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Tomography of a velocity model and location of microseismic events with P, Sv and Sh waves.

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Summary

This abstract demonstrates the feasibility of a joint use of P- and S-waves with surface monitoring network. Using the best quality microseismic events from a dataset recorded with three components sensors; we first estimated an optimal velocity model through simulated annealing. We subsequently used it to detect and locate smaller events in a relative way. Our results show that the location - while using only P–waves - is poorly constrained and adding an S phase gives significant improvement.

Introduction

Microseismic monitoring is important in hydraulic fracturing treatments for shale gas production. It allows detecting and locating microseisms induced by the hydraulic fracturing. Knowing microseismic events positions is crucial in inferring the created fracture orientations and dimensions, what improves the efficiency and easies the production. That is why it is so important to find reliable microseismic event locations.

Surface microseismic monitoring is usually undertaken using vertical sensors only, as using 3C sensors drastically increase the overall field operations cost. This in turn leads to using P-waves only in the subsequent processing. Although relative location algorithms relying on only P-waves will estimate a reliable epicentral position - even when using a homogeneous velocity model, the spatio-temporal location is achieved with both an incorrect origin time and a significant vertical uncertainty. Theoretically speaking, including S-waves puts additional constraints on origin time which in turn improves the overall location accuracy. This approach is common in global seismology (e.g. James et al., 1969, Gomberg et al., 1990) and in downhole microseismic monitoring (Eisner et al., 2010). Cieplicki et al. (2013) have recently shown an example of combined modes hypocentral determination using a surface network. Implementation of P and S combined processing requires reliable propagation times i.e. at least a 1D velocity model. Moreover, Kolinsky et al. (2009) showed using S-waves in hypocentral location does not improve the accuracy unless anisotropy is taken into account. These issues are however of second order when considering relative detection and location methods.

This abstract demonstrates the feasibility of a joint use of P- and S-waves with surface monitoring network. Using the best quality microseismic events from a dataset recorded with three components sensors; we first estimated an optimal velocity model through simulated annealing. We subsequently used it to detect and locate smaller events in a relative way.

Method

To decrease uncertainty in a microseismic events location and detection, we used P-, Sh- and Sv-waves. We used the data set from hydraulic fracturing monitoring, recorded by 15 three components sensors. Additionally, we derived a 1D, 10 layers velocity model from a VSP.

Simulated Annealing

Seismic tomography, which is used to constrain velocity models, is solved as an inverse problem. We minimized a first arrivals time-based cost function using a subset of 13 strongest microseismic events. The relationship between travel times and distance is non-linear. Furthermore, the optimization problem is under-determined, which increases the complexity of a cost function. Henceforth, we need to explore non-linearly the space of possible solutions, to find the global minimum. For this reason we used a simulated annealing method (Kirkpatrick S., 1983). The aim of the velocity model inversion it is to minimize time residuals between observations and modeled arrival times.

Following Bardainne and Gaucher (2010) we conducted a test for complexity, repeatability and coherence to find the best possible inversion. The number of inversion parameters depends on the velocity model which is to be used and the result of each inversion is repeatable and independent of the initial model. To calculate travel times, we used analytical and numerical modules (time 3 D - based on the 3D eikonal equation developed by Podvin and Lecomte (1991) and an anisotropic ray tracer).

Relative detection and location

To detect and localize microseismic events we use a relative migration-based approach which involves three steps: beamforming, joint detection and joint location. First, we correlate the data with a template which is one of the events used in the velocity calibration. All locations will be relative to the template's hypocenter.

Cross-correlating amounts to applying the average propagation from the hypocentral region to the array. The origin time and hypocentral coordinates are estimated with a grid search in a volume surrounding the template: each perturbation on the template's coordinate is translated as a move-out applied to the correlation functions. Each trace is sign corrected before being stacked all together into a time and space dependent curve, whose 4D maximum provides hypocentral coordinates and origin time. Finally, reliability of detections is checked. Obviously, relative location simplifies many issues. Effectiveness of this method depends less on a velocity model or statics.

Examples

Final results show that using P- and S-waves in microseismic location minimizes vertical uncertainty (figures 1, 2 and 3). The use of P- and S-waves gives more constrained locations and a suitable velocity model reduces even further the uncertainty.

