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Violet Grove time-lapse data revisited: a surface-consistent matching filters application

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Summary

We apply the surface-consistent matching filters to a real data set from the Violet Grove area in central Alberta. Detecting time-lapse difference on this data has proved to be difficult due to the small impedance contrast at the Cardium reservoir, where CO_2 is injected, and the low injection volume. However, we consider this data to examine the surface-consistent matching filters algorithm in order to minimize differences observed above the reservoir interval. After applying the surface-consistent matching filters to the monitor survey, we reduce most of the mismatch caused by acquisition differences and near surface variations. The nonrepeatable noise in the data are difficult to remove since they are often nonstationary. The shallow window above the reservoir is dominated by the near-surface noise. Despite this issue, we notice an improvement in the pre-stack and the post-stack difference image after applying the surface-consistent matching filters.

Introduction

CO_2 sequestration, also known as carbon capture and storage (CCS) in deep geological formations, is a multidisciplinary technology that involves capturing, transporting, and storing CO_2 gas. The geophysicist's role in this technology includes evaluating the earth's subsurface response to the injected CO_2 gas. The earth's subsurface variations include, but not limited to, P-wave and S-wave speeds decrease (e.g. Wang et al., 1998), density decrease (e.g. Avseth et al., 2005), increase in seismic wave attenuation (e.g. Hilterman, 2001), and other important seismic property changes reported in many geophysical papers. To monitor these effects, we acquire seismic data at different calendar times hoping to capture the subsurface change in the time-lapse seismic image.

Almutlaq and Margrave (2012) presented a prestack surface-consistent matching filters algorithm that condition time-lapse data and reduce nonrepeatable noise. The algorithm was presented with a modeled time-lapse data and in this paper we demonstrate it on a real data example from the Violet Grove site in Alberta, Canada.

Time-lapse data

Three phases of surface and borehole seismic data were acquired at the Penn West Pembina Cardium CO_2-EOR pilot site (about 100 km southwest of Edmonton, in central Alberta) between March 2005 and March 2007 (Alshuhail et al., 2011). During this period, approximately 60,000 tonnes of CO_2 were injected in the Cardium Reservoir which has a maximum cumulative thickness of about 20 m at a depth of about 1600 m. A time-lapse seismic data set, consisted of 2D surface seismic, a small sparse 3D survey, and 2D vertical seismic profile (2D VSP), was designed and acquired as part of the monitoring program. The main objective of the seismic program is to verify the CO_2 plume, and to evaluate the integrity of the storage.

The data consist of six 2D lines, each is about 3 km long with 20 m receiver interval, 40 m source spacing, a 2 kg dynamite charge at 15 m depth, approximately 3000 m maximum source-receiver offset, and a record length of 4 seconds with a sample rate of 1 ms. The data quality is reasonable and the main reflections were easy to pick after stacking starting from the shallow top Ardley Coal Zone to the Viking Formation which is sandstone dominated. The Cardium Formation is a low impedance unit on the baseline seismic, and even after injecting the CO_2 gas, it shows as low amplitude on the monitor survey.

The surface-consistent matching filters

Almutlaq and Margrave (2012) showed that the surface-consistent data model can be extended to the case of designing matching filters to equalize two seismic surveys. This matching filter algorithm is based on Taner and Koehler (1981) model where a seismic trace is represented as the convolution of four terms expressed by:

$$d_{ij}(t) \approx \underbrace{s_i(t) * r_j(t)}_{Near-surface} * \underbrace{h_k(t) * y_l(t)}_{Subsurface} \tag{1}$$

where "*" denotes convolution in the time domain, $d_{ij}(t)$ is the seismic trace resulting from the i^{th} source recorded into the j^{th} receiver, $s_i(t)$ is source response, $r_j(t)$ is receiver response, $h_k(t)$ is offset response at offset location k, and finally $y_l(t)$ is midpoint response below surface location l (Indices k and l depend on i and j through the acquisition geometry).

Extending this model such that the data term represents two data sets, we can rewrite equation 1 with two subscripts: 1 for baseline survey and 2 for a monitor survey. Now that we have expressed both surveys with their surface-consistent models, we can derive a set of matching filters that equalizes the monitor to the baseline (or vice versa) designed over a temporal window where changes are not expected.

The following steps highlight the Almutlaq and Margrave (2012) approach to the surface-consistent matching filters:

- in the time-domain, compute a trace-by-trace matching filter for each pair of traces from baseline and monitor surveys.
- FFT the above result , then
- for every frequency, solve the surface-consistent system using least-squares method,
- accumulate the solution frequency-by-frequency,
- IFFT the result to obtain surface-consistent matching filters,
- and finally, apply these filters to the monitor survey.

