Feasibility Testing of Time-lapse Seismic Monitoring with Full Waveform Tomography

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Summary

Full waveform tomography reveals subtle sub-wavelength perturbations in the velocity model, given a sufficiently accurate starting model. Time-lapse seismic surveys over reservoirs are typically intended to detect small changes in a relatively well-known overall velocity field due to localized effects such as CO_2 injection, steam injection, petroleum production, and more. Full waveform tomography is ideally suited to detect and reveal the extent of these effects, both spatially and in terms of the magnitude of the effect on the velocity. Our early investigations strongly suggest that waveform tomography deserves serious consideration as a primary analysis tool for time-lapse seismic analysis.

Introduction

Waveform tomography represents a natural extension of the concept of standard traveltime tomography. In this approach, the whole waveform of the transmitted signal is used in the inversion process, rather than simply the first arrival time. This method originated 25 years ago with the work of Lailly (1983), Tarantola (1984), and Mora (1987). It has been subsequently developed by many others, including Woodward (1992). Lately the primary champion of this method has been Gerhard Pratt and his research group. A subset of these publications includes Pratt (1990), Pratt & Worthington (1990), Pratt *et al.* (1998), Pratt (1999), Pratt & Shipp (1999), Sirgue & Pratt (2004), and Brenders & Pratt (2007a, 2007b).

To date, applications of this method to the analysis of time-lapse seismic data have been sparse. We believe that this method is ideally suited to this analysis. In time-lapse analysis, it is common to have a well-established velocity model of the relevant geology, due to past surface seismic surveys, VSP investigations, and well-log data. The waveform tomography process requires a sufficiently accurate starting model, typically constrained by requiring that modelled diving waves travelling from source to receiver in the starting model must be within a half wavelength of the actual recorded data (Pratt, 1999).

Given a velocity model that accurately models the first-arrivals of seismic waveforms on a baseline survey, it may be possible to use this method to analyze time-lapse changes in the imaged region. Subtle local perturbations to this velocity field should be recoverable given sufficient data. The purpose of this study is to investigate two major questions. First, is waveform tomography feasible for time-lapse monitoring? Second, if so, what acquisition parameters would maximize the effectiveness of this method?

Inversion testing and results

Our primary test model is a laterally-homogeneous section derived from the horizontal extension of a P-wave sonic log from the Pikes Peak field. A perturbation of -500 m/s over an area of approximately 100m horizontally and 30m vertically is introduced to simulate the effect of steam injection on the p-wave velocity of the region (Figures 1 and 2). Raytracing (Figure 3) through a smoothed version of this velocity model reveals that our survey size is sufficient to capture the diving waves that pass through the perturbed region. The model dimensions were constrained by computational limitations.

The forward modelling was performed on the perturbed model using the 2D acoustic frequency-domain finite difference code, "OMEGA", developed by Gerhard Pratt. The simulated seismic surface reflection survey was recorded with receivers placed along the surface of the model at 10 m spacing. Sources were placed with 20 m spacing. Sources and receivers were located across the entire 2000 m extent of the survey. The waveform tomography inversion was then performed using the original (unperturbed) background velocity model as its starting point. Constant-frequency inversions were carried out with Gerhard Pratt's "FULLWV" software, beginning at 5 Hz, and then using this result as input into a 6 Hz inversion. Although in many cases it is possible to use many (or few) frequencies to optimize the convergence (Sirgue & Pratt, 2004), for this inversion we found that results were best with an inversion beginning no higher than 5 Hz, and that beyond 6 Hz no appreciable improvement was detectable. All inversions were constrained to update the model within a region of 500 m by 500 m, centred at the anomaly. This stabilizes the inversion. This constrained region is shown in all difference plots of the inversion results.

The updated velocity model with the 5,6 Hz inversion is shown as a difference-plot with respect to the starting (background) velocity model in Figure 4, zoomed into the region of interest shown in Figure 2.

The same starting velocity models were also used in a simulated VSP survey. In this survey, source locations across the 2000m extent of the model were used at 20m spacing. Receivers were placed in a borehole from 300m to 600m deep, at 10m spacing. This well bore bisected the perturbed (steam-injection) site. This borehole is marked in green in Figure 1. The updated velocity model with the 5,6 Hz inversion is shown in Figure 5, again as a difference-plot with respect to the starting (background) velocity model zoomed into the region of interest shown in Figure 2.

Conclusions and future work

The waveform inversion procedure is providing significant updates to the background velocity model at well below the wavelength scale. Both surface seismic and VSP approaches yielded useful updates to the model that were consistent with the true anomaly both in terms of spatial extent and in magnitude. Although the maximum amplitude of the anomaly (~300 m/s for the surface seismic, and ~400 m/s for the VSP survey) is somewhat less than the true amplitude (500 m/s), this is not surprising as the discovered spatial extent of the anomaly is somewhat larger than the true anomaly.

Both images gained the most benefit from 5 Hz data, with some minor improvement with the addition of 6 Hz. Although it was hoped that higher frequencies would focus the image better, in practice, higher frequencies did not converge effectively within the region of constraint. We are investigating the reasons for this with further modelling studies.

The results we have seen strongly indicate that waveform tomography merits further investigation as a viable method for analyzing a time-lapse signal in seismic data. Both surface and VSP methods provided comparable images, with slightly better results from the VSP method.

