Moment tensors of events induced in Cotton Valley gas field from waveform inversion.

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Abstract

Induced microseismicity resulting from hydraulic fracturing is routinely monitored to provide essential information about a three-dimensional (3-D) geometrical shape of fracture on the scale of 10s to 1000s of meters. However, a better understanding of how the microseismic events are related to the fracture growth may provide crucial information about the fracture itself and reservoir properties, which can be used to increase reservoir production. The fundamental question remaining is whether the observed microseismic events are caused directly by propagation of the fracture itself (fracturing events) or if they are a result of the released tectonic stress that is due to increased pore pressure (leak-off events). Both interpretations lead to the possibility of the increased production: the first interpretation allows mapping of the fracture pattern in a very accurate and detailed way, providing a very good image of the drainage pattern. The second interpretation allows measurement of stress changes in the reservoir, its connectivity, and many other reservoir characteristics. Nolen-Hoeksema and Ruff (2001) give a good overview of the related research. Recently Urbancic and Zinno (1998) observed in the Cotton Valley dataset that the ratio of the radiated P- to S-wave energy decreases with distance from the treatment well. This increase was interpreted as volumetric injection of fracturing liquid in the vicinity of the treatment well. However, measurements of simple P- to S-wave energy ratios may be strongly biased because of rapidly varying radiation patterns of microseismic events. Inverting for the radiation pattern (moment mechanism), Rutledge and Phillips (2002) found that the ratio of the P- to S-wave amplitudes does not imply volumetric mechanism and is consistent with a pure shear. A point measurement of the ratio of P- to S-wave amplitudes is difficult to constrain. For this reason earthquake seismologists generally use waveform inversion to analyze the mechanism of seismic events (i.e., moment tensor determining the radiation pattern and its volumetric, tensile, and pure shear component).

Determination of source mechanism by waveform inversion is a routine task with long-period teleseismic data, which are processed by several groups or agencies providing catalogs of moment tensors of large earthquakes of magnitudes exceeding about 6: Harvard CMT, USGS, ERI catalogs. These groups use different methodologies to retrieve the moment tensor, but all of them apply deviatoric constraints to stabilize the solution; i.e., they exclude the volumetric component a priori. The reason for the deviatoric constraint of inversions is the sensitivity of the moment tensor solution to the model of the crust, which is usually poorly known. The use of long-period (low-frequency) data improves the obtained solution because the mismodeling of the crust is below the wavelength of the records inverted. However, model accuracy may be important when dealing with short-period (high-frequency) waveforms; i.e., with records of weak seismic events observed in local scale. For regional

earthquake inversion, the usual frequency range is 20-50 s (0.05-0.02 Hz) and location accuracy within 1 km. A typical source-receiver distance is 100-200km (Kawakatsu, 1995).

In the induced microseismicity studies the available frequency range is 25-400 Hz (for the Cotton Valley experiment) and location accuracy is on the order of meters (2 m for Cotton Valley dataset - Rutledge and Phillips, 2002) with a typical source-receiver distance of 500-1,000 m. Therefore, we need to know the velocity model with approximately 500 times greater accuracy in hydraulic fracture monitoring (HFM) inversions than in regional earthquake inversions. However, most of the HFM models consist of 50 to 100 m thick layers while regional inversions use one-dimensional (1-D) crustal models with layers several kilometers thick. By extensive synthetic experimentation it was demonstrated that inexact modeling of the medium (inexact Green's function) generates spurious non-double-couple (DC) components in the retrieved mechanism. Kuge and Lay (1994) pointed out that the non-DC components may be doubtful because of inexact modeling of the medium as well as imperfect location. Šílený and Vavryčuk (2000, 2002) studied the effect of the neglect of anisotropy of the medium during construction of its response; i.e., they inverted anisotropic waveforms by using isotropic Green's function only, and demonstrated the appearance of spurious non-DC components. It appeared that the crucial point for the success in retrieval of the mechanism was the ability to align the synthetics to the data in the course of the inversion independently on each of the components of the three-component records. This trick takes into account the existence of split S-waves in anisotropic media which propagate with different velocities, and effectively compensates the anisotropy by aligning each of the split S-waves to the single S-wave in the isotropic Green's function. The common conclusion of the synthetic experiment's inversion of high-frequency data by using inexact Green's function as a result of poor modeling of the medium is twofold: fairly robust reconstruction of the orientation of the deviatoric mechanism, and appearance of spurious source components, particularly non-DC components in the complete moment tensor even if the true mechanism was a pure shear faulting.

