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New method for discriminating 4D time shifts in the overburden and reservoir

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SUMMARY

Understanding seismic changes in the subsurface is important for reservoir management and health, safety and environmental (HSE) issues. Typically the changes are interpreted based on the time shifts in seismic time-lapse (4D) data, where sources are at the surface and receivers are either at the surface or in a borehole. With these types of acquisition geometry, it is more straightforward to detect and interpret changes in the overburden, close to the source and receivers, than changes in the deeper part close to the reservoir, because the time shift is accumulative along its ray path from source to receiver. We propose a new method for reconstructing the reflection responses of the overburden and the reservoir, separately, for 4D time shift analysis. This method virtually moves sources and receivers to a horizontal borehole level, which enables a more direct interpretation of the time shifts to the changes close to the borehole, instead of to the surface. A realistic field model is used to demonstrate the method, and we observe a clear discrimination of the different time shifts in the overburden and reservoir, which is not obvious in the original datasets.

INTRODUCTION

Seismic time-lapse surveys have become a standard tool (Landrø et al., 2003) for subsurface monitoring in the oil industry. Both surface reflection data and VSP data have been used to investigate subsurface changes using the recorded traveltime differences. Because time shifts are cumulative along the raypaths, with sources at the surface, the changes in the overburden (Meunier and Huguet, 1998; Guilbot and Smith, 2002; Røste et al., 2015), close to the source, are more commonly detected than those in the reservoir. Although formal results have been reported, such as Meunier et al. (2001) and Hatchell and Bourne (2005), the time shifts due to changes in the reservoir can be harder to pick out because of the signal's longer raypath to the surface, signal-to-noise ratio, multiple reflections in the data, and etc..

Here we propose to first redatum the data to have both sources and receivers in a horizontal borehole, and then estimate the 4D time shifts on the redatumed data. Different from previous virtual source methods (Bakulin and Calvert, 2004; Mehta et al., 2008) that retrieve the reflection of the underburden (or reservoir), our suggested scheme does not require multi-component data and is able to also retrieve the reflection response of the overburden from below, resulting in two redatumed responses for 4D traveltime analysis, one for the overburden and one for the reservoir. In addition, each of these responses is free from the internal multiples from the other side. More theoretical background on the redatuming schemes is given in the next theory section, followed by the numerical results obtained using a field model from the North Sea.

THEORY

The basic idea is to aim at retrieving the reflection responses of the overburden and the reservoir separately so that, for example, when analysing the 4D changes in the overburden, there are no interfering reflections coming from the reservoir, and vice versa. Secondly, because traveltime is accumulative along the ray path, it would be advantageous to have both sources and receivers in the borehole close to the target, so that the time shifts one would observe can be more easily interpreted as changes in the nearby overburden and the reservoir.

The essential ingredient we use here to achieve such separation is the so-called focusing function, developed in the theory of Marchenko method (Rose, 2002; Broggini et al., 2012; Wapenaar et al., 2013). Here we apply the two of the suggested redatuming schemes from Liu et al. (2016) for detecting 4D travel time shifts. Fig. 1 shows the flow chart of the redatuming schemes. Essentially, the schemes reconstruct the reflection responses at the borehole level using the surface reflection data and direct arrivals' traveltime in the borehole data. To retrieve the reflection response of the reservoir, we solve the following equation (Amundsen, 2001; Wapenaar et al., 2011) for $\widehat{\mathscr{R}}^{\cup}(\mathbf{x}_i^{'}|\mathbf{x}_i)$ in the frequency domain (indicated by the $\widehat{}$), using a damped-least squares approach (Menke, 1989),

$$\widehat{G}^{-}(\mathbf{x}_i^{'}|\mathbf{x}_0^{''}) = \int_{\partial D_i} \widehat{\mathscr{R}}^{\cup}(\mathbf{x}_i^{'}|\mathbf{x}_i)\widehat{G}^{+}(\mathbf{x}_i|\mathbf{x}_0^{''})d\mathbf{x}_i, \tag{1}$$

