 2004; Lee et al., 2014). Vavryčuk (2015) performed a linear inversion for composite events, based on a subset of earthquakes interpreted to share a common focal mechanism. The method used amplitudes of P- and / or S-waves, or full waveforms observed at limited number of stations, in which the moment tensor and the scale factors for individual multiple events were obtained.

This study uses both the P-wave polarities and Sh/P amplitude ratios to invert for the focal mechanism of composite microseismic events in the Marcellus shale formation of West Virginia and Pennsylvania, USA. To investigate the effects of various factors on the focal mechanism inversion results, a synthetic experiment is implemented.

Method

It has been shown that, for the source mechanisms of induced seismicity and microseismicity, non-double-couple (non-DC) components tend to be larger than that of the natural earthquakes (Šílený et al., 2009; Zhang et al., 2016). Nevertheless, the double-couple (DC) component, in general, is the dominant component (Kamei, et al., 2015). Under the assumption that composite microseismic events have identical focal mechanisms, we use an objective function defined as:

$$\Phi = \alpha \cdot \frac{1}{M}\sum_{k=1}^{M}[\log_{10}|R_k^{theo}| - \log_{10}|R_k^{obs}|]^2 + (1-\alpha)\cdot\frac{1}{N}\sum_{k=1}^{N}[(P_k^{theo} - P_k^{obs})^2/4] \quad (1)$$

where *M* is the number of stations for which the Sh/P amplitude ratio can be calculated; *N* is the number of stations with clear polarity of P-wave first motion; $|R_k^{theo}|$ and $|R_k^{obs}|$ are the modeled and observed Sh/P amplitude ratios in the absolute sense at the *k*th station; P_k^{theo} and P_k^{obs} are the modeled and observed polarities of P-wave first motion at the *k*th station, which have values +1, -1 and 0 representing the positive, negative and null polarities respectively; α is a weighting factor for the fitting error of Sh/P amplitude ratio.

The focal mechanism of composite events is obtained by an exhaustive search algorithm over all the possible strike angles with a sampling of 2°. The focal mechanism with the least error between the observed and modeled polarities as well as the amplitude ratios is then taken as the final focal mechanism of composite microseismic events.

Data Examples

The dataset used in this study is from the Marcellus Surface Microseismic Experiment (MSME) which was conducted by the Microseismic Industry Consortium to record continuous ground motion data during and after multistage fracturing treatments in Marcellus Shale formation of West Virginia and Pennsylvania, USA. Under the sparse monitoring array, only 13 events with moment magnitude ranging from 0 to 1 were identified visually with sufficiently high S/N. Figure 1 shows hypocenter locations of the 13 events. In this study, we assume that these events share a common focal mechanism and therefore can be treated as composite events for the purpose of determining the common focal mechanism.

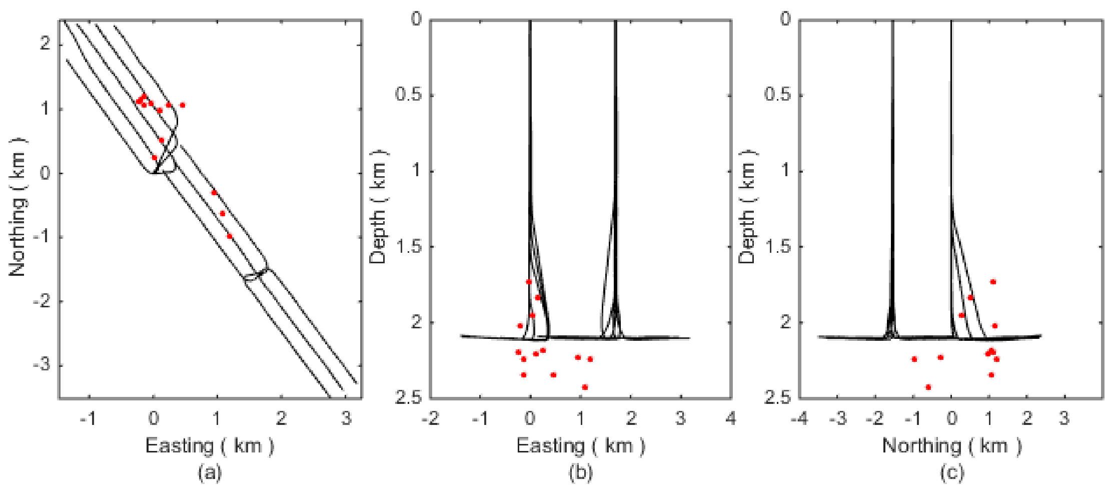
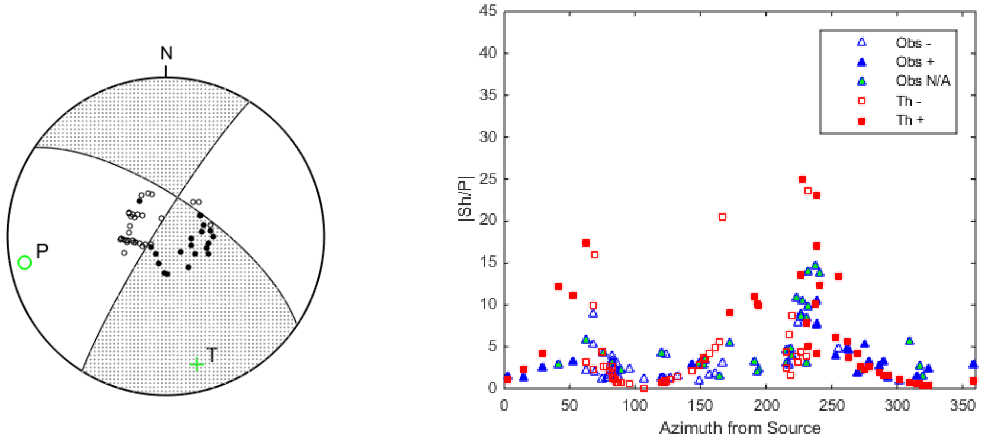