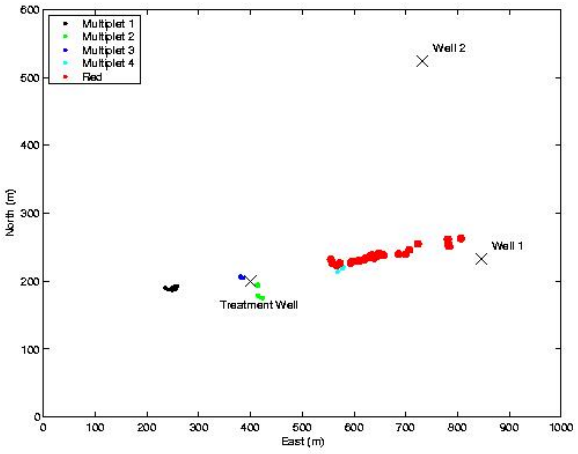

Figure 1: Map view of the HFM experiment at the Cotton Valley. The observation wells 1 and 2 are represented by crosses, the treatment well is near the center. Selected 75 microseismic events were divided into 5 groups: Red event on trend of fracture and 4 sets of 10 mulitplets of the main trend.

To test the waveform inversion technique we have used the best dataset available; the hydraulic fracturing experiment at Cotton Valley. Rutledge and Phillips (2003) give a good overview and analysis of this dataset showing that hydraulic fracturing induced seismicity along the natural fractures, and the mechanisms of the induced seismic events are consistent with these re-activated natural fractures. Figure 1 shows a map with locations of the strongest induced events. The selected 75 microseismic events (from a dataset of one thousand events) are the large events with a good signal-to-noise-ratio. These events were analyzed by Rutledge and Phillips (2002) using 10 stations in two observational wells (8 receivers in the Well 2 and 2 receivers in the Well 1). The absolute and relative locations were done in a 1-D

isotropic model derived from the acoustic velocity logs and modified to fit the travel-time data. The final velocity values in the 1-D model differ significantly from the observed acoustic velocity logs for some layers. It is possible that anisotropy of the reservoir would explain this difference. In this study we use the same 1-D model of velocities, extended by estimates of density.

Demands on the model increase with frequency of the waveforms being inverted; thus, we used the lower frequency part of the spectra to filter out complexities originated in scattering on small-scale inhomogeneities, which are not included in the 1-D model of the field. Band-pass filtering suppressed frequencies below 25 Hz and above 50 Hz, providing fairly simple smooth signals. The cut-off frequency of the filter is below estimated corner frequency of the seismograms (~300+ Hz), which allows us to avoid the search for the source time function (assuming delta function) and invert simply for the moment tensor only. The choice of the windows of the data and the synthetics to be matched is crucial: the choice of windows should ensure the proper alignment of individual phases in the waveforms of data and synthetics. Obviously, we have to be close enough to the proper alignment of the phases with major amplitudes, which are matched preferentially in the least-squares norm applied. Otherwise, a misalignment can occur, the synthetic phases that do not correspond to the phases in the records are matched. If the model of the medium is not exact, the delay of the major phase in the synthetics differs from that one in the data, which introduces a misalignment and results in incorrectly inverted moment tensor with artificial volumetric (or tensile) components. Therefore, synthetic seismograms should be allowed to align with the data during the inversion. Moreover, the process must be iterative, because synthetics depend on the mechanism, which is being determined. There are two options for alignment with three-component data: (1) it is performed simultaneously on all three components (synchronous alignment to correct for heterogeneity), or (2) it is determined independently for each component regardless of correlations on the others (asynchronous alignment to correct for anisotropy). The former option is the approach usually applied, while the latter one is reasonable if the medium is anticipated to be anisotropic (Šílený and Vavryčuk, 2000). This is just the case of the Cotton Valley gas field, as Rutledge and Phillips (2002) suggested: to explain arrival times for the sake of localization of the events, they deviated the model from the measured well logs and argued for anisotropy.