We tested different velocity model parameterizations: gradient velocity model, 1D multi-layer blocky model, multi layers gradient velocity model, anisotropic layered model. Best results were obtained with the latter parameterization. Finally, both the anisotropic and the homogeneous velocity models have been used to re-locate events while using P-, Sv- and Sh-waves. The calibration of the anisotropic model was based on the residuals minimization of absolute relocation of the 13 biggest events which were picked. To compare, we also used the homogenous velocity model, because it allows analytical travel-time calculations and it is commonly used in a method of relative detection and location. However, the homogenous model does not give correct results in a method of absolute relocations.

Adding the S-phase to the localization algorithm improves the localization focus (figures 1, 2 and 3). Moreover, using P- and S-waves to perform the detection on a complete fracturation stage increases the sensitivity – we find more microseismic events.

The localization method uses the difference between modelled travel times for a template position and event position, which minimizes importance of a velocity model.

Therefore, using the homogeneous model and P- and S-waves with a relative method gives satisfactory results (figure 2), which is not possible with an absolute location method. The main contributor in reducing the uncertainty in the vertical direction is the simultaneous use of P- and S-waves (table 1). Moving from isotropic and anisotropic velocity model is a second order improvement. However, the anisotropic velocity model constrains the most microseismic location. Reducing the uncertainty in vertical location by 200ft (table 1) is not negligible if we consider depth and thickness of a shale gas reservoir.

Table 1 *The difference between vertical uncertainties (higher than 0.9) for microseismic location done with P- waves and P- and S- waves with homogenous velocity model, P- and S-waves with anisotropic velocity model.*

P waves, homogenous model	P and S waves, homogenous model	P and S waves, anisotropic model
2800 ft	1000 ft	800 ft

Conclusions

Relative location using P- and S-phases reduces the trade-off between depth and origin time. In general, joined processing of P- and S-waves requires more complex velocity models. However, we showed that the method of relative location lowers the significance of a velocity model and in general simplifies all the issues connected with S-wave utilization. The location - while using only P–waves - is poorly constrained and adding an S phase gives significant improvement, even with the homogenous velocity model. Our results show that the use of an optimized velocity model and P- and S-waves decreases even more the uncertainty in vertical direction. Reducing uncertainty gives more reliable microseismic events positions, what provides more trustworthy information about fractures in reservoir and easies hydraulic fracturing operations.

The optimized velocity model will become more important for the events located further from the template which is why we anticipate using 3D anisotropic models for increased accuracy. We are also planning to use S-waves recorded only on the vertical components in order not only to reduce costs but also to use data recorded with different acquisitions (e.g.: patch).

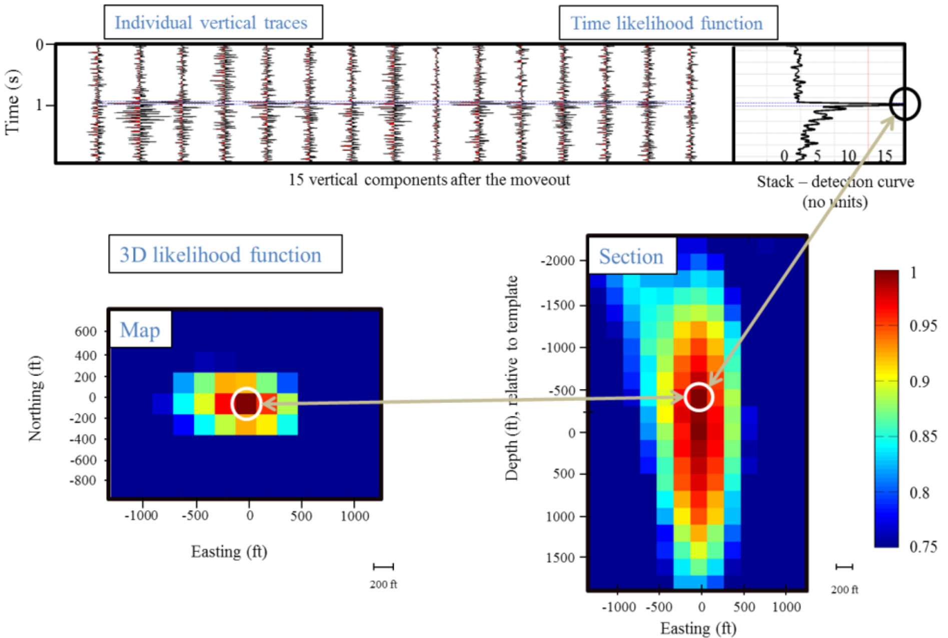

***Figure 1** Results of re-location using P- waves and homogenous velocity model. The maximum of the detection curve corresponds to the event localization in space. Strong, vertical uncertainty on cross-section (right side) is visible. Depth of the event: 11160 ft. Presented coordinates are relative to the template position.*

