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Determining Microseismic Event Locations by Semblance-weighted Stacking

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Summary

Estimation of hypocentre locations is a key element of microseismic data processing. In particular, accurate hypocentres are critical for estimating the stimulated reservoir volume. Here, we describe a semi-automated semblance-weighted stacking approach for hypocentre determination that we have developed within matlab. Our current implementation of this procedure is tailored for borehole geophone arrays and is limited to isotropic, horizontally layered media. Event locations are obtained using a 2-D lookup table, computed using an efficient ray-bending algorithm that is robust in the presence of large velocity gradients and strong velocity contrasts at layer boundaries. An interactive procedure is used to scan through the microseismic events and select an approximate time (either P or S arrival) on a single trace. For all depth-distance pairs in the lookup table, semblance-weighted waveform stacks are calculated within P- and S-wave corridors. The location is selected based on the largest semblance-weighted stack value in conjunction with an azimuth determined from energy analysis using horizontal geophones. An advantage of our approach is that the need to obtain accurate P- and S-wave arrival-time picks is eliminated.

Introduction

Microseismic methods have emerged as an important tool for hydraulic fracture monitoring (HFM) and other continuous monitoring applications at the mine or reservoir scale. In general, microseismic data are acquired continuously at high sample rates over a period of hours, days or longer. The events of interest comprise a tiny fraction of the total recorded data, and in the case of a borehole-acquisition geometry they are typically very broadband (10’s – 1000’s Hz) and characterized by a significant dynamic range (up to 80 dB). Acquisition of high-fidelity three-component data is essential to achieve successful results. Basic processing for this type of data is very different from the processing used for seismic exploration, but shares much in common with methods used for routine analysis of data from earthquake-monitoring networks.

As part of ongoing development of a complete microseismic data-processing package, we have implemented a semi-automatic event-location algorithm. Our method is based on a semblance-weighted stacking approach, not unlike classical velocity-analysis methods used for processing conventional seismic data. Although our algorithm is currently limited to horizontally layered, isotropic media, it is easily generalizable to more complex models including anisotropy. Our present method computes arrival times for each geophone level using a ray-bending algorithm that is robust in the presence of strong velocity gradients. The purpose of this paper is to describe our new method, and illustrate it using examples of HFM datasets from Alberta.

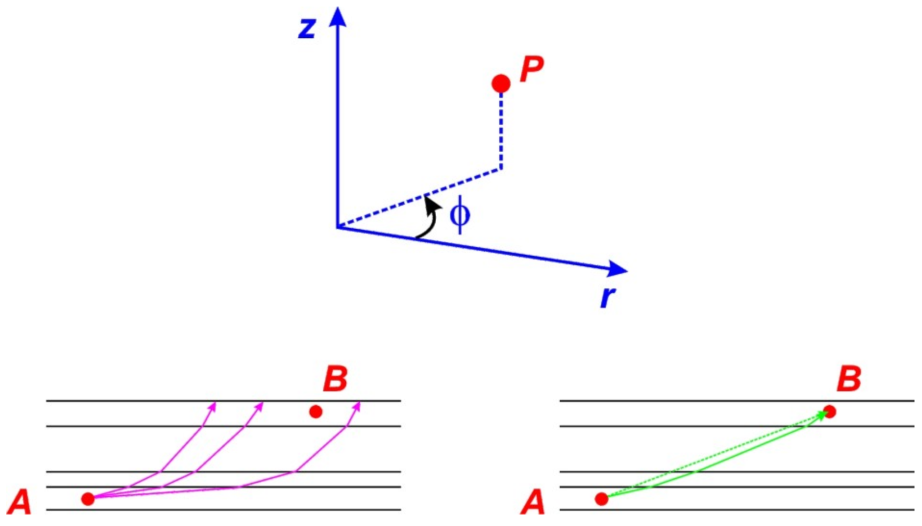

Figure 1. Top panel: cylindrical co-ordinate system used for event location in a 1-D layered model. Lower left: ray-shooting algorithm to trace ray from *A* to *B*. Lower right: ray-bending algorithm.