As an example of the procedure, Figure 2 shows results of the inversion of records of the strongest event of Multiplet 1 (see Figure 1) performed both without the alignment and with the asynchronous alignment. This event has excellent signal-to-noise-ratio in the 25 to 50 Hz frequency band. Reduction of the variance is not large, amounting to about 40% only (usual successful reduction of regional inversions results in 70+% variance reduction), which indicates the model is inaccurate. However, the option of asynchronous alignment helps to improve the fit, increasing the variance reduction from 41% to 50%. The most interesting feature is the change in the composition of the moment tensor. The inversion was performed for an unconstrained moment tensor, i.e., the moment tensor was decomposed into all three parts: volumetric (ISO), double couple (DC) and compensated linear-vector dipole (CLVD or tensile). There is 69% of the DC in the moment tensor retrieved without the alignment, while the percentage increases to 76% if the asynchronous alignment is applied. Non-DC components may be artifacts of inaccurate modeling. Therefore, their drop with the option of asynchronous alignment, which was proved by previous synthetics experiments to compensate partly the effects of anisotropy un-modeled in the Green's functions, may indicate that the mechanism of this event is actually a DC, which is partly masked by spurious non-DC components. The inverted strike and dip of the DC part are consistent with Rutledge and Phillips (2002) and Nolen-Hoeksema and Ruff (2001).

In summary, we have shown that the waveform inversion of moment tensor mechanisms is feasible for the low frequency data and it can provide unique information about the HF induced microseismic events, such as fracture planes and their volumetric/shear portion. The inverted properties of the microseismic events are in agreement with the previous study of Rutledge and Phillips (2003), i.e. the induced seismicity appears to be mainly pure shear with nearly vertical fault planes.

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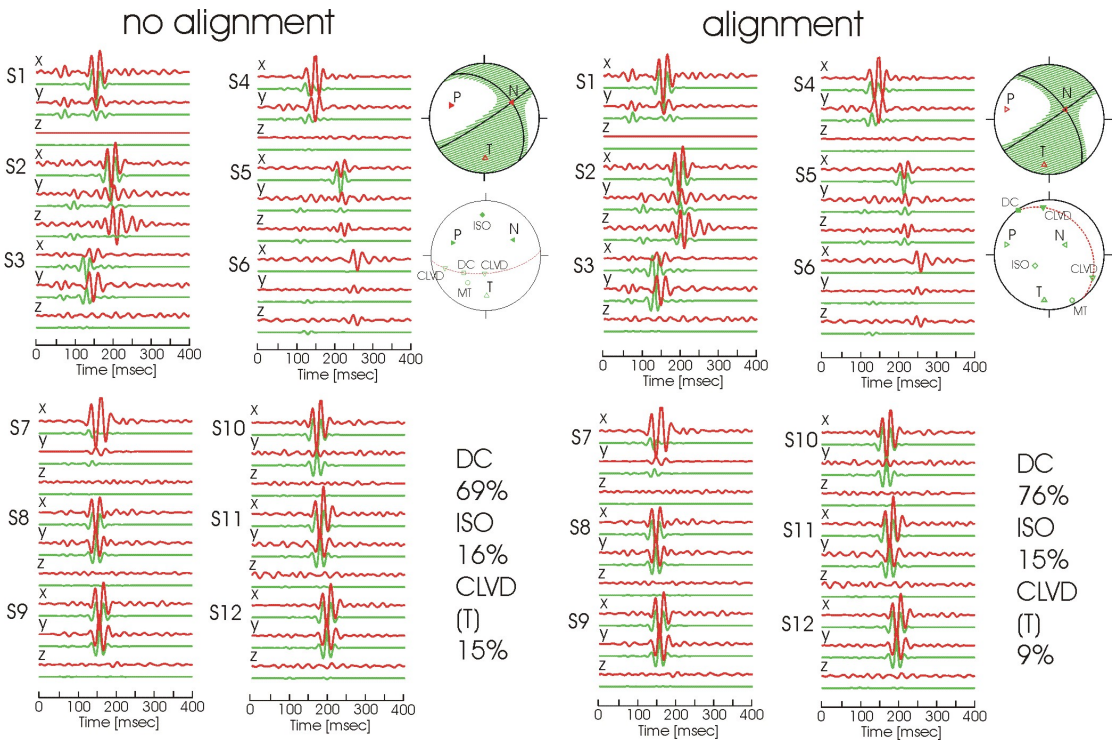

Figure 2: Example of the waveform inversion results for strongest event of Multiplet 1 of Figure 1. LHS shows inversion without alignment, RHS shows inversion result with the asynchronous alignment.