Locating microseismic events with S-wave data only

Wenhuan Kuang, Wei Zhang, Jie Zhang, GeoTomo LLC*

Summary

Microseismic monitoring is a practical technique for mapping hydraulic fractures. Accurate imaging of the event location is critical for fracture interpretation. Microseismic data, however, often present weak P-waves or no P-waves at all because of low signal-to-noise ratio. S-waves, on the other hand, are relatively large, and reliably observed. Therefore, it will be significantly meaningful if we can use only S-phase to determine the source location. We design two synthetic experiments to understand the possibility of using only S-phase to locate the microseismic events. In the first experiment we use only S-wave traveltime information to locate events, while in the second experiment we utilize S-wave traveltime along with incident angle to enhance accuracy. The experiment results suggest that using only S-wave traveltime information is not feasible to locate the microseismic events. But using S-wave traveltime and incident angle can produce an acceptable solution if the source-receiver distance is comparable with the acquisition aperture.

Introduction

Passive monitoring of microseismic events has become a common tool for understanding underground process such as hydraulic fracturing, drill-cutting injection and geothermal hot-dry-rock stimulations (Warpinski, 2009). This technique has been proven especially valuable for monitoring shale-gas production because analyzing microseismic data to locate fracture points allows reservoir engineers to follow the progress of a hydraulic-fracture stimulation project. However, locating fracture-point hypocenters using microseismic monitoring and analysis is often plagued by uncertainties and inaccuracies. One aspect of the issues comes from the misidentification of the onset of arrivals (Kao and Shan, 2004). This is especially true for P-phase when the signal-to-noise ratio is poor since the P-phase usually has relatively small amplitude compared with S-phase. It will be of great advantage if we can locate microseismic events using S-phase information only. It is doubtful that single phase information cannot accurately locate events on sensor arrays in a single borehole. However, there is no quantitative analysis on the location uncertainties though utilizing single phase. In this study, we use synthetic microseismic datasets to test the capability of using a single S-wave phase to locate microseisms. We design two experiments. The first experiment only uses traveltime information of S-wave, while the second experiment utilizes both traveltime and incident angle information by projecting the recorded components to the SV-wave particle motion axis. By projecting vertical and horizontal components to the correct SV-wave particle motion axis, the energy should be maximized. Then we stack the energy over receivers by aligning the projected traces. We will describe the details in the following sections.

Applying S-wave relative traveltimes

We design a three-layer velocity model and common acquisition geometry as shown in Figure 1. There are four test sources at four different locations: 150 m, 300 m, 500 m and 800 m in the middle layer along with 12 receivers in the left borehole. The receiver interval is 15 m, and the acquisition aperture is 165m in total. Figure 2 shows the raypath for the four sources. We calculate S-wave traveltime for all the four testing sources as our real traveltime data.

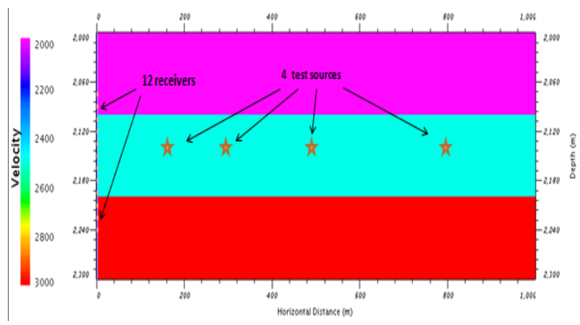

Figure 1: Velocity model and acquisition geometry with four test sources and 12 receivers in the well.

We use a grid search algorithm to find the location that best fitting the relative time residuals. Each grid point is assigned a value that measures the difference between real and theoretical arrival times with an unknown origin time. The grid point with the smallest time residual is considered to be the most likely location. Here, the traveltime residual value is defined as (Zimmer, 2011)

$$t_{res} = \sqrt{\frac{\sum_{n}[(T_i - t_i) - \frac{1}{n} \times \left\{ \sum_{n} (T_i - t_i) \right\}}{n}} , \qquad (1)$$

where T_i is the recorded traveltime, t_i is the computed traveltime, n is the number of receivers. The second term under the radical sign is a constant shift between the identified and calculated arrival times to account for the unknown origin times.

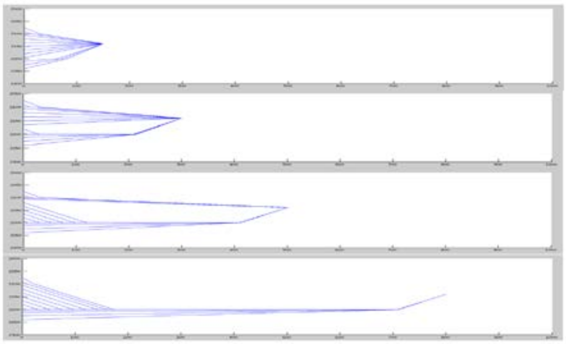

Figure 2: Raypath of the four test sources. The raypath varies with the source-receiver distance.

