Coda-wave interferometry and time-lapse seismic reservoir monitoring

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Summary

Coda-wave interferometry employs the sensitivity of multiply scattered waves to detect minute changes of the propagation velocity. In most applications the underlying assumption is that the velocity changes take place approximately uniformly in a large region. Time-lapse seismic reservoir monitoring, on the other hand, aims to infer local time-lapse changes from seismic reflection measurements at the surface. Hence, coda-wave interferometry, applied directly to time-lapse seismic data for reservoir monitoring, cannot infer such local changes in a reservoir. Recently, we developed a Marchenko-based methodology to isolate the response of a target zone from the full reflection response. We apply this methodology to Troll-field data and successfully predict the internal multiples of the target zone. This confirms that in principle the Marchenko-based isolation method can be used to prepare time-lapse seismic data for coda-wave interferometry, which in turn can be used to infer time-lapse changes in a reservoir caused by production or storage of resources in the subsurface.

Coda-wave interferometry and time-lapse seismic reservoir monitoring

Introduction

Coda-wave interferometry, introduced by Snieder et al. (2002), employs the sensitivity of multiply scattered waves to detect minute changes of the propagation velocity. It has been applied in a wide variety of disciplines, such as inferring temperature changes in granite samples (Grêt et al., 2006), structural health monitoring of bridges (Stähler et al., 2011) and monitoring of changes in the interior of a volcano prior to an eruption (Sens-Schönfelder and Wegler, 2006; Brenguier et al., 2008). In all these situations the velocity changes are assumed to take place approximately uniformly in a large region. Time-lapse seismic reservoir monitoring, on the other hand, aims to infer *local* time-lapse changes in an aquifer, a geothermal reservoir, a CO_2-storage reservoir or a hydrocarbon reservoir from seismic reflection measurements at the surface, i.e., far away from the area where the changes take place (Lumley, 1995; Landrø and Stammeijer, 2004; Hatchell and Bourne, 2005; Macquet et al., 2019). Coda-wave interferometry, applied directly to time-lapse seismic data for reservoir monitoring, cannot infer such local changes in a reservoir. Recently, we developed a Marchenko-based methodology to isolate the response of a target zone from the full reflection response (van IJsseldijk and Wapenaar, 2023). This opens the possibility to monitor minute time-lapse changes in a reservoir from its primary and internal multiple reflections, with methods akin to coda-wave interferometry.

Review of coda-wave interferometry

We review the principle of coda-wave interferometry (Snieder et al., 2002; Grêt et al., 2006) at the hand of Figure 1. An ultrasonic impulse is sent into a granite sample and its response is observed by an ultrasonic receiver (Figure 1(a)). The sample is gradually heated from the inside by a heating coil. The ultrasonic responses for temperatures of 45 and 50 degrees centigrade are shown in blue and red, respectively, in Figure 1(b). Note that these responses contain long scattering codas. The insets in Figure 1(b) show the two responses in time windows around the direct arrival and far in the scattering coda. The responses in the window around the direct arrival show hardly any difference; however, in the window far in the scattering coda they show a clear time shift δt (which is quantified by applying a time-windowed cross-correlation). Apparently the temperature change gave rise to a change in the propagation velocity of the sample. Assuming the relative velocity change ($\delta c/c$) is constant throughout the sample, it is equal to minus the observed relative time change, i.e., $\delta c/c = -\delta t/t$. In this example the relative velocity change is in the order of -0.1%, which illustrates the sensitivity of the method.