where $G^{-}(\mathbf{x}_i^{'}|\mathbf{x}_0^{''})$ and $G^{+}(\mathbf{x}_i|\mathbf{x}_0^{''})$ are the up-downgoing wavefield at the borehole level ∂D_i. They are constructed using the focusing function and the surface reflection response. For finding the focusing function, an iterative Marchenko scheme (Wapenaar et al., 2014) is used with the inputs shown in Fig. 1. However, with our approach, the initial estimate for the focusing function is derived from the borehole data (instead of some model-based estimate), which is important in order to capture the subtle changes in the base and monitor states. To retrieve the reflection response of the overburden from below, we solve the following equation for $\widehat{\mathscr{R}}^{\cap}(\mathbf{x}_i^{'}|\mathbf{x}_i)$,

$$-\left\{\Theta\left[\int_{\partial D_0} \widehat{f}_1^{+}(\mathbf{x}_0|\mathbf{x}_i^{'})\widehat{\mathscr{R}}^{\cup}(\mathbf{x}_0^{''}|\mathbf{x}_0)d\mathbf{x}_0\right]\right\}^{*} = \int_{\partial D_i} \widehat{\mathscr{R}}^{\cap}(\mathbf{x}_i^{'}|\mathbf{x}_i)\widehat{f}_1^{+}(\mathbf{x}_0^{''}|\mathbf{x}_i)d\mathbf{x}_i, \tag{2}$$

where the superscript * denotes conjugation. The operator Θ means to first apply inverse Fourier transforms, followed by a time window which passes data only for $t < t_d(\mathbf{x}_i^{'}|\mathbf{x}_0^{''})$ (where $t_d(\mathbf{x}_i^{'}|\mathbf{x}_0^{''})$ is the direct arrival's traveltime), and then Fourier

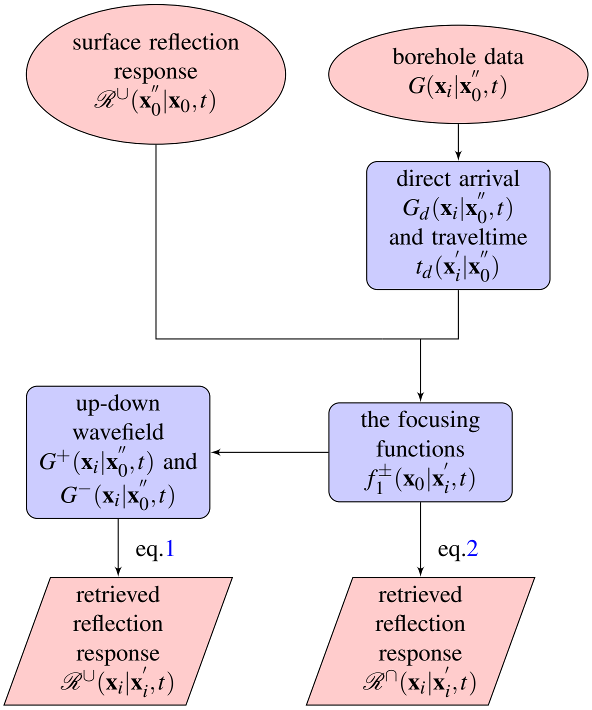

Figure 1: Flow chart for the redatuming schemes.The ellipses indicate the input and the trapezia indicate the output. The intermediate steps are indicated by the boxes.

transform back to the frequency domain. In this equation, $\widehat{f}_1^{+}(\mathbf{x}_0''|\mathbf{x}_i)$ is calculated using the iterative Machenko scheme. More details of the schemes can be found in Wapenaar et al. (2014) and Liu et al. (2016).

The redatuming flow (Fig. 1) is repeated for each 4D survey and yields two sets of reflection responses for the time shift estimation, one for the overburden and one for the reservoir. Then one can use a time shift estimation algorithm, such as crosscorrelation, for time shift analysis in the area of interest.