Figure 3 shows the distribution of the traveltime residuals for four test sources at different distances: 150 m, 300 m, 500 m, and 800m from the receiver array. The blue color denotes small traveltime residuals, i.e., the most likely location. We can see that there is a large area in the vicinity of the true location. The residuals of the grid points in the area are around 2 ms. Even though the smaller distance gives a better constrain of the source location, but still, considering the picking error is about 1 or 2 ms, we cannot distinguish which position nearby is the best.

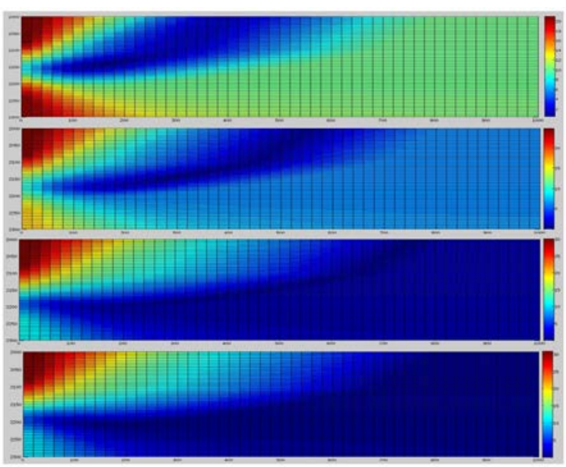

Figure 3: Residual distribution of four different test sources.

We pick three wrong positions in the near area of the true position from the second panel in Figure 3. To compare with the true position, we remove the origin time and shift together by using the second term in equation (1). Figure 4 shows these three wrong relative traveltime curves along with the true curve. The time differences between these three wrong positions and true position are very small. Only one receiver has a relatively large difference of 1.5 ms. For real data we cannot distinguish microseismic event positions due to the time difference of only one receiver. Traveltime curve in the located area is very similar to each other that we cannot locate the microseismic events using only S-wave traveltime.

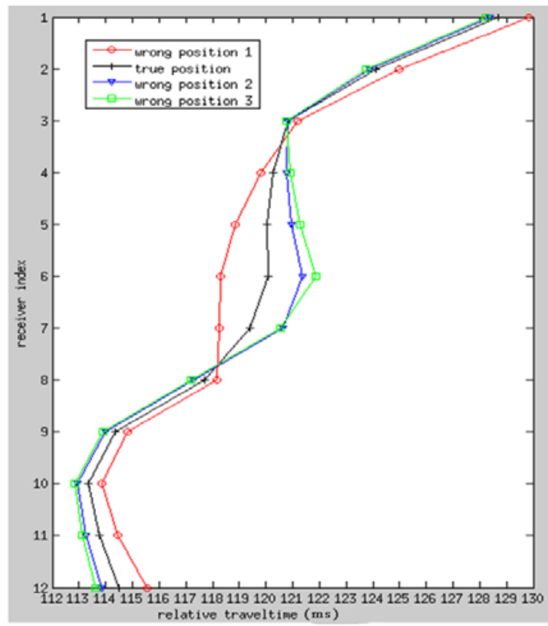

Figure 4: Relative traveltime curves of three wrong positions (red, green and blue) and the true position (black).

Applying relative traveltime and incident angle

From previous experiment, we can see that using only traveltime from a single phase cannot locate the event. In this experiment, we test if utilizing joint traveltime with incident angle information can reduce the non-uniqueness. We exploit the incident angle information by projecting the recorded components to the S-wave particle motion direction. Then we apply migration based SSA method (Kao and Shan, 2004) to locate the microseismic events.

For a 2D case, as shown in Figure 5, there are only P- and SV-wave components. We assume that receivers record only horizontal and vertical components. The SV-wave particle motion plan is perpendicular to the P-wave incident direction. If we project the recorded components to the true SV particle motion direction, the RMS energy should be maximized. Based on this principle, we can project the energy to a certain direction that is perpendicular to the P-wave propagate direction for all the search grids.

Here, we define the brightness value at each grid point as:

$$bri = \sum_{i=N_1}^{N_2} \{\sum_{r=1}^{mr} (S_{xir} \cos\theta + S_{zir} \sin\theta)^2\}^2, \qquad (2)$$

where the subscript x and z denote for horizontal and vertical components, respectively. Subscript r for receiver index, and i denotes time series in SV-wave time window.

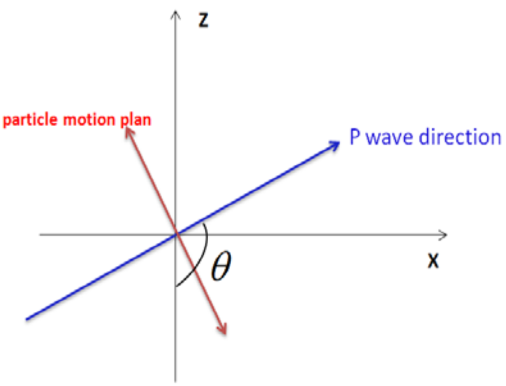

Figure 5: Schematic illustration of SV-wave projecting.

