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Experiences in pre stack and post stack wavelet processing on time lapse data

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Abstract - Wavelet processing techniques aim at estimating, manipulating and, optionally, removing the wavelet resulting from the filtering effect caused by acquisition on the Earth reflectivity. Two approaches are tested, based on logs from a well. In a first approach, near zero offset propagation wavelets are extracted from stacked data from different vintages using the zero offset reflectivity. The peculiarity of the acquisition of each vintage is then removed by means of inverse filtering. Time lapse differences are detected comparing the output data in terms of amplitude envelopes and pseudo acoustic impedance. A pre stack approach is also tested on a single vintage data set: offset dependent wavelets are extracted from data after calculation of non zero offset reflectivities. Inverse filtering on pre stack data provides an increase in temporal resolution and in the accuracy of the determination of stacking velocities.

1. Introduction

This work concerns post stack and pre stack wavelet processing, based on borehole Vp, Vs and density data. In the convolutional model seismic data are described as a convolution of reflectivity time series and wavelet time series (Robinson and Treitel, 1980; Kanasewich, 1981). The reflectivity is the full bandwidth theoretical behaviour of subsurface materials involved in acoustic wave propagation. The wavelet is the footprint of the acquisition system and of the real anelastic ground, and is responsible for the temporal resolution. The result is a band limited and system dependent set of time series: the data traces. In other words, what is recorded in seismic data is a band-pass filtered and phase modified version of the Earth's true reflectivity. What is aimed at by wavelet processing is first to estimate and then to recover this filtering effect, thus increasing temporal resolution and subtracting system dependent effects.

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Such a procedure is quite well established, if applied in the post stack domain to near zero offset high signal-to-noise traces, but almost inexperienced in the pre stack domain. One of the aims of this work is to explore the feasibility of a pre stack approach on real data.

Both pre stack and post stack propagation wavelets, extracted using well log data, do not require any minimum phase assumption and can be considered to be more accurate than the ones obtained by traditional spiking deconvolution.

Such wavelets can be useful in some target oriented applications, such as high resolution velocity analysis for coherent AVO estimation or pre stack inverse filtering, aimed at limiting the interfering effects of thin layers. Furthermore, the capability of manipulating the propagation wavelets allows spectral cross calibration to be applied on time lapse data, either in the stacked or unstacked domain.

2. Available data

2.1. Seismic data

The seismic data presented in this work are 2D profiles extracted from 3D volumes acquired, in the Oseberg area (North Sea), in 1982, 1989, 1992 and 1999.

This data were processed in order to identify possible time lapse effects, both on post and pre stack (time lapse AVO) reflection amplitudes, due to fluid substitution caused by oil production and gas injection. Each one of these data sets underwent a parallel, strictly amplitude preserving processing sequence, mainly aimed at recovering the effects of amplitude decay and removing multiple reflections. At the end of processing, all of the data underwent surface consistent cross-calibration: the amplitude peculiarity of vintages was treated as a surface consistent component and removed. More details on this subject can be found in Stucchi et al. (2000) and in Mazzotti et al. (2001).

2.2. Well log data

A borehole log was recorded in December 1986 next to the area covered by seismic data. Although its position is about 750 m south of the mean trajectory of seismic lines, it was chosen because of the availability of measured Vs data (for a small depth interval, including the Brent Group, which is the actual reservoir) apart from usual Vp and density. Data are plotted in Fig. 1, after some outlier rejection and smoothing.

As is visible in Fig. 1, the most important reflectors are the top and the base of the Cretaceous units. The Brent Group interval is also recognisable because of the low Vp and density, due to lithological as well as hydrocarbon saturation and porosity factors.

3. Wavelet processing

Borehole data provide the direct knowledge of the reflectivity series in a small neighbourhood of the well. In such a small region it is possible to determine, directly from seismic data, the propagation wavelet. The wavelet operator is estimated as a least square linear filter, solving a set of linear equations (Robinson and Treitel, 1980): when convoluted with the appropriate reflectivity series, it will give the best reproduction (in a least square sense) of seismic data, both in the stacked or unstacked domain.

