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4D Tomography and Deformation from Microseismic Data

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Summary

Microseismic data is used to calculate seismic deformation in response to hydraulic fracturing throughout a reservoir. This information is incorporated into a 4D tomography code that calculates changes in seismic velocity over the volume of the reservoir and as a function of time as deformation progresses. Changes in velocity are attributed to either deformation or the presence of fluids. A comparison is made between the velocity anomaly and deformation fields and is used to help distinguish between fluid induced changes in velocity and damage induced changes.

Introduction

Analysis of microseismic data is becoming increasingly important for understanding the effects of hydraulic fracturing on reservoirs. Typically, the locations of microseismic events are used to identify areas of active deformation and their fracture orientations and geometries provide information related to the development of the discrete fracture network. Used in this way, microseismic data provides information on discrete fractures at discrete positions and times in the reservoir.

While useful, it is an open question whether microseismicity is directly mapping the fully fluid-activated discrete fracture network or a combination of different affects, including damage induced fractures. Microseismicity is known to occur in regions surrounding the injection zone due to changes in stress and therefore may not always be indicative of the presence of fluids (Urbancic and Baig, 2013). On the other hand, fluids may move through the reservoir activating smaller fractures that do not generate microseismicity at the observable level as related to array geometry and instrumentation type.

Both deformation and the introduction of fluids will result in a change in the bulk properties of the reservoir. In this study, microseismic events are used as sources and travel time tomography employed to image changes in seismic velocity associated with hydraulic fracturing. Comparisons between regions of significant velocity change and regions of high deformation can then be made to help identify areas influenced by fluid injection. As such, this paper makes use of microseismic data to study both the discrete and bulk properties of the reservoir using one self-consistent data set.

Method

Microseismic events are processed to provide location and seismic moment release. The reservoir is discretized into a grid of 3D volume elements and the events grouped by the volume in which they occur. The seismic moments of the events are used to determine the time for which the cumulative moment in each volume is equal, for example, to 50% of the total moment for that volume. This provides an approximate time for each element that separates pre-deformation from post-deformation associated with hydraulic fracturing.

The velocity model used for the reservoir consists of a 1D background model (used to locate the events) and a 3D velocity perturbation, both of which are anisotropic. The 1D velocity model and its associated Thomsen parameters are derived from an inversion using perforation shots with known time and position and an initial velocity model based on local sonic logs. The 3D velocity model is comprised of a grid of volume elements (matching the grid discussed above) that conserve the anisotropy of the background 1D model and is obtained through the use of travel time tomography. The 1D model is a good representation of the local geology. The 3D model is meant to further capture small lateral variations and changes resulting from the hydraulic fracture treatment program.

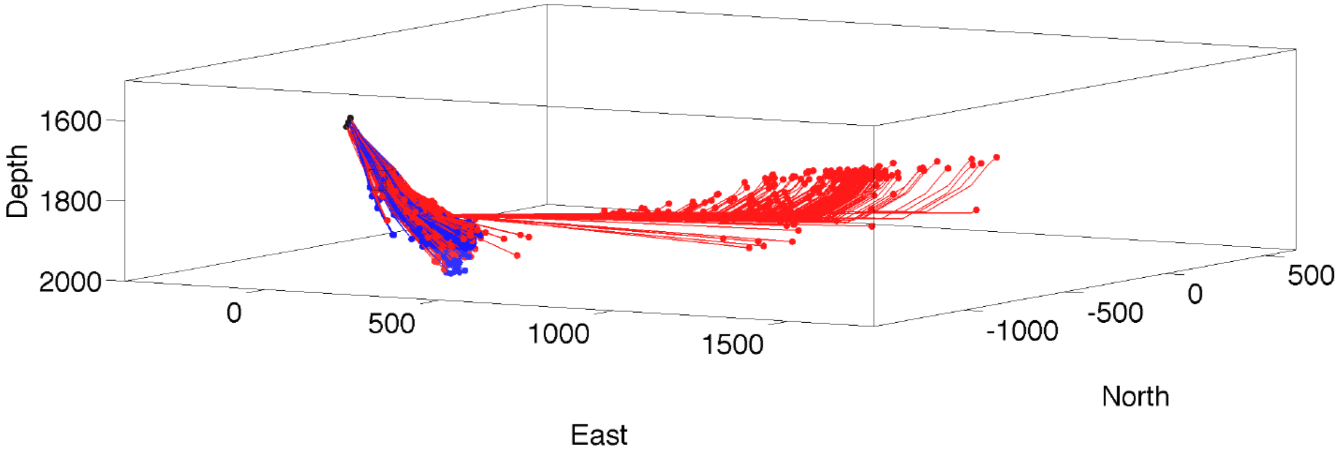

Figure 1: Ray paths passing through a volume element before (blue) and after (red) hydraulic fracturing. Colored dots indicate the position of the microseismic events and black dots represent sensors.