The incident angle θ is defined anticlockwise from negative z axis, from 0 to 180 degrees. For each grid position, we first perform ray tracing to calculate the S-wave traveltime and P-wave incident angle, and then use equation (2) to calculate the brightness function to measure the brightness value, the position with the maximum brightness value is considered to be the likely position.

We calculate the synthetic dataset by applying elastic wave modeling of a point earthquake source in a multi-layered half space using the Thompson-Haskell propagator matrix technique (Zhu and Rivera, 2002). We assume a double couple source and a triangle source time function for the forward calculation. We use the same velocity model and acquisition geometry in the first experiment for the four test sources. Figure 6 shows the simulated waveforms of the first test source. The top panel shows the horizontal component, and the bottom panel is for the vertical component. The discontinuity in the middle receivers and the phase reversal between top and bottom waveforms are caused by source radiation pattern. Figure 7 shows the brightness distribution of the four sources with different source-receiver distances. The maximum brightness value represents for the best location.

The source-receiver distance in the top panel in Figure 7 is 150 m, which is equivalent to the acquisition aperture. For the source-receiver distance equivalent to acquisition aperture, using S-wave joint traveltime with incident angle information to locate the events can give acceptable accuracy. But when the source-receiver distances are larger than acquisition aperture, using S-wave joint traveltime and incident angle information is not feasible to locate the microseismic event locations, as shown in the bottom three panels in Figure 7.

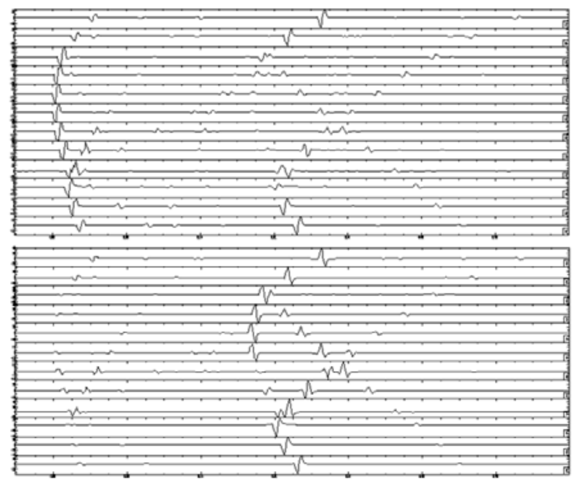

Figure 6: Synthetic waveforms for the first test source with the distance of 150 m. (a)Top panel: horizontal component waveforms for 12 receivers; (b) Bottom panel: vertical component waveforms.

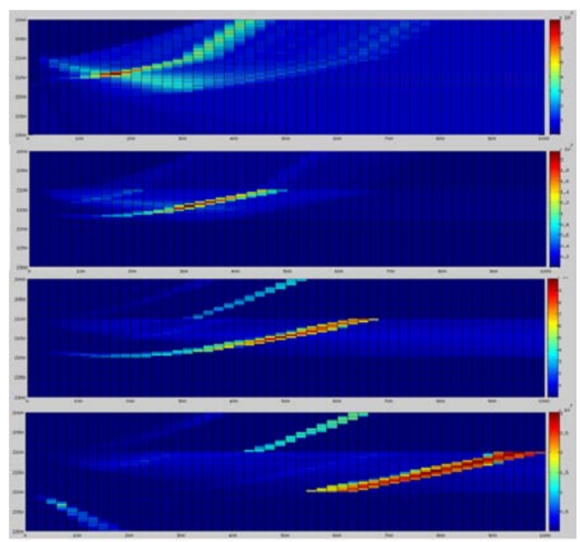

Figure 7: Brightness distribution of four different test sources.

Conclusions

We analyze the feasibility of only using S-waves to locate the microseismic events. We test the capability of using relative traveltime of S-phase, and also relative traveltime along with incident angle of S-phase by projecting the recorded components to the S-wave particle motion direction. Using only S-wave traveltime information to locate is not feasible due to large ambiguity in solutions. Using both relative traveltime and incident angle information can work well only if the source-receiver distance is comparable with the acquisition aperture. For larger source-receiver distances than the acquisition aperture, joint traveltime with incident angle information method may fail because of the lack of incident angle sensitivity with respect to raypath.

From these experiment results we can see that, using only traveltime and incident angle information of S-wave to locate the microseisms events for real field data is not available for most cases. In our experiment, we do not utilize amplitude information among different receivers. One possible locating solution is to exploit the relative amplitude information among different receivers.

Acknowledgements

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