# Coda wave interferometry analysis for poroelastic reservoir monitoring

Katianne Alcantara and Deane Roehl
Tecgraf Institute at Pontifical University of Rio de Janeiro
Rua Marques de São Vicente 225, Rio de Janeiro, Brazil 22453900

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## Abstract

The coda of seismic waves is the signal after the directly arriving phases and is dominated by waves that repeatedly sample the medium. Small changes due to reservoir processes, which may have no detectable influence on the first arrivals (e.g., those used in Full Waveform Inversion), are amplified by this repeated sampling and may thus be detectable in the coda. A synthetic scenario based on a field from the North Sea and the spectral element method (SEM) with implementation of poroelastic formulations were used to simulate the 4D seismic data. The reservoir velocity at the time of the monitor survey was changed by 2% relative to the baseline survey. The time lags are very sensitive to the velocity changes, suggesting that coda-wave interferometry analysis could be used to detect small time-lapse reservoir changes, if the signal-to-noise ratio of the 4D seismic effects is large enough and localization of the reservoir changes is possible.

## Introduction

The coda of seismic waves is the signal after the directly arriving phases, as shown in Figure 1. Coda waves are sensitive to small and distributed changes in the medium, as due to the scattering they follow longer paths, allowing a small space to be repeatedly sampled. This use of multiple-sampling coda waveforms is known in the literature as coda wave interferometry (CWI). The technique presented by (Snieder 2006), is capable of monitoring time-lapse changes in the wave field. One condition that must be satisfied for this theory to be applicable is that the scattering mean free path must be considerably larger than the wavelength. This can hinder the coda wave interferometry analysis using seismic waves acquired with low frequencies. With this condition, the primary change observed in a perturbed medium is in the phase of the wave field. Thus, as an example, a perturbation in the velocity propagation is correlated to a phase perturbation.

The velocity change induces measurable phase shifts in the coda. Snieder proposed to obtain the relative signal delay by cross-correlating two signals over a time window. Choosing the time window based on the source frequency, we perform cross correlation between the two signals, looking for the time lag with the maximum correlation. This value is saved as a function of the time in the window center. The time delay $\delta t$ between two signals with times $t_1$ and $t_2$ increases linearly with the travel distance $d$. The event duration $t_1$ is equal to the distance $d$ over the wave velocity $v_1$. Eq. 1 shows that time delay over original time $t_1$, can be written as the ratio of the velocity perturbation $\delta v$ by the original velocity $v_1$.

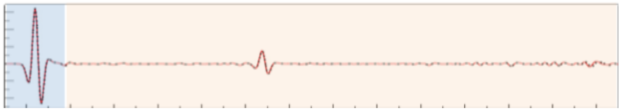

Figure 1 - First arrival (in blue) followed by coda wave (in orange).

$$\frac{\delta t}{t_1} = \frac{t_2 - t_1}{t_1} = \left(\frac{d}{v_2} - \frac{d}{v_1}\right) \div \frac{d}{v_1} = \frac{v_1 - v_2}{v_1} \approx -\frac{\delta v}{v_1} \qquad \text{Eq. 1}$$

We use the average velocity change $\langle \delta v / v \rangle$ from Eq. 1 for quantitative detection of reservoir changes. The algorithm correlates the synthetic data in each sensor used in the base acquisition with the corresponding sensor used in the monitor acquisition. The output is the time lag average $\langle \delta t / t \rangle$ as a function of sensor depth.

Zhou et al (Zhou, Huang, and Rutledge 2010), using synthetic and real VSP data, show that coda wave interferometry can be used to monitor $CO_2$ sequestration, estimating velocity changes in the order of 10%. Tang et al (Tang et al. 2015) detected changes in reservoir velocity of 2% using synthetic data from the elastic Marmousi II model. Based on this work we conducted numerical experiments in order to study the feasibility of coda wave interferometry for monitoring reservoir time-lapse characteristics. Using the VSP geometry, velocity changes of 2% were applied in a reservoir from the North Sea field using poroelastic simulations. Although our first results are promising, work needs to be done to define how to best implement the method in the field.