NUMERICAL EXAMPLE

We demonstrate the method using a field model in the North Sea. Fig. 2 a) shows the model and the acquisition geometries. It is assumed that the source signal deconvolution is applied in recorded datasets and the surface related multiples are removed from the surface data. The 4D velocity change is shown in panel b), where there is a maximum velocity increase of 6 m/s in the reservoir below the borehole and a maximum velocity decrease of also 6 m/s directly above the borehole. The velocity change in the overburden fades to a minimum at the depth of about 500 m, and then increases again towards the surface, while the velocity change in the reservoir diminishes monotonically with depth. Therefore, positive time shifts should be expected for the overburden and negative time shifts should be expected for the reservoir. Fig. 2 c) and d) shows the subsurface states and the virtual source and receiver positions in which the reflection responses are retrieved for 4D analysis. Notice that in each case, the other half of the model is homogenized, meaning that the interfering reflections from those places would be removed in the redatumed results. A few examples of the redatumed responses (in red) are checked against the modelled reference responses (in black) in Fig. 3. We see that most of the traveltime of the reflections match well, and in addition, there are indeed no interfering multiple reflections from the other side in both cases. Then we select the redatumed zero-offset traces from these two figures and plot the corresponding ones on top of each other in Fig. 4 a) and b). For comparison, the original borehole reflection data are plotted in Fig. 4 c). The ones with the 4D effects are in red, and the ones without are in black. With a closer look in this figure, we see that with the original data in c), the signals in red always have a traveltime delay. This is due to the velocity decrease in the overburden and the sources are at the surface. The velocity increase (negative time shift) in the reservoir can not be detected with a naked eye here, while in panel b), the redatumed response using our method, the signals in red are seen to arrive before the one in black, indicating a negative time shift. These negative time shifts are further confirmed by a standard cross-correlation estimation (Landrø et al., 2001), shown in Fig. 5 d), e) and f). For this crosscorrelation method, we first interpolate the responses to a sampling interval of 0.2 ms, and then use a crosscorrelation time window of 100 ms. Positive time shifts in the overburden are also correctly revealed, seen in Fig. 5 a), b) and c), while in Fig. 6, the time shifts estimated using the original borehole reflection data, the negative time shifts in the reservoir are not detected. Furthermore, by comparing Fig. 4 a), b) with that in c), we notice that the individual reflection events from the overburden and the reservoir can be more clearly identified for traveltime picking after the redatuming, which would facilitate further processing and interpretation, such as horizon identification and so on. Also notice that these new time shift estimates are cumulative from the borehole, instead of from the surface, therefore this proposed approach would complement well to those 4D analyses on the shallower part of the overburden (Osdal and Landrø, 2011) using surface surveys.

CONCLUSIONS

We apply two redatuming schemes based on interferometry and the Marchenko method to retrieve the separate reflection responses of the overburden and reservoir for 4D traveltime analysis. We show that these schemes are effective for discriminating the traveltime shifts in the overburden and reservoir. The method is completely data-driven and requires only single-component data. The numerical experiment shows promising potential for reservoir monitoring and field management, especially for deep reservoirs.

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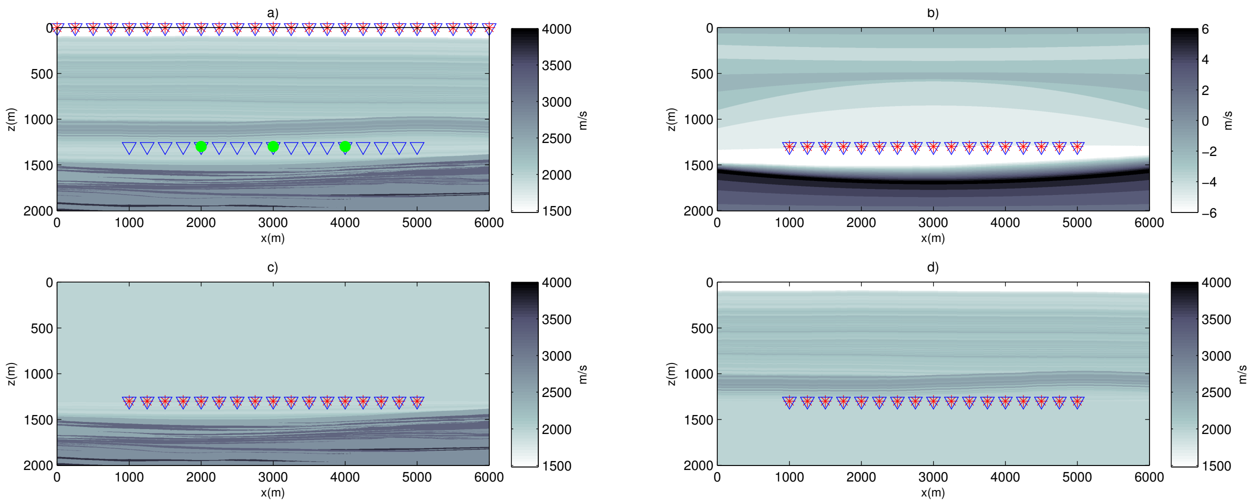

Figure 2: P-wave velocity model and datasets geometries. a) The P-wave velocity model for simulating the synthetic data. b) The 4D velocity anomaly. c) and d) are the subsurface states in which the redatumed responses of the reservoir and the overburden are retrieved, respectively. It is reflection-free in the overburden in c) and also in the underburden in d). The stars denote sources and the triangles denote receivers. The green dots indicate the positions of the reference shots.