Thus our algorithm takes trace-by-trace matching filters and decomposes them into surface-consistent factors.

Field example

In this study, we only consider the vertical component of the data from Phase I and III since these surveys were recorded at the beginning and at the end of the monitoring project and are expected to have the largest time-lapse differences.

Table 1 summarizes the parallel processing steps of both baseline and monitoring surveys. For this data set, we compute and apply all four terms of the surface-consistent matching filters. The monitoring survey contains more noise compared to the baseline (due to increasing field activities) and even after attenuating most of the coherent noise in the pre-processing stage, some noise level is still observed (Figure 1) particularly in near offsets.

Table 1: Processing work flow. The difference between conventional processing and this flow is the addition of surface-consistent matching filters.

Baseline	**Monitor**
Geometry assignment	Geometry assignment
Ground roll attenuation	Ground roll attenuation

Trace edits	Trace edits
Amplitude recovery	Amplitude recovery
Surface-consistent Amplitude correction	Surface-consistent Amplitude correction
Surface-consistent Spiking deconvolution	Surface-consistent Spiking deconvolution
-	**Surface-consistent matching filters**
Velocity analysis	-
Surface-consistent residual statics	Surface-consistent residual statics
CDP stack	CDP stack
Poststack migration	Poststack migration

We compute and apply the four-component surface-consistent matching filters for a shallow window above the reservoir as highlighted in the top panel of Figure 1. The window is centered on the Ardley Coal which is a relatively good reflector and the only one visible above the Cardium reservoir on prestack data. The difference between the baseline survey and the monitor survey is quite large at this level and dominated by noise. After applying the four term surface-consistent matching filters, the difference reduced considerably. Because of the low fold and high random noise in the shallow window, we designed another gate below the reservoir where good quality reflectors are present. It is not common in time-lapse processing to start by matching a gate below the reservoir but we are attempting this in order to examine the performance of the surface-consistent matching filters on a relatively high signal to noise event. The result is shown in the bottom panel of Figure 1. The difference after applying the matching filter is significantly small and display a much better result compared to the shallow window.

Figure 2 illustrates the migrated stack of baseline, monitor and their difference. Amplitude and phase difference is obvious throughout the section. After applying the surface-consistent matching filters (Figure 2) computed from the shallow window, the difference reduced significantly compared to the prestack example. This result is encouraging and illustrates the progressive decrease of the error after applying the surface-consistent matching filters.

Conclusions

In summary, we successfully apply the surface-consistent matching filters to a real data set from Violet Grove area in central Alberta. The time-lapse difference due to CO_2 has not been investigated in this study even though previous reporting concluded that it was difficult to detect on surface seismic. Despite that, we decide to use one line from this data to examine the surface-consistent matching filters algorithm. We evaluate two zones: a shallow one above the reservoir centered on the Ardley Coal Zone, and a deeper one below the reservoir. Both results are encouraging and show progressive decrease in amplitude and phase difference between baseline and monitor survey.