Method

A velocity model is required to compute event locations. The model is generally constructed by smoothing and blocking available sonic-log data (P- and S-wave). Once a satisfactory velocity model has been obtained, a lookup table is created in order to compute hypocentre locations. In the current implementation of our microseismic processing system, events are located assuming a 1-D (horizontally layered) isotropic background velocity function. For such a model, the most appropriate co-ordinate system is cylindrical (Figure 1) and the lookup table is parameterized according to depth (z) and radial distance from the observation well (r). Note that most rays propagate almost horizontally through the 1-D layered medium. Such geometries often introduce problems for classical ray-shooting algorithms, since even small changes in velocity between adjacent layers can produce shadow zones associated with post-critical incidence. For this reason, ray-theoretical travel times are computed here using a ray-bending algorithm (e.g., Cerveny, 2001), which gives an approximate but very robust solution under these circumstances.

For traditional hypocentre location methods it is necessary to pick P- and S-wave arrival times in order to obtain a location for identified microseismic events. Given the very large number of events that are recorded during a typical HFM job, this step can be tedious and error prone. As an alternative approach is developed here that uses a semblance-weighted stacking method that only requires a single arrival time to be picked for a given event.

The first component step in our procedure uses an interactive module that enables the user to scroll through a large number of events very quickly. The events are first sorted by signal-to-noise ratio (SNR), which allows the user to start picking more obvious, high-SNR records prior to making less obvious picks. The interactive module operates by plotting a trace-normalized record section and querying the user whether to discard or keep the event. If the user decides to keep the event, one arrival is picked (approximately) using a mouse click on the plotted record. This is used as a reference time pick for the subsequent step.

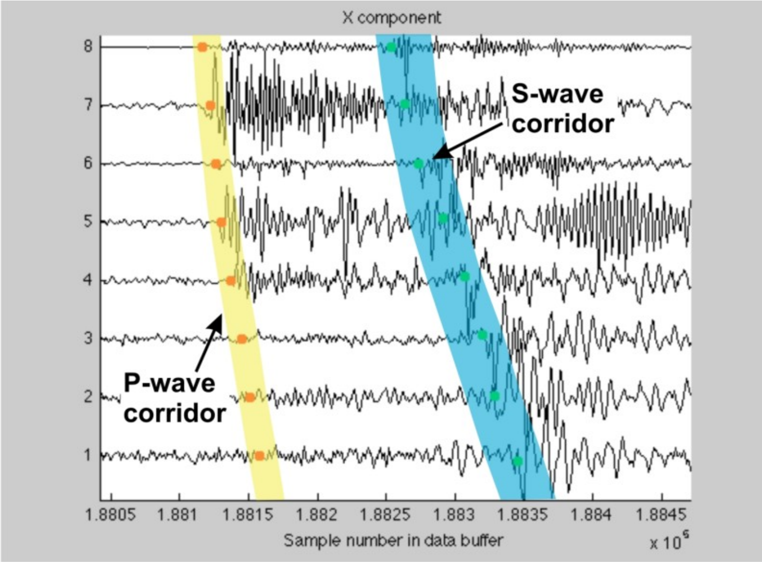

Figure 2. Corridor-stacking method. P-wave picks and S-wave picks are shown for reference – in practice only one such pick (either P or S, not both) is used. See text for details.

All selected events are saved to disk for further processes, which is driven by the lookup table. For every depth-distance pair in the lookup table, the P- and S-wave arrival times (t_P and t_S) are extracted for each geophone. With no loss of generality, a bulk time shift is then applied to the t_P and t_S values such that the appropriate moveout curve (P or S) passes exactly through the arrival picked during the interactive analysis. A user-specified time window around each moveout curve is used to establish corridors (Figure 2) for computing P- and S-wave semblance-weighted stack function. For a given time window (corridor) of seismic data u_i, $i = 1,\ldots,N$ from the kth component ($k = x,y,z$) of the jth geophone level ($j = 1,\ldots,M$), the semblance, σ, is defined as:

$$\sigma_k(u,N) = \frac{\sum_{j=1}^{M}\sum_{i=1}^{N} u_{jk}^2(\tau_j + i)}{\left(\sum_{j=1}^{M}\sum_{i=1}^{N} u_{jk}(\tau_j + i)\right)^2} \quad , \qquad (1)$$

where τ_j is the trace sample index for the start of the P- or S-wave corridor. Within the P-wave corridor, the semblance-weighted stack is given by:

$$S_P = \sum_k \sigma_k^q \sum_j \sum_i u_{ijk} \quad , \qquad (2)$$

where q is a user-defined exponent. A similar definition applies for S_S. The product of S_P and S_S is then used to determine the optimal hypocenter location with respect to r and z (Figure 3).