## Numerical modeling and CWI analysis

Numerical simulations of wave propagation in poroelastic media were based upon the spectral element method (SEM) with implementation of poroelastic formulations (Morency and Tromp 2008). The acquisition geometry mimicked a VSP acquisition with receivers positioned downhole in a well. Figure 2 shows the acquisition geometry with receivers at a spacing of 25 m and a shot at the wellhead. The source is a Ricker wavelet with dominant frequency of 15 Hz. A single shot was recorded for 4 seconds. The model consists of a free surface at the top with absorbing boundary conditions on the sides. The displacement is recorded at the receiver locations in the well. The properties for baseline synthetic seismic acquisition were based on a Field from the North Sea (Firme et al. 2014), Table 1 shows Vp and Vs values as a compilation of the materials poroelastic properties for base and monitor. For the monitor acquisition the reservoir permeability and porosity were altered due to changes in Vp and Vs of 2%.

| | **Depth (m)** | **Vp (m/s)** | **Vs (m/s)** |
|---|---|---|---|
| Water | 0-390 | 1500 | 0 |
| Overburden | 390-3800 | 3126 | 1064 |
| Upper Carbonates | 3800 - 4300 | 3788 | 1660 |
| Lower Carbonates | 4300 - 5050 | 5282 | 2689 |
| Upper Cap-rock | 5050 - 5200 | 4820 | 2643 |
| Lower Cap-rock | 5200 - 5600 | 2834 | 1255 |
| Reservoir (base) | 5400 - 5600 | 1321 | 719 |
| Reservoir (monitor) | 5400 - 5600 | 1347 | 733 |
| Underburden | 5600 - 6000 | 3927 | 2174 |

Table 1- Compressional wave velocity (Vp) and Shear wave velocity (Vs) as a compilation of base and monitor poroelastic properties.

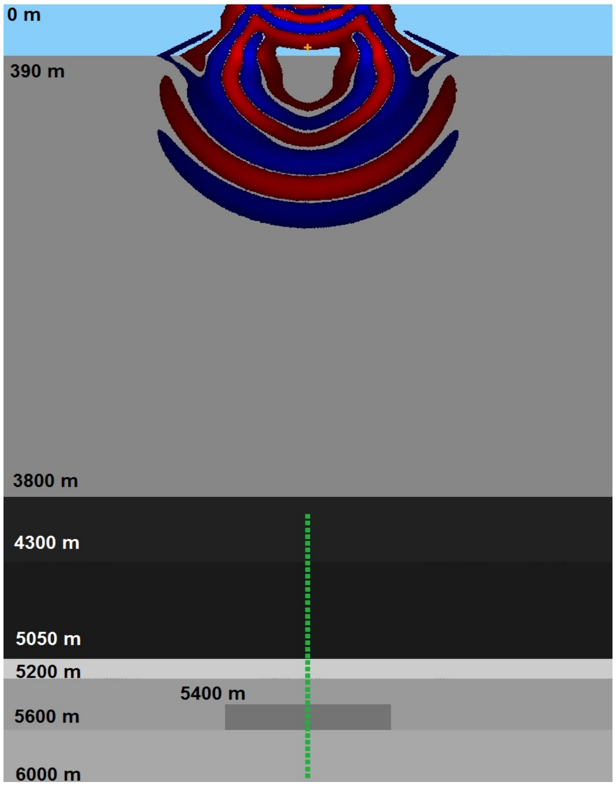

Figure 2 - A frame of the seismic wave propagation through the model.

Figure 3 shows a comparison between unperturbed and 2% perturbed velocity seismic records for the sensor at 5420 m depth (very near the top of the reservoir section). It is possible to observe small differences between base and monitor seismic traces, however the difference was not large enough to produce time shifts that can be seen without the interferometry analysis.

A systematic analysis was performed in order to determine the best temporal window length. Our results suggest that 3-4 times the wave period is enough to avoid oscillation of the results. The wave with 15 Hz has a period of approximately 0.07 s, thus we use a time window of 0.3 s. The CWI analysis was performed cross correlating each sensor in base and monitor. We average the values for the time lags over the VSP to obtain the mean $\delta t$ change for each receiver before and after the 2% change in reservoir velocity.