Figure 1 (a) Map view and (b), (c) side views of the locations for the 13 composite microseismic events.

By adopting the proposed focal mechanism inversion method for composite microseismic events, we obtain the source mechanism for the 13 composite events in the Marcellus shale formation (Figure 2 (a)), which is northwest or northeast trending strike-slip and accompanied by a minor thrust-faulting component. The solution estimated here exhibits good agreement with a previous study by Ellison (2014), in which two dominant fracture orientations, northeast to southwest and northwest to southeast were found within the focal mechanisms based on the surface and shallow subsurface microseismic monitoring in the Marcellus Shale, Pennsylvania and West Virginia. Figure 2 (b) shows the fitting result of P-wave polarity and Sh/P amplitude ratio (in the absolute sense) between the observed and modeled values. Most stations exhibit a good polarity fit. In terms of the Sh/P amplitude ratios, the observed and modeled data exhibit a similar trend, but some individual stations show relatively larger errors.



(a) (b)

Figure 2 (a) Inverted focal mechanism of the 13 composite microseismic events. (b) |Sh/P| fitting results between the observed and theoretical values.

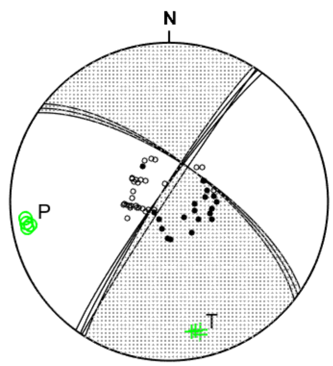


Figure 3 Result of Jackknife test. The composite solution obtained by using all the 13 events is shown with color fill.

In order to investigate the stability of the inversion and the possible bias introduced by individual events, we applied a Jackknife procedure to the Marcellus dataset by removing one event from the 13 events each time, and an inversion is performed using the remaining 12 events. In the Jackknife test, as shown in Figure 3, all the 13 solutions are very close to the solution in Figure 2 (a) and exhibit less deviation, which indicates the stability of the inversion for the Marcellus dataset.

Discussion

Sh/P amplitude ratio can be affected by a number of factors, such as geometrical spreading, absorption and transmission. To test the sensitivity to these factors, a synthetic experiment was performed to investigate the effects on the inversion results from the amplification factor on |Sh/P| as well as incorrectly picked polarities.

Figure 4 shows the locations for eight stations used in the synthetic experiment, which are evenly distributed around 15 randomly generated composite microseismic events within 800m from the center of this area. The depths of the 15 events range from 1900 m to 2200 m. We quantify the effects of amplified amplitude ratios and wrongly picked polarities on the focal mechanism inversion results. Figure 5 shows the results obtained by using the amplified |Sh/P| and polarities with errors, in which yellow area means the inverted focal mechanisms have an error of $\leq$ 4° for all the three angles, strike, dip and rake, whereas blue area indicates the region with unacceptable errors. We conclude from Figure 5 that reliable focal mechanisms can be obtained if both the amplification factor is within the range of 0.2 ~ 7, and there are less than 50% of the wrongly picked polarities.

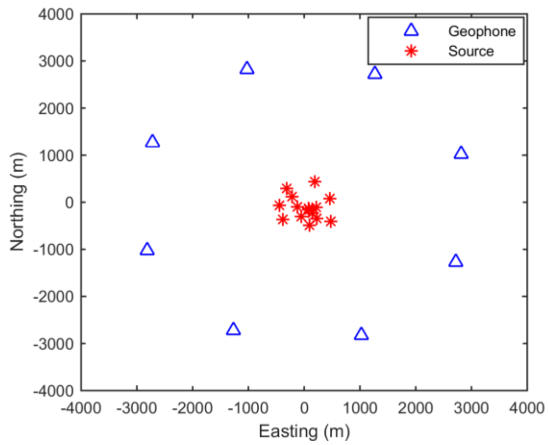


Figure 4 Locations of the microseismic sources and stations in the synthetic experiment.