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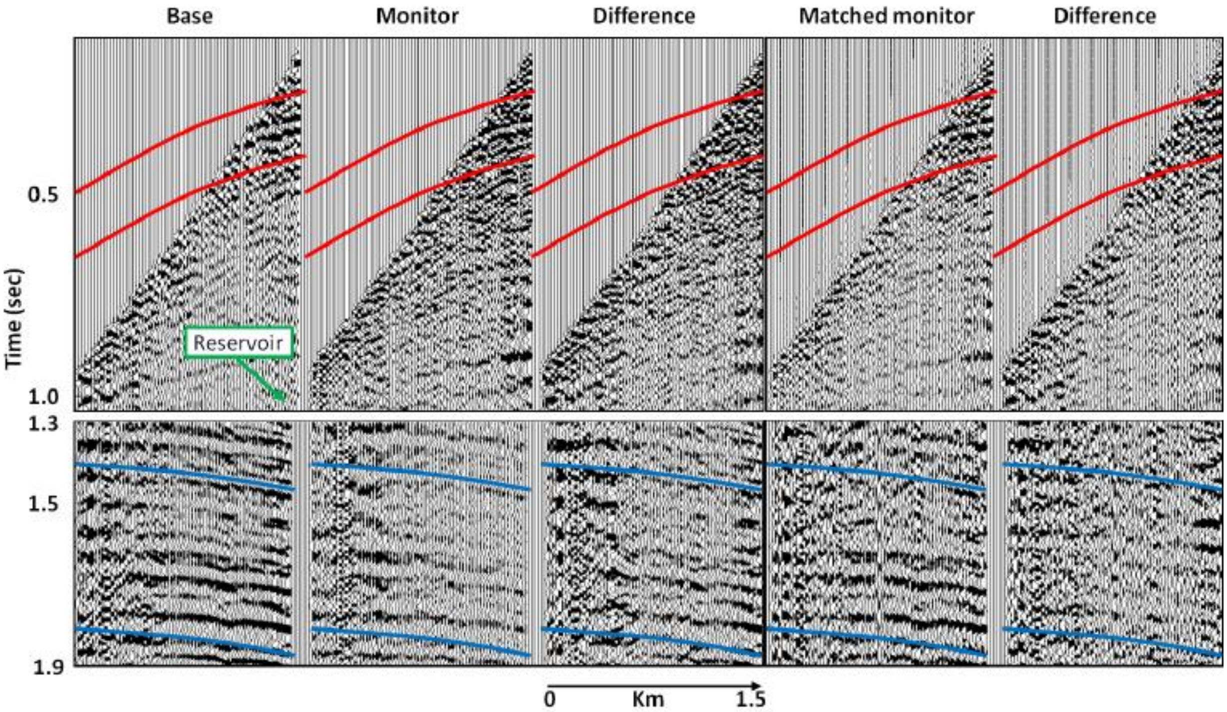

Figure 1: A prestack shot record near the injection well. In top panel is a baseline, a monitor, their difference, the matched monitor and difference after applying matching filters based on shallow window above reservoir. Note there is a slight improvement after applying the matching filters but it is not as good as computing the matching filters from a deeper window (i.e bottom panel). This is due to higher signal to noise ratio and higher fold in deeper window.

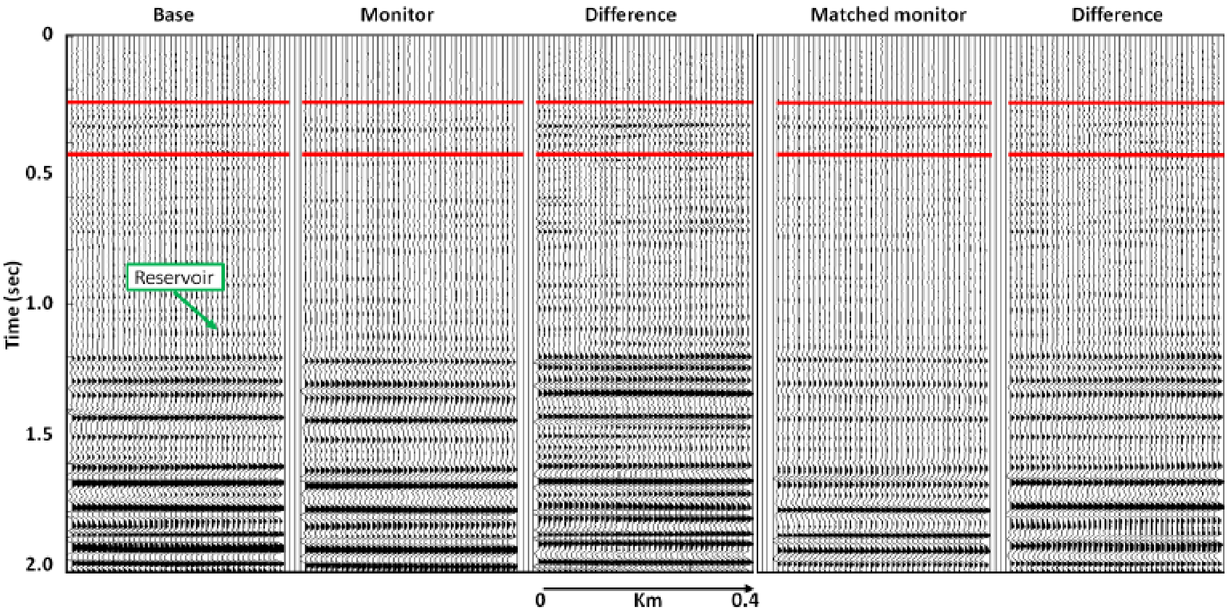

Figure 2: A poststack comparison of baseline, monitor, difference, matched monitor and difference between the baseline and the matched monitor. The matching filters computed here is from a window above the reservoir as indicated between the two red lines. This is a short segment of the 2D line with the well in the middle.