Figure 4 shows the absolute velocity change versus the receiver depth. Coda waves can detect the velocity changes taking place in the reservoir. Time shifts with values lower than the standard deviation are observed before and after the reservoir. This can be caused by reflections and refractions from the reservoir. The maximum absolute velocity variation was in the sensor immediately above the reservoir- cap rock interface. The value 2.63% ± 0.43 %, greater than the 2% inserted in the model, can be caused by layer reverberation or constructive interference, leading to an increase in the time shift. The sensors inside the reservoir present a decrease in the absolute velocity change. This is consistent with the response of a wave passing through a well in a poroelastic media. Wave propagation in poroelastic media is mostly affected by porosity and permeability, which change the wave speed and amplitude, causing attenuation. Although we have simulated a deep reservoir, the attenuation was not enough to impair the CWI analysis.

The results suggest that coda wave interferometry has potential as a method for reservoir time-lapse monitoring. Further work with smaller perturbations around 1% should be tested in order to determine the detection limits.

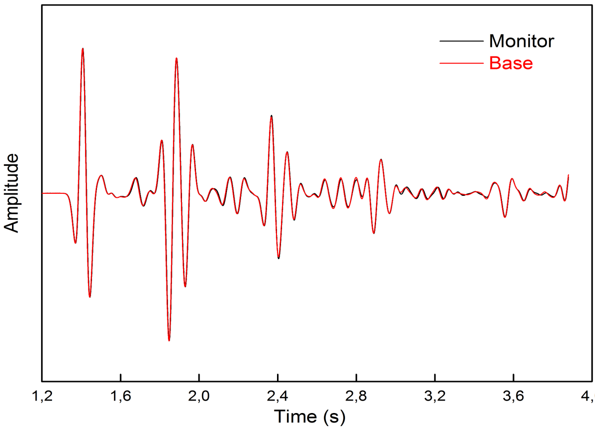

Figure 3 - Comparison between unperturbed and 2% velocity perturbation seismic records for the sensor at 5420 m depth; small differences between base and monitor can be observed.

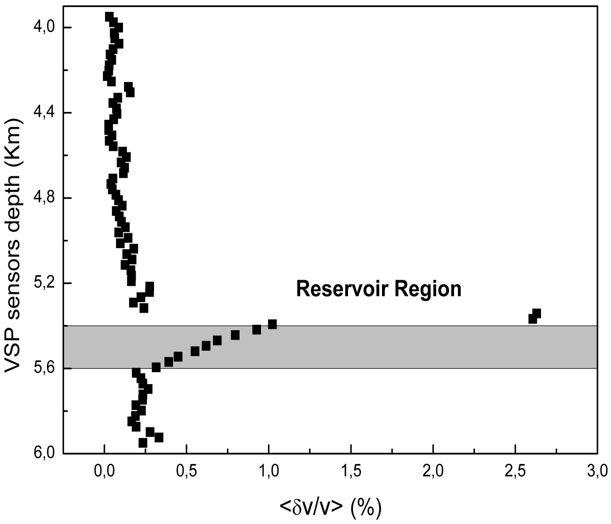

Figure 4 – Absolute velocity variation versus the receiver depth for the time-lapse VSP data.

## Conclusions

The sensitivity of monitoring systems to time-lapse effects such as changes in pressure, fluid, lithology, leakage from fractures, among others is an important issue in the oil and gas industry. Seismic processing is time expensive; a method that can provide a response in an early stage in terms of reservoir variations can be a valuable tool. We have investigated the application of coda wave interferometry as an option for this problem using synthetic time-lapse VSP data. Numerical simulations of poroelastic media reinforce that coda wave interferometry has potential as a method for reservoir time-lapse monitoring. The attenuation present in the poroelastic modeling, did not affect the CWI analysis, even with the synthetic scenario based on a deep reservoir in a North Sea field. We were able to measure small velocity variations. The larger time lags, and consequently, the maximum values for the absolute velocity variation, were found at the reservoir-cap rock interface, decreasing inside the reservoir layer. Further work will be required in order to determine the limits for time shift detection using coda wave interferometry and also the best geometry acquisition to detect these time shifts. The signal-to-noise ratio affects the 4D monitoring; thus, in the future we will examine this effect in our numerical simulations.

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