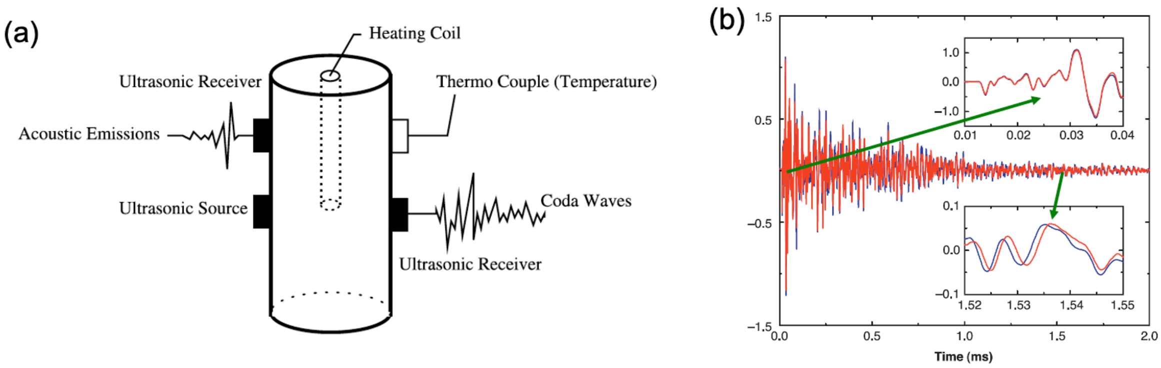

Figure 1 *Principle of coda-wave interferometry (from Snieder et al. (2002) and Grêt et al. (2006)).*

Can we apply coda-wave interferometry to time-lapse seismic reservoir monitoring?

Figure 2 shows numerically modelled time-lapse responses (baseline and monitor) of a target zone, consisting of a reservoir layer (light blue) between two reflectors. The half-spaces above and below the target zone are homogeneous. Time-lapse changes take place in the reservoir layer only. The rightmost frame shows the central trace of the baseline and monitor responses (blue and orange, respectively). The green

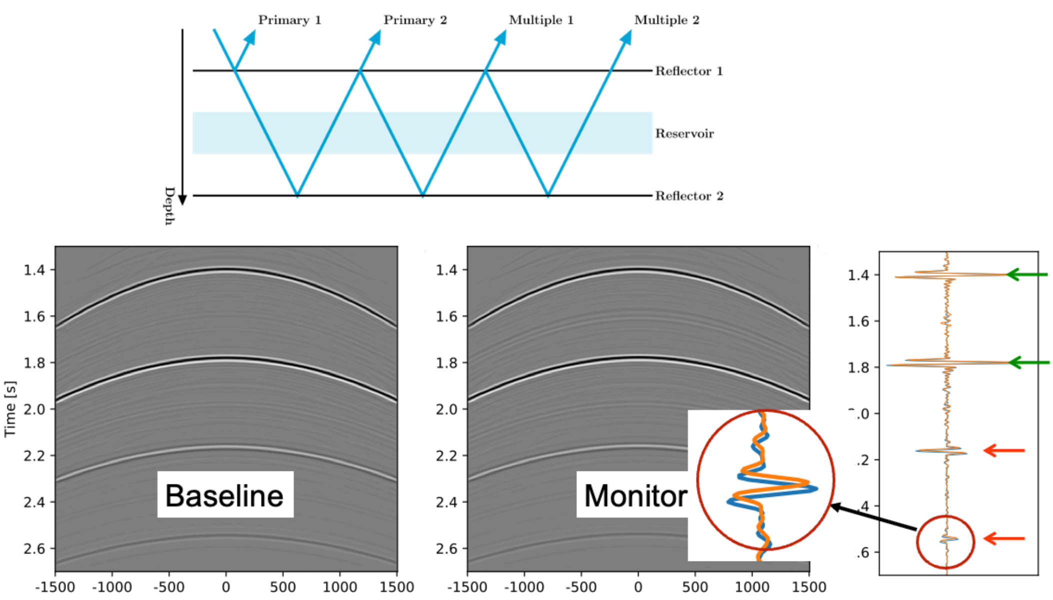

***Figure 2** Time-lapse responses for an isolated target zone.*

arrows indicate primaries and the red arrows internal multiples. The inset shows a time-window around the second multiple. Similar as in Figure 1, this coda-wave is sensitive to minute velocity changes in the reservoir layer. Figure 3 shows the time-lapse responses of the same target zone, but this time the target zone is embedded between an inhomogeneous overburden and underburden. The inset shows a time-window around the second multiple of the target zone. However, due to interference with the responses of the overburden and underburden, it is impossible to derive the velocity changes in the reservoir layer from these responses. To address this issue, we developed a procedure, based on the Marchenko method, which suppresses the responses of the over- and underburden from the total reflection response (van IJsseldijk and Wapenaar, 2023). This leads to an isolated response of the target zone (primaries and internal multiples), free from interference with the responses of the over- and underburden. In other words, this method retrieves the situation of Figure 2 from that of Figure 3. The only input that is needed (apart from the reflection data) is an approximate indication of the two-way traveltimes to the top and bottom of the chosen target zone. Cross-correlations of the primary of the upper interface with the primary of the lower interface and with the multiples yields the primaries and multiples of the target zone, observed at the upper interface. In case of time-lapse data, this target-zone isolation process is carried out for the baseline and monitor surveys. For further details we refer to the aforementioned paper.