The 3D velocity perturbations are calculated using the microseismic data and travel time tomography which employs a modified form of the Simultaneous Iterative Reconstruction Technique (SIRT) to allow for an anisotropic velocity. Elements of the 3D velocity field with sufficient ray path coverage are permitted two distinct velocity values: one for pre-deformation and one for post-deformation. Rays traveling through an element prior to the deformation transition time will travel at the pre-deformation velocity while rays passing through afterwards will travel at the post-deformation velocity. Taking the difference between the post-deformation and pre-deformation velocities is expected to reveal changes directly associated with the treatment. Elements with little deformation or that lack appropriate ray path coverage will have only a single velocity value for all times.

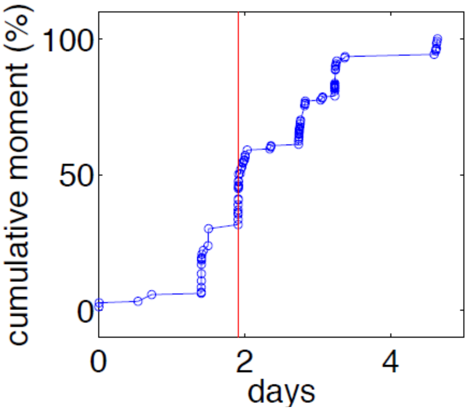

Figure 2: Cumulative moment for microseismic events occurring within the volume shown in Figure 1. The red line indicates the time at which 50% of the deformation has occurred.

Examples

Approximately 90000 microseismic events are observed throughout the hydraulic fracturing of the reservoir and processed to provide location and seismic moment release. The reservoir is divided into ~20000 equal volume elements and the deformation transition times calculated for each. Figure 1 shows ray paths through a single element before (blue) and after (red) deformation. Figure 2 shows the cumulative moment for all events within the volume element and the deformation transition time when 50% of the deformation has occurred. At this point the rock is considered damaged.

A subset of ~20000 high quality events are used to calculate the 3D velocity field as well as the change in velocity. Figure 3 shows results for a high resolution local study of the change in P-wave velocity in response to hydraulic fracturing around a single stage. A large drop in velocity is found directly on-zone and is likely the result of deformation.

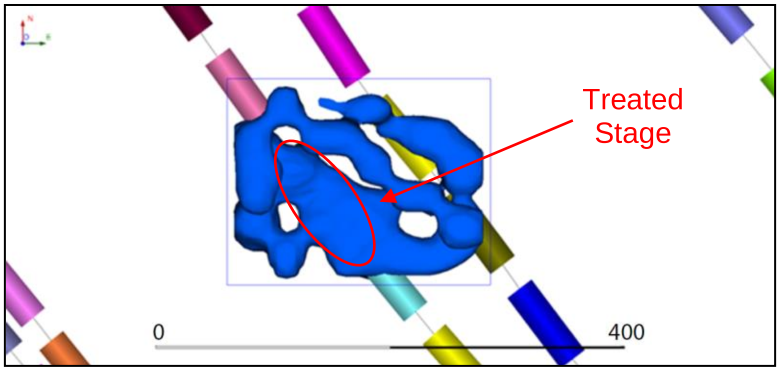

Figure 3: Hydraulic fracturing is observed to decrease the p-wave velocity. The blue iso-surface shows the volume that experienced a seismic *P*-wave velocity change of -400 m/s or more following treatment (the stage treated is outlined by the thin red line).

Figure 4 shows iso-surfaces at ±100 m/s for a global calculation of the velocity change throughout the entire reservoir. In general, a greater volume of the reservoir shows a decrease in seismic velocity than an increase following hydraulic fracturing. This is consistent with the idea that deformation should decrease seismic velocity.

