Time-lapse VSP monitoring of steam injection

Anna Droujinina, British Geological Survey and Heriot-Watt University, Colin MacBeth and Patrick Corbett, Heriot-Watt University*

Summary

An equalization tool is designed using the time-frequency representation of a signal. It is shown that this processing helps distinguish between the footprint of the acquisition components and subsurface changes. This technique is applied to the monitoring of steam injection using walkaway VSPs. A high resolution Wigner-Ville transform makes it possible to detect small changes in seismic attributes and examine the repeatability of seismic sources. It is concluded that time-frequency filtering is a particularly effective technique for removing the random components of the seismic signals, and could have the potential to eliminate the foot-print in 4-D seismic data and, hence, to extract information about changes in reservoir properties present in seismic data.

Introduction

In reservoir monitoring, changes in seismic attributes are normally directly associated with rock properties. However, seismic data are also very sensitive to acquisition parameters, recording system characteristics and near-surface conditions, which also change with time. It is thus extremely important to eliminate these as they cause differences from one survey to another that do not directly correspond to sub-surface changes, and complicate interpretation. Here, we choose to avoid the commonly used data "matching" techniques for tackling the repeatability problems of time-lapse data. This is because of the difficulties in finding a satisfactory calibration event, as all parts of the subsurface could change during stress re-distribution. Instead, we propose transforming seismic signals into the time-frequency domain.

Time-frequency representations for a wide variety of purposes are well developed within sonar and speech analysis, and also music decomposition (timbre morphing). In fact, linear time-frequency representations of seismic signals via the Short Time Fourier transform have been actively used in seismology and seismic processing since the 1960's. Unfortunately, the linear representations have a limited resolution when discriminating weak reflection patterns in seismic data with a high noise content. In seismic literature, non-linear methods based upon the bilinear representations have been published only in recent years (Tobback et al.,1996). In particular, the Wigner distribution function (WDF) has been shown to be far more effective, due to its better localization properties. It is the WDF that is applicable to the problems that arise in the field of time-lapse VSP. The novel aspect of the method presented here is the particular combination of time-frequency analysis methods and standard VSP processing techniques.

Theory

The time-frequency distribution is a transform that maps a single dimentional signal into a two dimensional time-frequency map, which describes how the spectral content of the data evolves with time. The WDF $W(t,\omega)$ of the signal $x(t)$ described in a time domain is given by the Fourier transform of a local autocorrelation function $R_{xx}(t,\tau) = x(t+\frac{\tau}{2})x^{\star}(t-\frac{\tau}{2})$ over the time shift τ as (Cohen,1995)

$$W_x(t,\omega) = \int R_{xx}(t,\tau) exp(-i\omega\tau) d\tau.$$

The frequency-domain WDF is defined by (Cohen,1995)

$$W_x(t,\omega) = \frac{1}{2\pi}\int X(\omega+\frac{\xi}{2})X^{\star}(\omega-\frac{\xi}{2}) exp(i\xi t) d\xi$$

with $X(\omega)$ being the direct Fourier transform of the signal $x(t)$. Since the WDF gives the decay envelope over time for each frequency component, it is possible to reconstruct the time-sampled signal from its time-frequency decomposition up to a constant phase factor (Boudreaux-Bartels et al.,1986):

$$x(t_1)x^{\star}(t_2) = \int W_x[\frac{1}{2}(t_1+t_2),\omega] exp[i\omega(t_1-t_2)] d\omega$$

and

$$X(\omega_1)X^{\star}(\omega_2) = \frac{1}{2\pi}\int W_x[t,\frac{1}{2}(\omega_1+\omega_2)] exp[-i(\omega_1-\omega_2)t] dt.$$

The principle above allows a straightforward extension of the WDF to remove the noise energy from seismic sections in the $t-f$ domain. An additional measure used for highlight differences in the surveys is expressed in terms of time and frequency dependent correlation coefficients via the time-frequency coherency function which is defined as (White and Boashash,1990)

$$C_{xy}(t,\omega) = \frac{W_{xy}(t,\omega)}{\sqrt{W_x(t,\omega)W_y(t,\omega)}}$$

with W_{xy} being the cross-WDF of two signals $x(t)$ and $y(t)$.

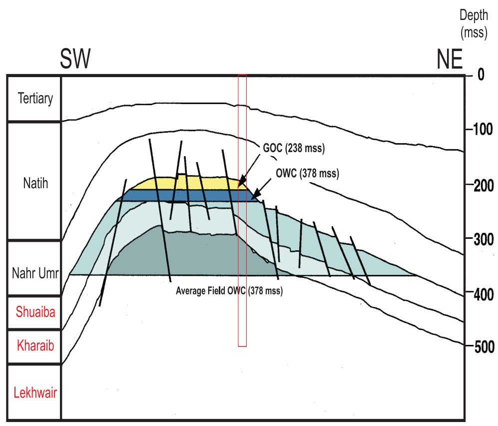

Figure 1: Cross-section of the field which contains an Aptian Shuaiba - Kharaib - Lekhwair carbonate reservoir. The position of the well and the current fracture fluid contact and oil-water contact levels are indicated.