3.1. Post stack wavelet processing

The post stack approach is quite straightforward because, in a horizontally layered Earth, Zoeppritz equations are reduced to a zero angle of incidence case: P wave reflection coefficients are easily derived for each model interface using the well known formula

$$r_i = \frac{\rho_{i+1} \cdot Vp_{i+1} - \rho_i \cdot Vp_i}{\rho_i \cdot Vp_i + \rho_{i+1} \cdot Vp_{i+1}} \tag{1}$$

where ρ_i and Vp_i, for $i = 1, 2, 3, ...$, are the elements of density and P velocity logs and r is the

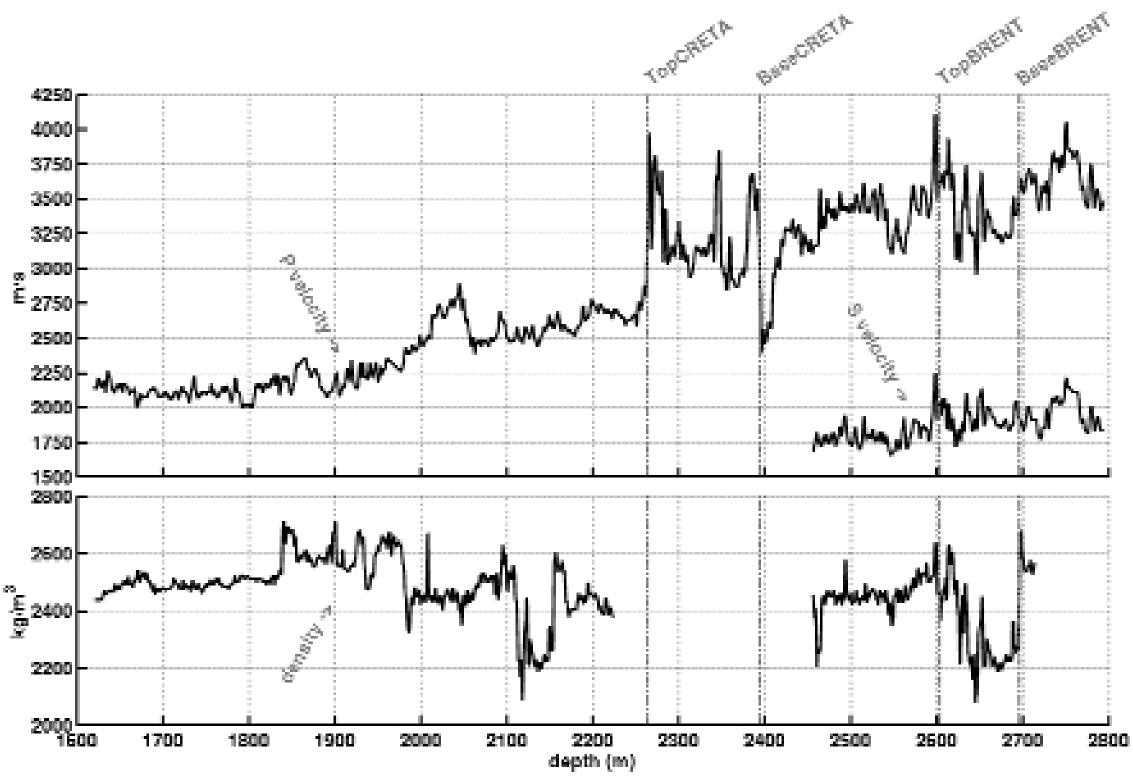

Fig. 1 - Vp , Vs and density well log data after outlier rejection and smoothing.