Application to Troll-field data

We apply the methodology to a time-lapse marine dataset of the Troll field in Norway. Figure 4(a) shows a zero-offset gather of the baseline survey. The red and green lines indicate the primaries from the top and bottom of the target zone. The arrows indicate multiples from the overburden. The blue and orange lines indicate where the first and second order multiples of the target zone should be expected, but unfortunately the recording time was limited to 2 s, so no response is visible there. Figure 4(b) shows the situation after Marchenko-based isolation of the target zone for the baseline survey. The arrows indicate the suppressed multiples from the overburden. The predicted multiples of the target zone are now visible between the blue and orange lines. Figure 4(c) shows the difference before and after isolation of the target zone. Similar results are obtained for the monitor survey (Figures 4(d)- 4(f)). Next, for Figure 4(b) we correlate the second primary (green) and the two multiples (blue and orange) with the first primary (red) to retrieve the traveltimes of the primary and multiples of the target zone for the baseline survey. We do the same for the monitor survey (Figure 4(e)). The time-lapse changes

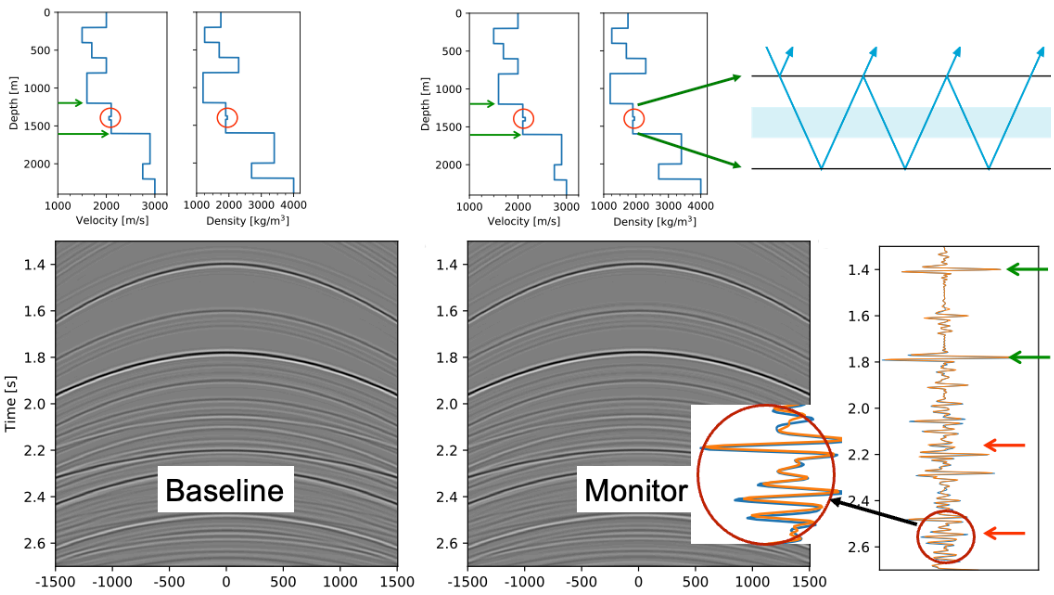

Figure 3 *Time-lapse responses for a target zone, embedded between an overburden and underburden.*

between the baseline and monitor traveltimes are shown in Figure 4(g) (primary 2 in blue, multiple 1 in orange and multiple 2 in green). The time-lapse changes for multiple 1 and 2 have been divided by 2 and 3, respectively, to compare them with the primary shift. Note that the match is very good, particularly in-between the red-shaded zones. Unfortunately the recording time was limited to 2s, which was too short to compare the predicted internal multiples with recorded internal multiples. Nevertheless, this example confirms that the Marchenko-based isolation method accurately recovers the target-related internal multiples.