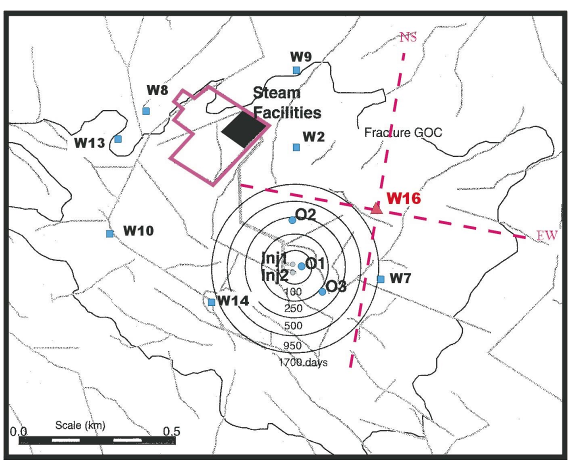

Figure 2: Expected design scenario for the steam pilot and schematic view on the walkaway VSP acquisition.

Application to multy-component VSP data

Time-lapse VSP data were acquired over the hydrocarbon storage reservoir during a pilot project designed to monitor the expansion of the steam zone during steam injection. The region is characterized by densely spaced high-permeability fractures running through a low-permeability matrix. The folded anticlinal structure measures approximately 3x6 km, with a maximum oil column of 165 m (Hartemink et al., 1997). A cross-section of the reservoir is shown in Fig.1. Fig.2 provides a conceptual picture of the design of the steam pilot and positions of walkaway VSP lines. The steam injectors are located in the centre of the circles, and predict a radial advance of the steam from a piston-like displacement. Laboratory measurements showed that reservoir velocities are normally quite sensitive to temperature and pressure changes. The velocity models obtained from the base and repeat surveys suggest that P-wave velocity in the time interval [250˜ms-450˜ms] is increased in the presence of steam. The $t-f$ equalization method has been applied to the data to estimate the average stacking trace in order to compensate for source signature changes with depth. The principle above has been implemented on the vertical component of the base and repeat surveys to estimate the downgoing shear waves. A set of displays in Fig.5 illustrates the result of the filtering in $t-f$ domain for the separation of up- and downgoing wavefield energy.

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Application of standard VSP processing procedures to monitor this process is complicated by source signature changing with depth and a high-energy downgoing shear wavefield. As a result, the relatively weak reflection patterns to be analyzed for possible time-lapse changes are not revealed. In the VSP acquisition, seismic sources are activated many times while remaining at a fixed surface location, and the source signature can change significantly time after time. Hence, the usual averaging over the common shot-receiver gather may result in a highly unconsistent source wavelet. In order to reduce an influence of incoherent/random components in the stacking procedure, an equalization processing tool has been assembled using the above theory. Filtering in $t-f$ domain was also found to be well suited to multiple suppression and the separation of up- and downgoing events for VSP data processing. The offset VSP traces deconvolved with the WDF can be used for wave mode identification and suppression. An example of such a processing is shown in Fig3. This separation provides a well-defined velocity field (Fig. 4) for both studies. This work concludes that useful reflection energy, or uncorrelated noise energy can easily be identified within the specific time and frequency intervals in $t-f$ plane. The principle above has been implemented on the vertical component for the base and repeat surveys to estimate the downgoing shear waves. A set of displays in Fig.5 illustrates the result of the filtering in $t-f$ domain for the separation of up- and downgoing wavefield energy.

The processing above provides a reliable time to depth conversion for the stacked data, with the resultant sections being displayed in Figure 6. This permits a valid comparison of the subsurface effects. Differences between the two surveys shows that P-waves anomalies occured at levels thought to be influenced by the steam. The results suggest that the steamed zone is expanding faster in northernly direction than orginally expected. This supports the concept of fracture-related anisotropic flow, which results in an elliptical steam zone.

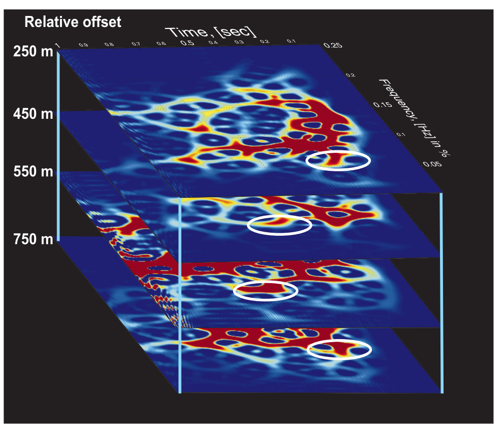

Figure 3: Filtering in $t-f$ domain. White circles indicate selected wave mode(downgoing shear waves) to be suppressed.