To determine the hypocentre location in 3-D, the azimuth from the observation well is required. This is determined by computing the direction of maximum horizontal energy in the P-wave corridor. The estimated azimuth is computed for all geophone levels, then a 'trimmed' average (discarding the maximum and minimum values) is used to determine the azimuth to the event. The associated 'trimmed' standard

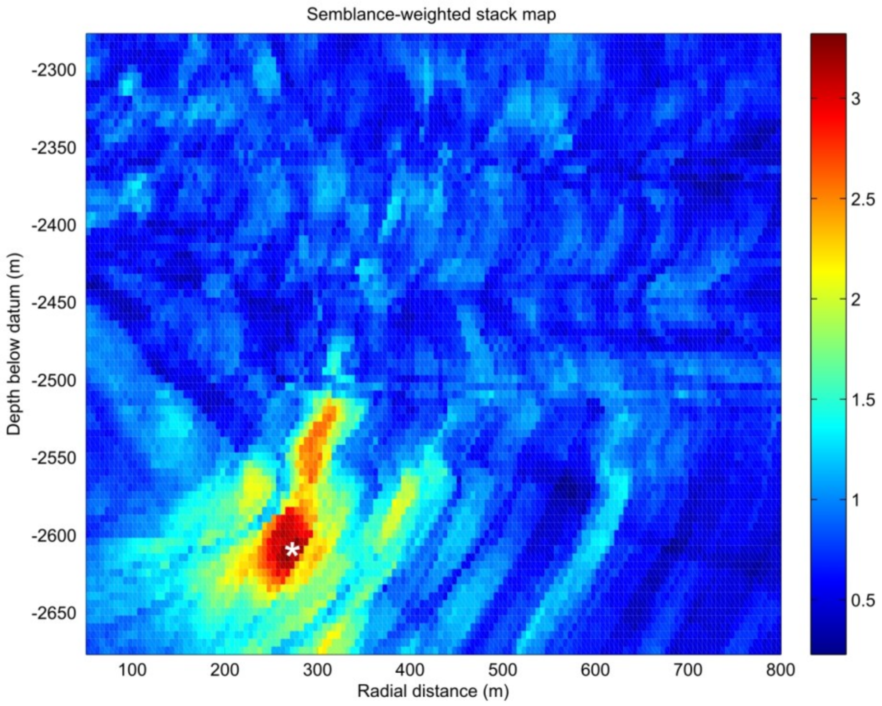

Figure 3. Map of the product S_P and S_S (equation 2) for all radial distances and depths in the lookup table. The largest value of this product, shown by the white star, corresponds to the radial distance and depth of the estimated hypocentre.

deviation is used as a proxy for uncertainty in azimuth. Once the azimuth is know, the *x,y,z* location of the hypocentre can be found by converting from cylindrical to Cartesian co-ordinates.

Conclusions

As part of a complete microseismic processing package, we have developed a semi-automatic semblance-based method for determining hypocentre locations that is suitable for three-component geophone data from a single vertical observation well. For every event detected during the HFM job, the method requires the user to select an approximate arrival (P or S) on a single trace. Aside from this step, no picking is required for automatic locations to be determined. Using a lookup-table driven procedure, the depth and radial distance of the event are determined based on the maximum semblance-weighted stack amplitude within a corridor centred on the P and S arrivals. The event location is then determined using the azimuth estimated from the P-wave particle motion. Planned future developments of this method include incorporation of more complex velocity models (3-D inhomogeneous models including anisotropy) and uncertainty estimates derived from the semblance distribution.

Acknowledgements

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References

Cerveny, V., 2001. Seismic ray theory. Cambridge University Press.