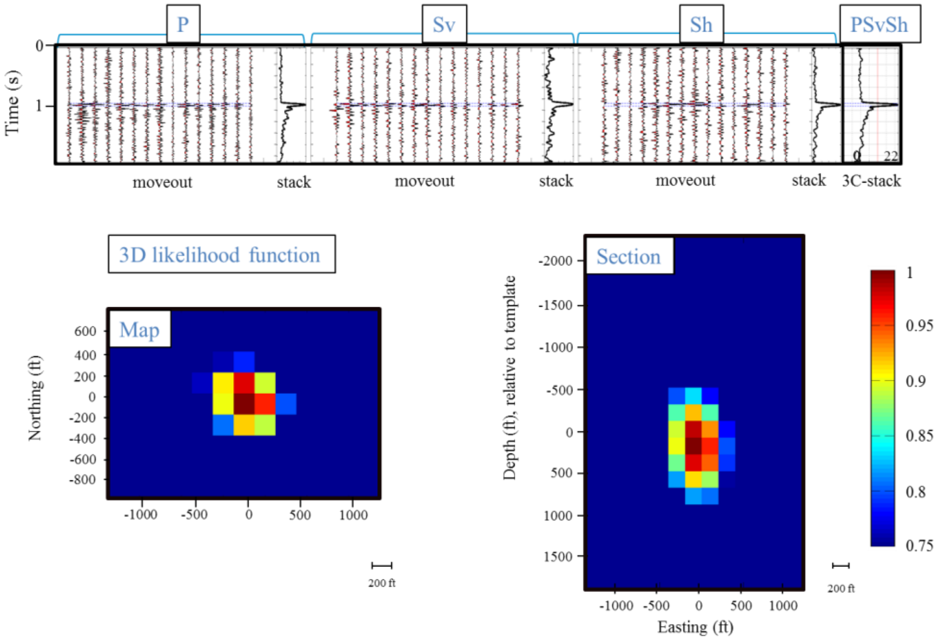

***Figure 2** Results of re-location using P- and S-waves and homogenous velocity model. Vertical and horizontal uncertainties are significantly reduced. Depth of the event: 11355 ft. Presented coordinates are relative to the template position.*

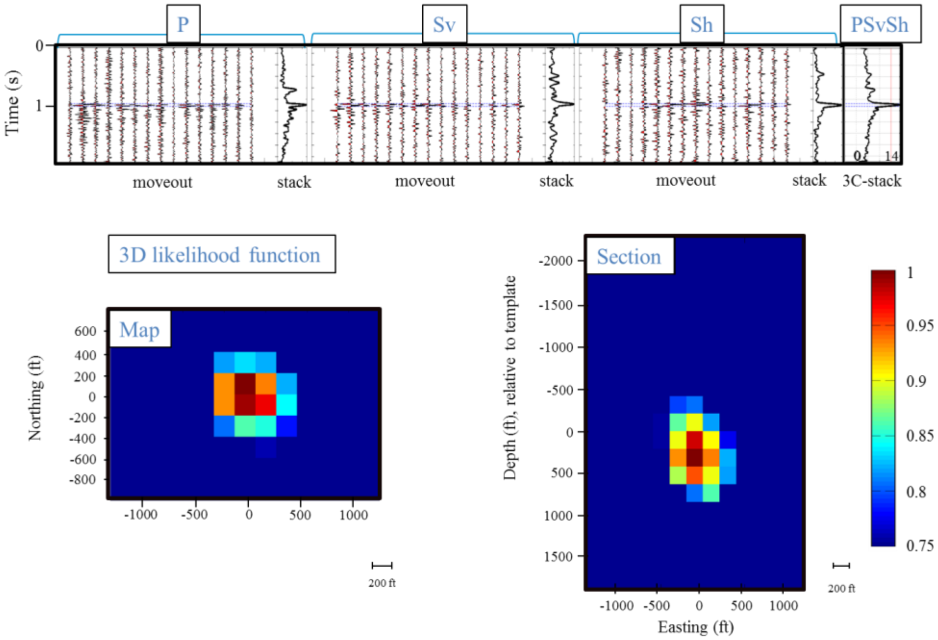

***Figure 3** Results of re-location using P- and S-waves and anisotropic velocity model. The constraint in horizontal and vertical position is the strongest. Depth of the event: 11400 ft. Presented coordinates are relative to the template position.*

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