Conclusions

We show that time-frequency transforms can be used to account for the acquisition foot-print, and in particular the lack of source repeatability. The technique is also well suited to the rejection of multiples, and separates up- and downgoing wavefields where reflectors are weak. It has been shown that the time-frequency coherency function based on the cross-WDF is a powerful tool for the examination of the similarity/differences between base and monitor surveys. This is an important step towards improving repeatability of time-lapse VSP data. It has the potential to be used on larger 4D multi-component datasets. Further processing and analysis of horizontal components could eventually provide additional information about expansion of the steam zone and reveal time-lapse changes in compressional and shear wave attributes affected by the steam.

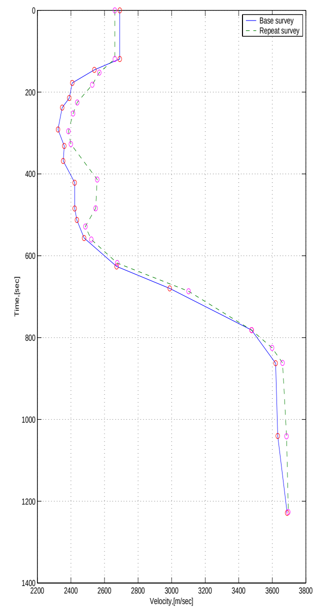

Figure 4: Velocity model for base and repeat surveys.

Acknowledgements

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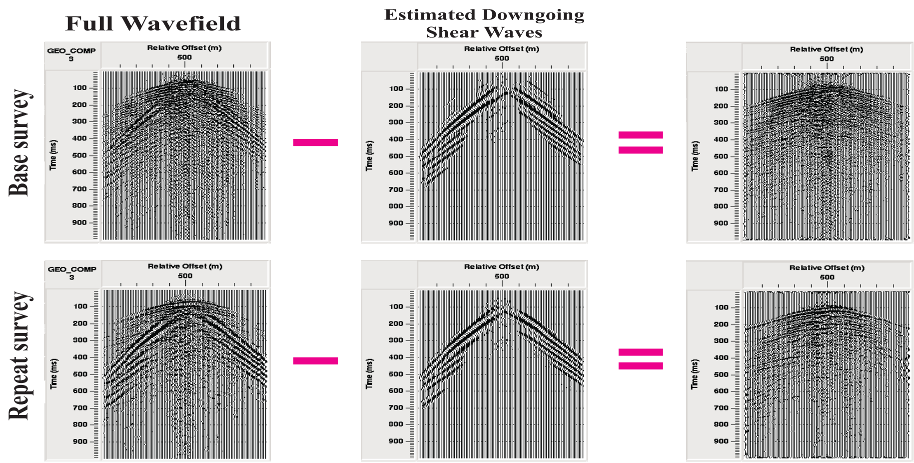

Figure 5: An example of up- and downgoing wavefield separation based on the filtering in $t-f$ domain.

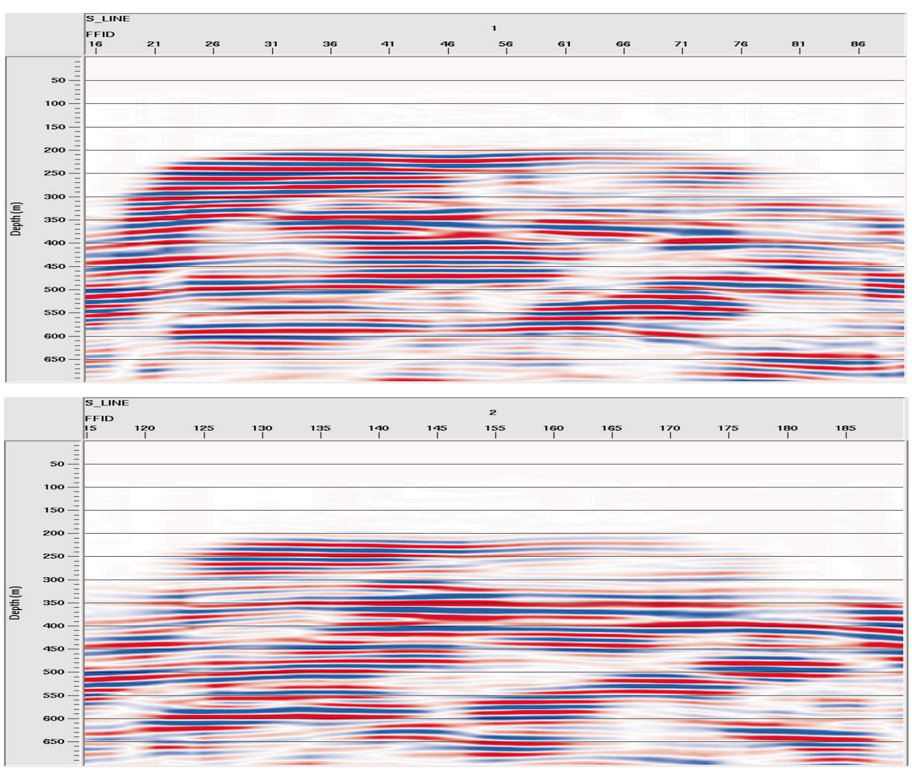

Figure 6: P-waves depth sections for base and repeat surveys (from South to North).