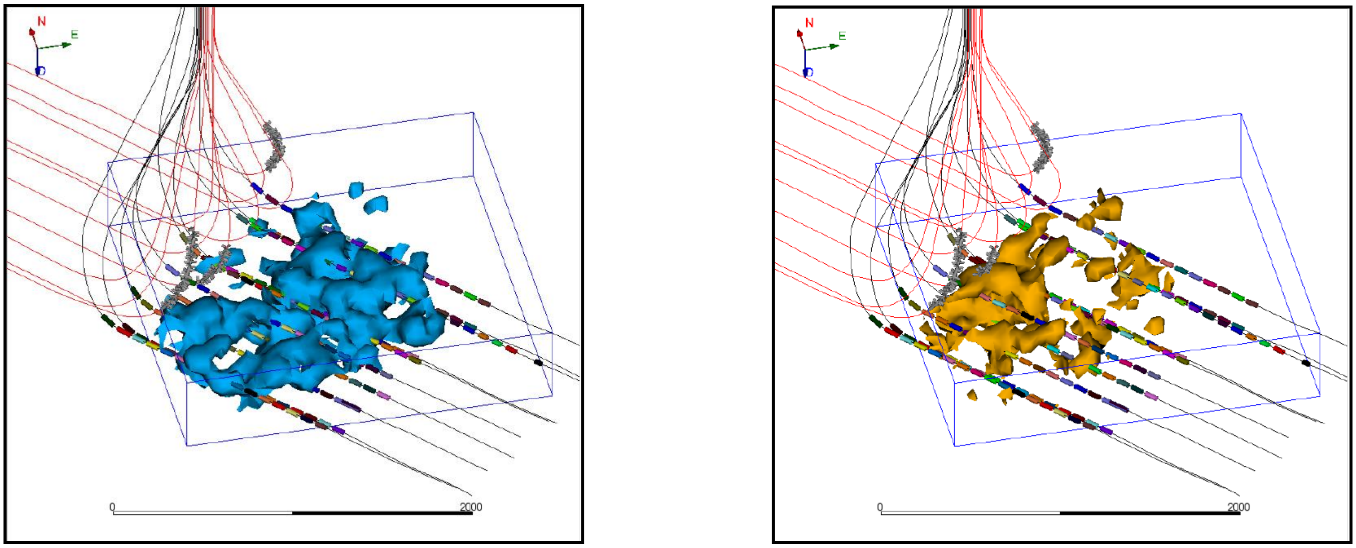

Figure 4: Iso-surfaces of -100 m/s (left) and +100 m/s (right) for the calculated change in velocity associated with hydraulic fracturing in the reservoir.

The majority of the positive velocity change shown in Figure 4 is observed close to the heels of the wells. One possible explanation for this involves the temporal evolution of stress in the reservoir. Hydraulic fracturing in the reservoir is accomplished via a zipper frac in which adjacent stages of wells are fractured together beginning at the toe of the well and progressing towards the heel. As fluids are injected into the reservoir peripheral stresses increase and diffuse outwards with time. Therefore, as the treatment program progresses from the toe to the heel there will be a gradual build up in stress. As such, it is possible that the increase in seismic velocity shown in Figure 4 is due to an increase in dynamic stress.

Figure 5 shows the distribution of P-wave travel-time residuals for rays before (left) and after (right) calculation of the 3D velocity model. Initially, using only the 1D background velocity model, the mean travel-time residual for the ray paths is 4.21 ms and the 90th percentile is 12 ms. With the calculated 3D perturbation model the mean residual decreases to 2.93 ms and the 90th percentile is reduced to 7 ms, demonstrating that the 3D model is effectively reducing travel-time errors. Remaining travel time errors are attributed to small lateral variations in anisotropy and mis-picks in the microseismic data.

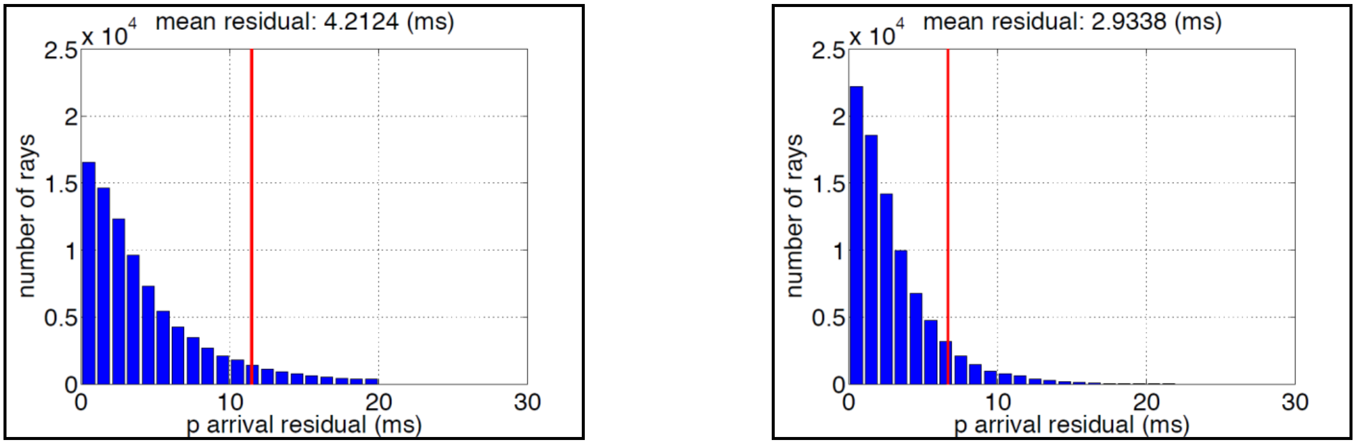

Figure 5: Distribution of travel-time residuals before (left) and after (right) the calculation and inclusion of the 3D perturbation for the seismic P-wave velocity. The red line indicates the 90th percentile for the travel-time residuals.

Conclusions

Travel time tomography utilizing microseismic data is employed to calculate changes in seismic velocity associated with hydraulic fracturing. Deformation times are calculated using the same microseismic data and this allows for true 4D tomography in which velocity changes continuously in both space and time. In the examples shown, velocity is found to be reduced substantially near the treatment zone. A more complete analysis of velocity changes and deformation rates over the full reservoir is ongoing and expected to provide useful information to help distinguish between microseismicity driven by fluid flow and dry events.

References

Urbancic,T. I. and Baig, A. M., 2013, Validating engineering objectives of hydraulic fracture stimulations using microseismicity, *First Break,* **31**, pp 73-79.