Seismic sources and acquisition geometry considerations are significant. First, this ``ideal conditions'' inversion required 5 Hz data. Although explosive-source surveys easily contain this frequency and lower, vibration-source surveys often begin their sweep at frequencies higher than 5 Hz. Second, raytracing revealed that only the longest offsets (nearly 2 km for a 500 m deep target) contributed significantly to the inversion. Also, VSP surveys are useful for reflection surveys, but in this case there was very little difference in results. We speculate that a crosswell survey or a VSP in a nearby observation well, either providing many raypaths travelling through the zone of interest, will yield improved results.

There are many open issues that will be addressed in the near future. First, we intend to move beyond the forward-modelling tools built into the inversion software program to allow us to investigate the impact of elastic effects and more. Second, as we gain familiarity with the inversion software, we expect to fine-tune our procedure, and optimize the selected frequencies for the inversion following Sirgue & Pratt (2004). Third, we will investigate the optimization of acquisition geometries, including testing cross-well surveys, to allow broad-band signals to propagate effectively through the target region more easily. Fourth, we will begin the inversion with a more realistic seismic-derived background velocity model rather than the ``perfect'' background velocity model used in this investigation, including noise, unknown source waveforms, and more. Fifth, we will look to find the limitations of the method in terms of perturbation size and magnitude. Finally, we also hope to address the possibility of using this method to detect azimuthal anisotropy and fracturing within the reservoir.

Acknowledgements

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Figures

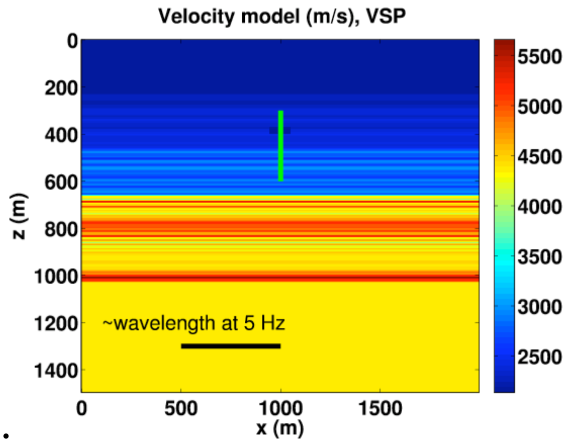

Figure 1: Full velocity model. The green line shows the location of the VSP.

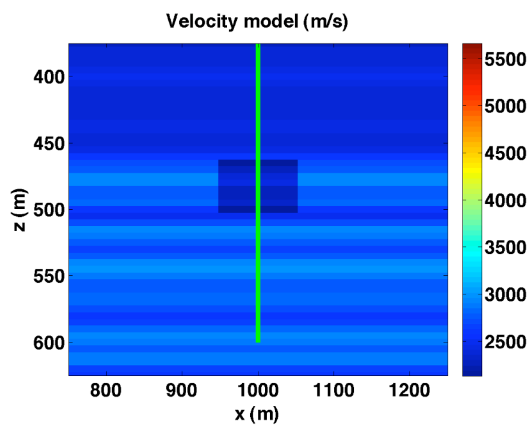

Figure 2: The steam-injection effect, with VSP marked in green.

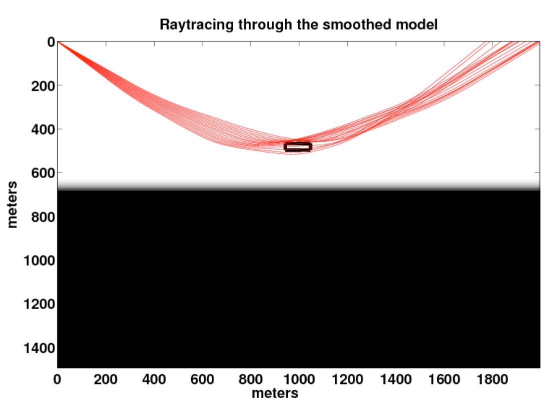

Figure 3: Raytracing through smoothed model.

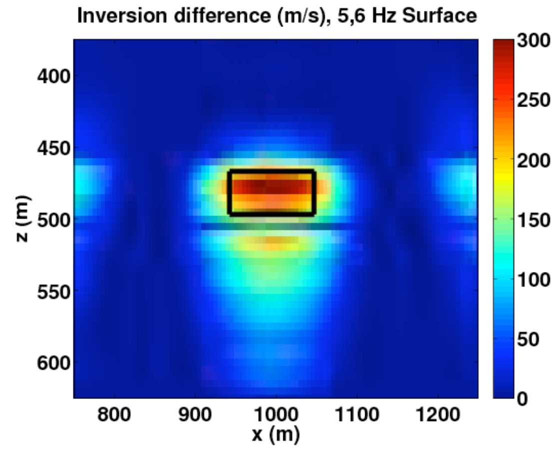

Figure 4: Recovered anomaly magnitude (surface seismic), with true chamber marked in black.

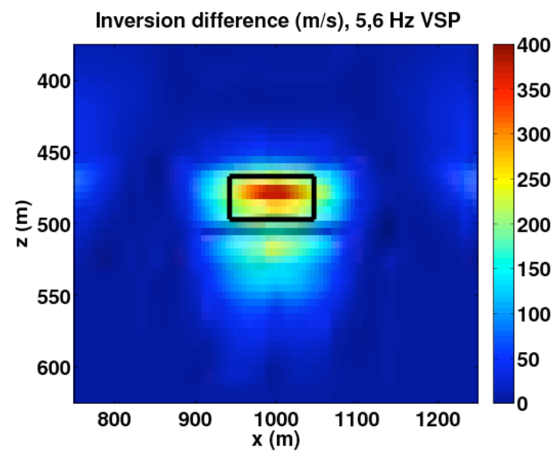

Figure 5: Recovered anomaly magnitude (VSP seismic), with true chamber marked in black.