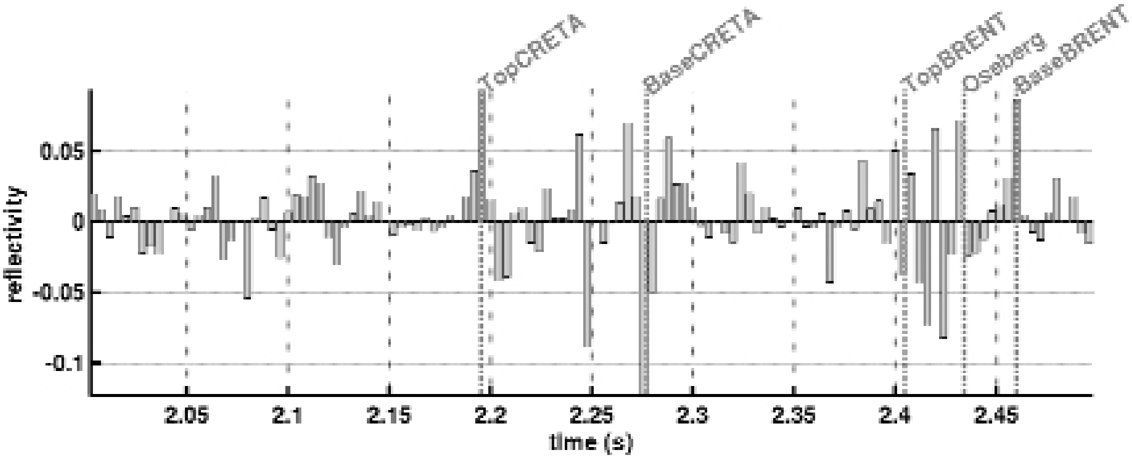

Fig. 2 - Zero offset reflectivity time series from well log data after resampling.

reflectivity series. The depth series is then converted to time using vertical ray travel times and resampled to match seismic data (Fig. 2).

WAVELET EXTRACTION. - Post stack wavelet extraction is performed on angle limited (0 to 10 degrees) CMP stack traces from the four vintages, in order to reduce possible AVO effects.

Wavelet operators (Fig. 3) are designed as 80 ms least square Wiener filters (Robinson and Treitel, 1980), where the input is the reflectivity series and the desired output is the stack trace closest to the well.

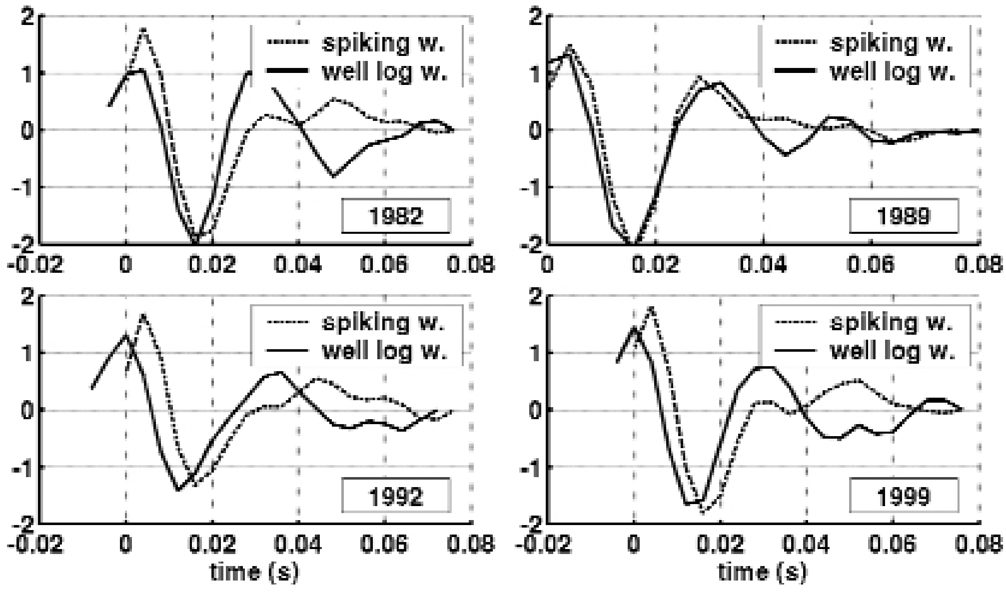

Fig. 3 - Wavelets (solid lines) extracted from angle limited stack traces using well log reflectivity in comparison with wavelets (dashed lines) obtained by traditional spiking deconvolution (minimum phase inverse of spiking operators). Substantial differences between the two exist in 1982 and 1999 results.