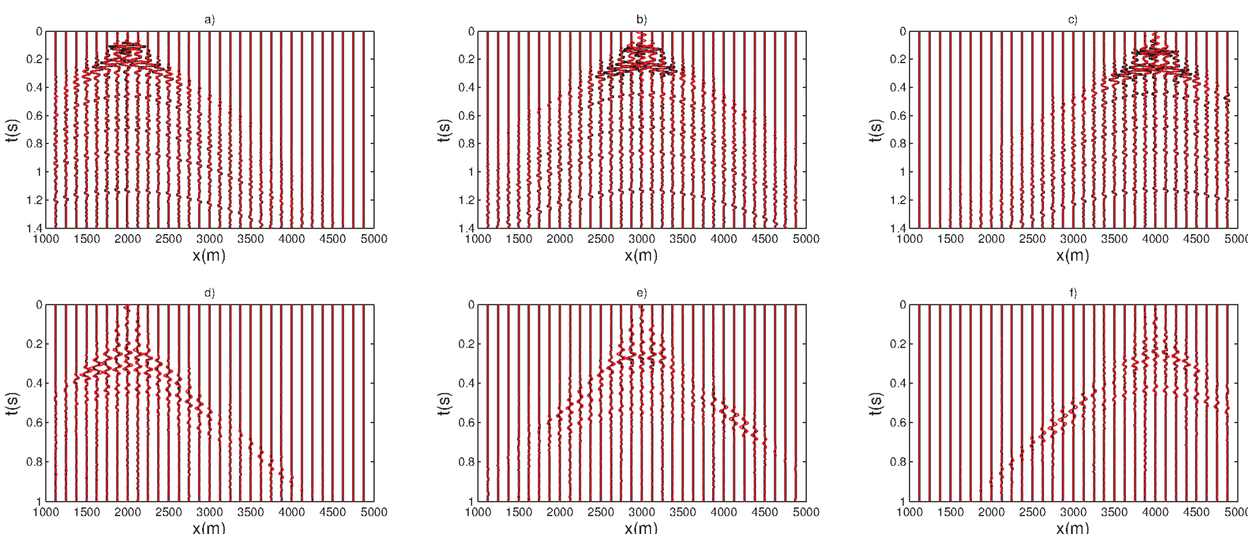

Figure 3: Comparison of the retrieved reflection response (in red), using the base datasets, with the directly modelled response (in black). The top row is the response of the overburden, and the bottom row is that of the reservoir. The source position in a) and d) at 2000 m, b) and e) at 3000 m, and c) and f) at 4000 m (indicated by the green dots in Fig. 2). These responses are retrieved in the states as in Fig. 2 d) and c), respective.

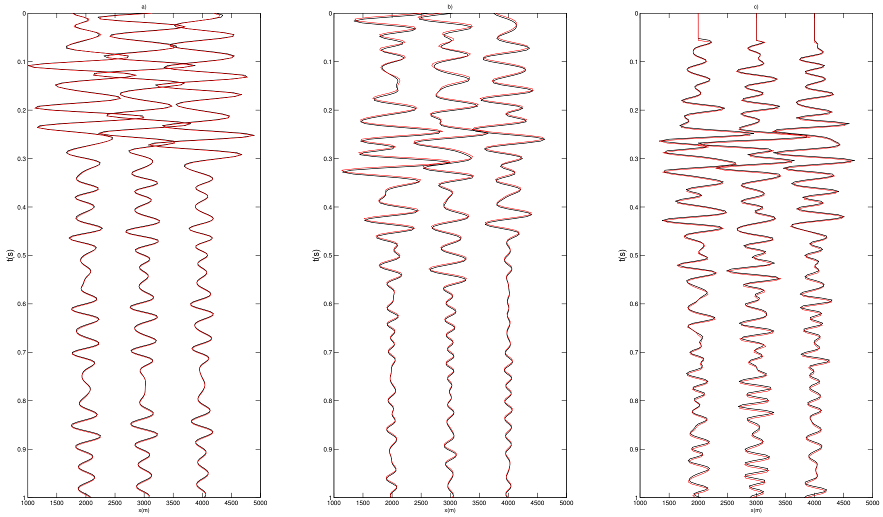

Figure 4: Zero-offset trace comparison of the redatumed responses before and after. The redatumed reflection responses of a) the overburden and b) the reservoir. c) The equivalent section from the original borehole data, with the time axis adjusted accordingly.

