Microseismic migration by semblance-weighted stacking and interferometry

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Summary

Migration-based methods are attractive for microseismic event location because they can automatically locate the events without manually picking P- and S-wave arrivals. For real-time processing, computational efficiency is important. In this study, we develop an efficient migration-based microseismic location algorithm for 3C data recorded in borehole. We use semblance-weighted stack to detect the moveout curves of P and S waves along the receiver array, then use cross-component cross-correlation on the semblance-weighted stack to create a map of the brightness function with consideration that the polarizations of P and S waves are almost orthogonal. To avoid wrong locations caused by cross-correlation between S wave and its multiples, the brightness function is divided by the P-wave energy. To avoid mis-interpret weaker reflected P wave as the first P arrival, we perform a second scan without the normalization of the P-wave energy while fixing the S-wave time window from previous scan. Location results on a real event record show the cross-component cross-correlation makes the algorithm work on a wide range of seismic data, and the semblance-weighted stack improves the location resolution.

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Introduction

Micro-earthquakes (microseismic events) induced by hydraulic fracturing can provide valuable information about the stimulation and be used to optimize the piping process if they are accurately located. Because the microseismic events are generally weak, they are commonly monitored by 3C sensor array deployed in vertical or deviated monitoring wells. The microseismic data exhibits a common feature of a weak P wave and relatively stronger S wave. Even for data recorded in borehole, the identification of the P wave for microseismic events is still a challenging task since the signal-to-noise ratio of the P wave is very low.

Though the conventional earthquake location techniques based on phase picking can be directly used to locate microseismic events, they require extensive user interaction to pick the P- and S-wave arrival times on the noisy microseismic data and thus they are seldom used as real-time location solutions. The popular single monitoring well also imposes additional difficulties: the moveout curve of a single phase (P or S wave) along the sensor array can not locate the event in an acceptable resolution, thus, both P- and S-wave arrival times have to be picked to avoid non-unique results. Only large events with high quality data can be located by picking-based methods.

Different location techniques have been developed toward automatically locating microseismic events without prior P- and S-wave picking, e.g., reverse time migration by wave-equation to find the energy focus point (Fish, 2012), back shooting ray along the incident angle using Gaussian-beam (Rentsch et al., 2007), fitting the waveform by search engine technique (Zhang et al., 2013). Migration-based methods are also automatic event location techniques by sliding and stacking traces along the P- and S-wave moveout curves from a trial source location. The maximum stacking quantity indicates the correct moveout from the trial source. Different stacking quantities can be used, including semblance (Chambers et al., 2010; Eaton et al., 2011), absolute amplitude (Kao and Shan, 2004), energy envelope (Gharti et al., 2010), or projected traces in the frequency domain (Haldorsen et al., 2012). To reduce the non-uniqueness and increase the spatial resolution, migration-based methods also require both P- and S-wave moveout curves to be simultaneously detected for the true location, which can be achieved by cross-correlation of the stacked quantities for P and S wave or deconvolution between stacked P and S wave (Haldorsen et al., 2012). The order of stacking along the moveout curve and measure of the similarity between P and S waves is also different in different methods, e.g., Michaud and Leaney (2008) calculated the SNR cross-correlation of the P and S wave first, then stacked along the moveout curve, while others performed the stacking first, then calculated the product for P and S wave.

We develop a new migration-based location technique that can rapidly locate microseismic events. It utilizes the semblance-weighted stack to extract the coherence of the P- and S-wave in the receiver array and uses the cross-correlation between different components to measure the similarity of stacked P and S waves. By using cross-component cross-correlation, it does not scan the azimuth angle to project P and S waves to separate axes. By using semblance-weighted stack, it maximally utilizes the coherency of the signal and the uncorrelated characters of the random noise to enhance the P and S waves.

Migration-based location method

Most microseismic data are recorded by the sensor array deployed in a single monitor well located nearby the horizontal treatment well. The P wave is generally weak and has a low signal-to-noise ratio. It may not be a trivial task to accurately pick P-wave arrival time on the noisy microseismic record. In conventional seismology, stacking is widely used to enhance signal-to-noise ratio. Semblance (Neidell and Taner, 1971; Kennett, 2000) is a quantitative measure of multichannel coherency between the receiver array by the energy ratio of the stack and the component traces.