Conclusions

We reviewed the principle of coda-wave interferometry. The relative velocity change of a medium can be derived from the relative time change in the late coda, assuming the velocity change is approximately uniform in a large region. This assumption is not fulfilled in time-lapse seismic reservoir monitoring, where the main velocity changes typically occur locally in a reservoir. We discussed that a Marchenko-based method can isolate the response of a target zone from the full seismic reflection response, with the aim to improve the determination of time-lapse changes in the target zone. We applied the method to Troll-field data and successfully predicted internal multiples of the target zone. This confirms that in principle the Marchenko-based isolation method can be used to prepare time-lapse seismic data for methods akin to coda-wave interferometry, which in turn can be used to infer time-lapse changes in a reservoir caused by production or storage of resources in the subsurface.

Acknowledgements

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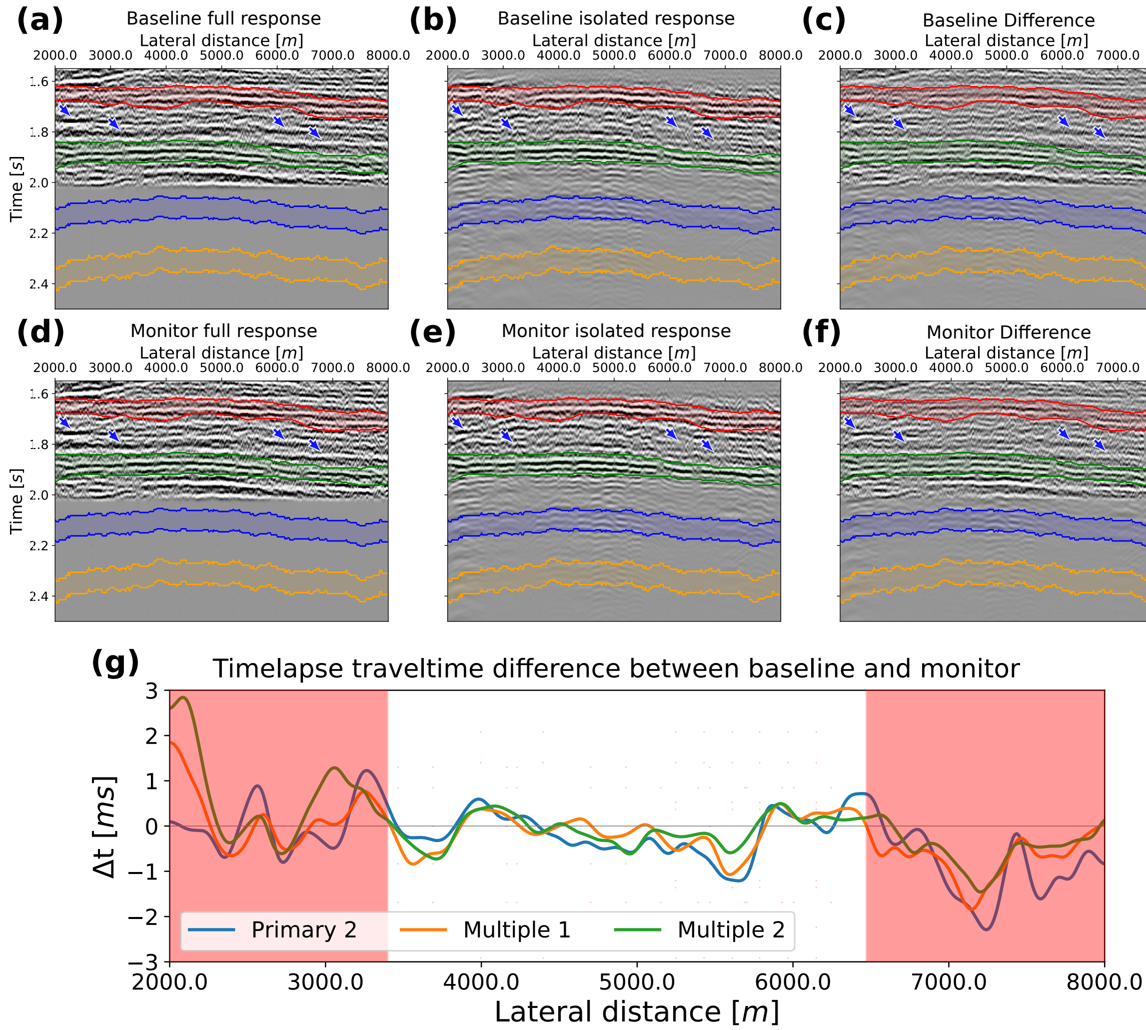

Figure 4 *Results of target-zone isolation applied to Troll-field data.*

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