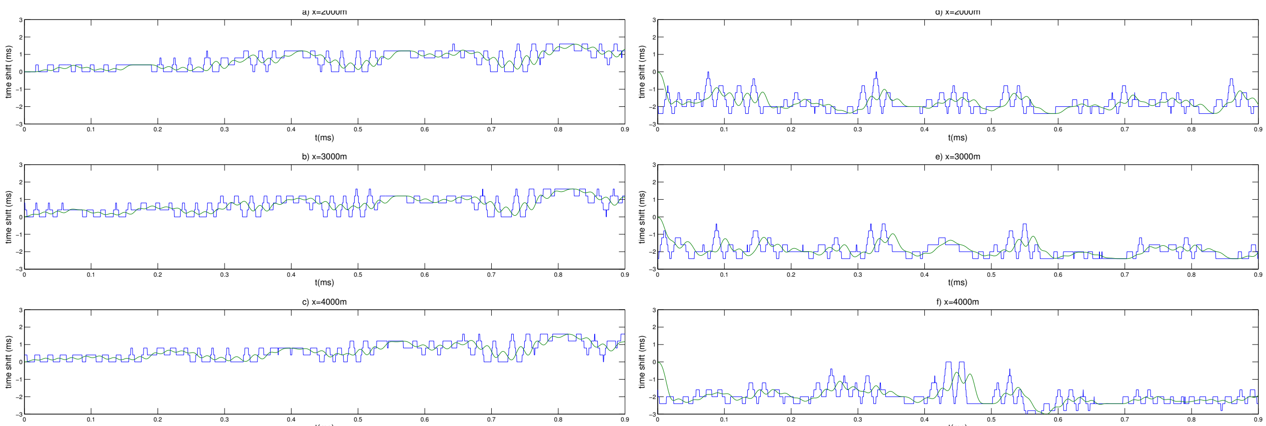

Figure 5: The estimated time shifts based on the redatumed results. a), b) and c) correspond to the ones in Fig. 4 a), for the overburden; d), e) and f) correspond to the ones in Fig. 4 b), for the reservoir. A smoothed curve is plotted in green on top of the original estimate.

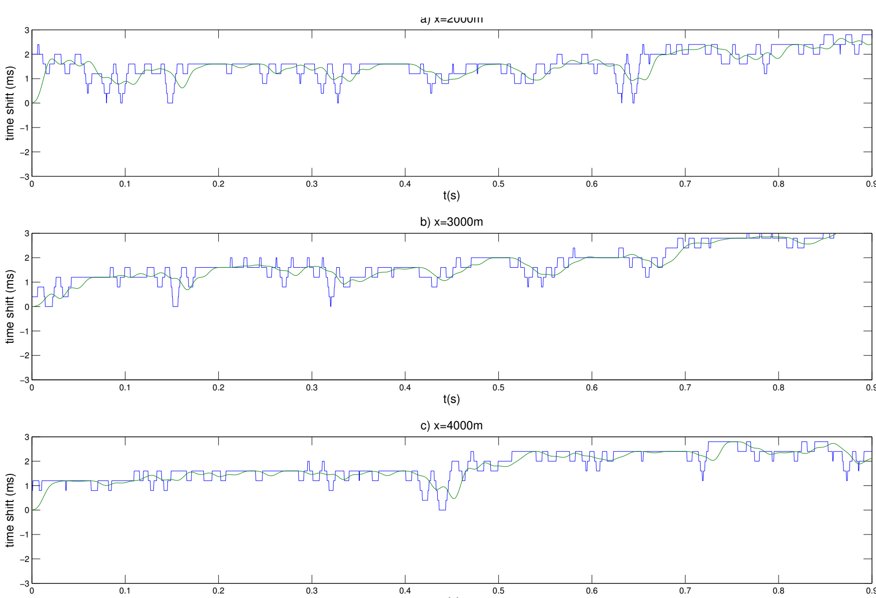

Figure 6: The estimated time shift using the original reflections in the borehole data shown in Fig. 4 c)