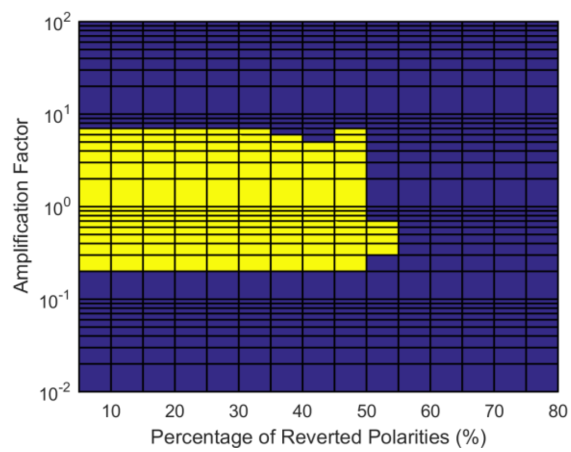


Figure 5 Impact of incorrectly picked polarities and amplification of the |Sh/P| on the focal mechanisms.

Conclusions

We propose an inversion approach to estimate focal solutions for composite microseismic events by using both P-wave polarities and Sh/P amplitude ratios, which can overcome the limitation of small azimuth coverage caused by sparse surface arrays. After applying the proposed method to 13 composite microseismic events in Marcellus Shale formation, we obtain an estimated composite focal mechanism that is a northwest or northeast trending strike-slip accompanied by a minor thrust-faulting component. This solution shows good agreement with a previous study by Ellison (2014) for the focal mechanisms of microseimic events in the same study area. A synthetic experiment in this study indicates that reliable focal mechanisms can be obtained if both the amplification factor on amplitude ratios is within the range of 0.2 ~ 7, and > 50% of polarities are picked correctly.

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References

Eaton, D. W., and A. B. Mahani, 2015, Focal mechanisms of some inferred induced earthquakes in Alberta, Canada: Seismological Research Letter, **86**(4), 1-8.

Ellison, M., 2014, Microseismic reveals fracture patterns: The American Oil & Gas Reporter.

Fojtíková, L., and J. Zahradník, 2014, A new strategy for weak events in sparse networks: The first-motion polarity solutions constrained by single-station waveform inversion: Seismological Research Letter, **85**(6), 1265–1274.

Got, J. L., J. Frechet, and F. W. Klein, 1994, Deep fault plane geometry inferred from multiplet relative relocation beneath the south flank of Kilauea: Journal of Geophysical Research, **99**(B8), 15375-15386.

Hicks, E. C., H. Bungum, and C. D. Lindholm, 2000, Stress inversion of earthquake focal mechanism solutions from onshore and offshore Norway: Norsk Geologisk Tidsskrift, **80**, 235-250.

Kamei, R., N. Nakata, and D. Lumley, 2015, Introduction to microseismic mechanisms: The Leading Edge, Special Section: Microseismic source mechanisms, 876-880.

Lee, M., T. Davis, and S. Maxwell, 2014, Source mechanism characterization of microseismic data at Pouce Coupe Field, Alberta, Canada: Unconventional Resources Technology Conference, 1510-1517.

Michael, A. J., 1987, Use of focal mechanism to determine stress: a control study: Journal of Geophysical Research, **92**(B1), 357-368.

Sato, T., J. Kasahara, T. Taymaz, M. Ito, A. Kamimura, T. Hayakawa, and O. Tan, 2004, A study of microearthquake seismicity and focal mechanisms within the Sea of Marmara (NW Turkey) using ocean bottom seismometers (OBSs): Tectonophysics, **391**, 303–314.

Šílený, J., D. P. Hill, L. Eisner, and F. H. Cornet, 2009, Non-double-couple mechanisms of microearthquakes induced by hydraulic fracturing: Journal of Geophysical Research, **114**(B8), B08307.

Vavryčuk, V., and S. G. Kim, 2014, Nonisotropic radiation of the 2013 North Korean nuclear explosion: Geophysical Research Letter, **41**(20), 7048-7056.

Vavryčuk, V., 2015, Inversion for the composite moment tensor: Bulletin of the Seismological of Society of America, **105**(6), 3024-3035.

Zhang, H., D. W. Eaton, G. Li, Y. Liu, and R. M. Harrington, 2016, Discriminating induced seismicity from natural earthquakes using moment tensors and source spectra: Journal of Geophysical Research, **121**(2), 972-993.