The semblance of P and S waves at time sample i for the trial location are defined as (Kennett, 1987, 2000)

$$\sigma_k^p(i) = \frac{\sum_{s=-N_p/2}^{N_p/2} w_s \left(\sum_{j=1}^{M} u_{jk}(\tau_j^p + i + s) \right)^2}{M \sum_{s=-N_p/2}^{N_p/2} w_s \sum_{j=1}^{M} u_{jk}^2(\tau_j^p + i + s)}, \quad (1)$$

$$\sigma_k^s(i) = \frac{\sum_{s=-N_s/2}^{N_s/2} w_s \left(\sum_{j=1}^{M} u_{jk}(\tau_j^s + i + s) \right)^2}{M \sum_{s=-N_s/2}^{N_s/2} w_s \sum_{j=1}^{M} u_{jk}^2(\tau_j^s + i + s)}, \quad (2)$$

where subscript k means the component, M is the number of receivers, τ^p and τ^s are the traveltime moveouts of the P and S waves with respect to a reference receiver for the trial event location, N_p and N_s are the number of time samples for the P and S waves, w_s is the weighting function centered at the time sample i.

Denote the linear stack of P- and S-wave along the moveout curves as

$$v_k^p(i) = \sum_{j=1}^{M} u_{jk}(\tau_j^p + i), \quad (3)$$

$$v_k^s(i) = \sum_{j=1}^{M} u_{jk}(\tau_j^s + i), \quad (4)$$

which enhances the coherent P and S waves while suppress the random noise. Unlike the conventional exploration seismology, the polarization of the P and/or S waves, even projected on the ray coordinate, could have different signs along the receivers if the sensors are located in the different radiation quadrants, which may probably happen when the event is close to the monitoring well. For such events, we use the absolute amplitude of the traces in Equation 1-4. To further enhance the coherent P and S waves along the receiver array, we adopt the following semblance-weighted stack (Kennett, 2000)

$$S_k^p(i) = (\sigma_k^p)^q v_k^p(i), \quad (5)$$

$$S_k^s(i) = (\sigma_k^s)^q v_k^s(i), \quad (6)$$

where the exponent q ranges from 1 to 4.

The true event location should produce the synthetic P- and S-wave moveout curves both fitting those in observations, which means the semblance-weighted stacks in equation 5-6 both reach maximum. Since the P and S waves come from the same source, they should have similar time variations. We can thus use cross-correlation to measure the similarity between P and S waves in the stacked traces at predicted arrival times. For events propagate parallel to the coordinate axis, the P and S waves will appear on different components since the polarizations of P and S waves are close orthogonal. We calculate the cross-correlation between different horizontal components to avoid scanning azimuth, which may be time consuming for real-time processing.

The brightness function is formed by the cross-component cross-correlation of the semblance-weighted stack

$$I_a = \left| \sum_{i=1}^{N_t} S_x^p(i) S_y^s(i) \right| + \left| \sum_{i=1}^{N_t} S_y^p(i) S_x^s(i) \right| + \left| \sum_{i=1}^{N_t} S_z^p(i) S_z^s(i) \right|. \quad (7)$$

In microseism, S wave generally has larger amplitude than P wave, and S-wave multiples generally follow the first arrival S wave. Directly using equation 7 on microseismic data may get larger brightness function value formed by cross-correlation between S wave and its multiples. To avoid mis-interpreting the S wave as the P wave, we define a new brightness function normalized by P-wave energy (Haldorsen et al., 2012)

$$I_r = \frac{I_a}{E_p} \quad (8)$$

For some events, we also observed there is a weaker coherent reflected P-wave between the first P-wave arrival and S-wave arrival in multi-layered structures. Dividing P-wave energy may mis-interpret reflected P wave as the first arrivals since its energy is smaller. Here we adopt a two-step approach of which the first step employs Equation 8 to find the S-wave window, then the final location is obtained by the maximum value of Equation 7 with the fixed S-wave window.

The above procedure will produce the event location in the vertical 2D plane. The azimuth angle from the polarization of P- or S-wave is used to project the 2D location to 3D.

Location example

Figure 1(a-c) shows 3C microseismic traces for an event recorded by 12 receivers deployed in a vertical monitoring

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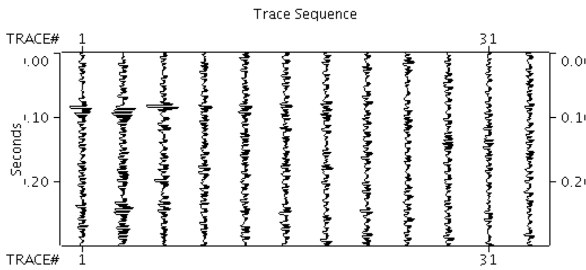
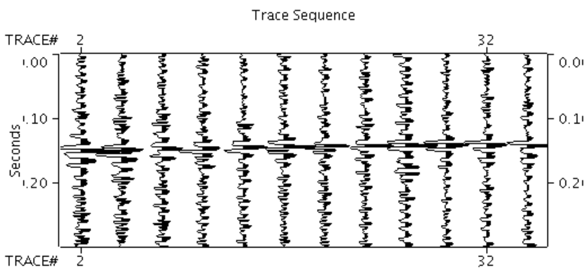
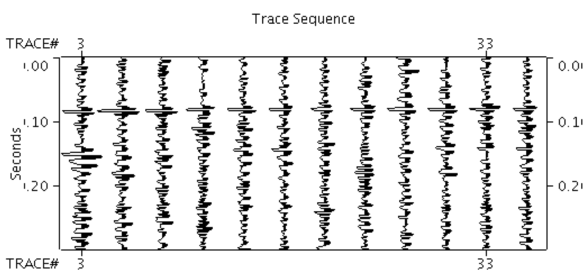


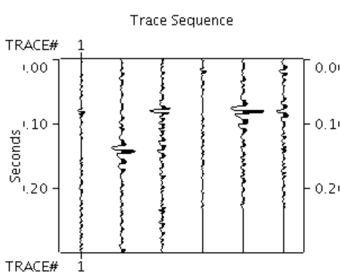
(a) Microseismic traces of the z-component



(b) Microseismic traces of the x-component

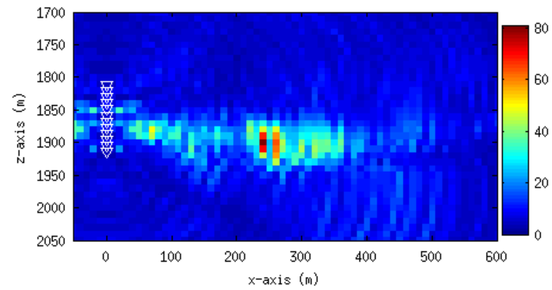


(c) Microseismic traces of the y-component

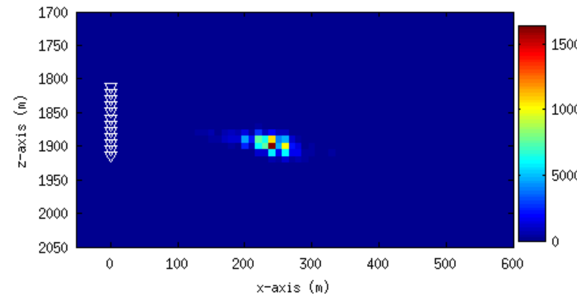


(d) Stacked traces for the final event location. Left three traces are z/x/y-components of the stacked P-wave; right three traces are those of the stacked S-wave.

Figure 1: 3C microseismic record and the stacked traces.



(a) Location result by cross-correlation of the linear stack of P- and S-wave (Equation 3-4) normalized by the P-wave energy



(b) Two-step location result by using the semblance-weighted stack of P- and S-wave (Equation 5-6)

Figure 2: Migration-based location result.

well. The P wave is visible only on the x-component around 70-80ms, while the S wave appears on the y-component around 130-140ms. There is no strong P or S wave on the vertical component. This event may happen with some offset along the y-axis, thus the seismic wave mainly propagated parallel to the y-axis. For these data, the cross-correlation on the same component can not correctly measure the similarity of the P and S waves since only single phase appears on single component. In contrast, the cross-component cross-correlation can work independently the wave propagation direction.

Location result by using the cross-correlation of the linear stack of the P and S waves (Equation 3-4) with P-wave energy normalization is shown in Figure 2(a). The linear stack of the P wave is not a good measure of the coherency of the signal, which causes scattered large brightness values with low spatial resolutions. Figure 2(b) shows the location result by using the semblance-weighted stack in Equation 5-6. The map of the brightness function exhibits more compact distribution and indicates the event location with a higher resolution. We can verify the location result from the stacked traces in Figure 1(d). After moveout correction, the stacked P- and S-wave align at the correct P-wave arrival time as shown in Figure 1(c).

Conclusions

We have developed a new migration-based location method. It utilizes the semblance-weighted stack to extract the coherence of the P and S waves in the receiver array and uses the cross-correlation between different components to measure the similarity of stacked P and S waves. By using cross-component cross-correlation, it does not need to scan the azimuth angle to project P and S waves to different axes. By using semblance-weighted stack, it maximally utilizes the coherency of the signal and the uncorrelated characters of the random noise to enhance the P and S waves. It can be used to locate microseismic events in real-time processing. We demonstrated the proposed method on a set of real event data. The result indicates that the semblance-weighted stack can significantly improve the location resolution. The stacked traces show that the algorithm can accurately detect the moveout curves and align the P and S waves together.

Acknowledgements

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