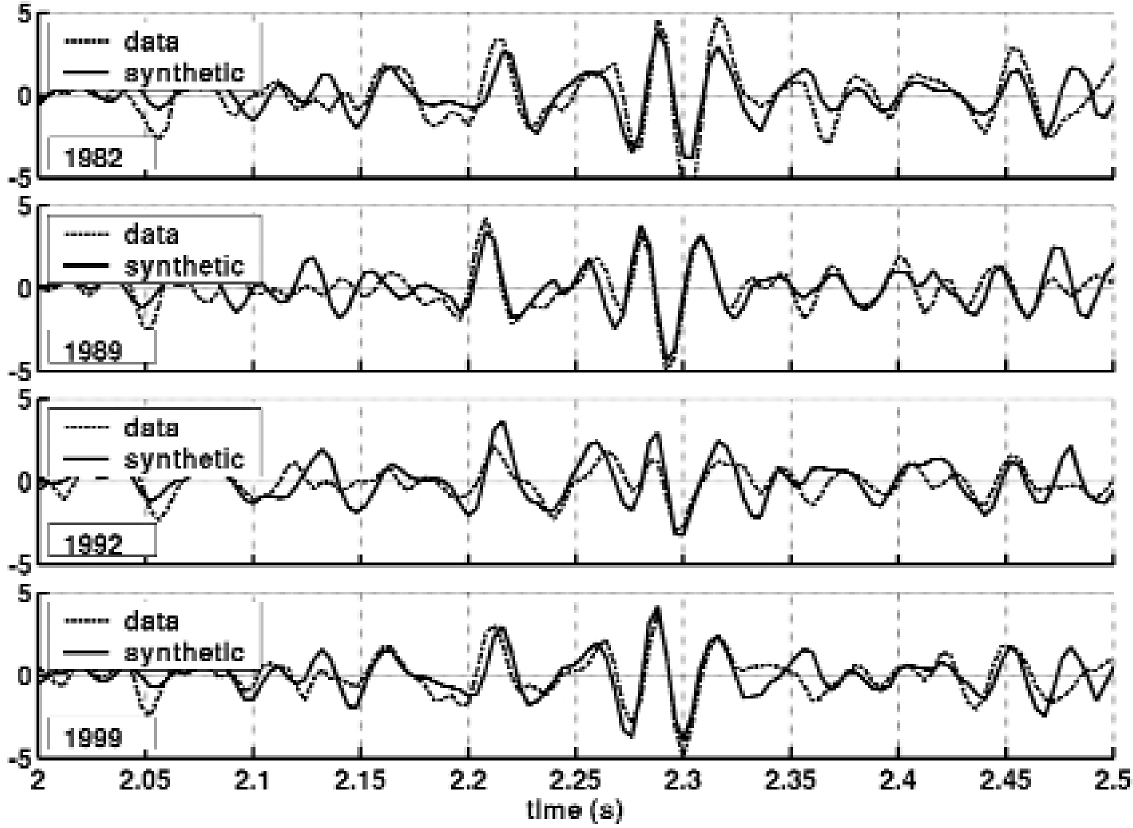

Fig. 4 - Comparison between angle-limited CMP stack traces (dashed lines) and synthetic data (solid lines). Synthetic traces obtained by convolution between reflectivity and extracted wavelets.

The quality of the match between seismic and well log data can be evaluated comparing synthetic seismograms, generated by convolution between zero offset reflectivity and the output wavelets. Fig. 4 shows satisfactory matching, with the exception of 1992 data, where the 10 degree stack is noisy.

INVERSE FILTERING. - The propagation wavelet is assumed to be stationary in a reasonably large neighbourhood (nearly 1850 m east and west of well location and in the time window between the top of the Cretaceous and the base of the Brent). Here the removal of the wavelet convolutional component can be performed by means of a linear inverse filter. This should produce a three-fold effect:

1. increase in the temporal resolution of seismic data;
2. phase of reflections set to zero, allowing a more correct definition of travel times;
3. subtraction of system-dependent effects, enabling a time lapse comparison between data from different vintages.

Fig. 5 reports an example of the effect of inverse filtering on 1989 data. The fact that the polarity of both top and base Cretaceous events is much clearer after deconvolution is noticeable: top Cretaceous is a clean black event (i.e. an increase in acoustic impedance with time), while base Cretaceous is white, coherently with the information provided by Vp and density logs (Fig. 1).

After the wavelet inversion, data are amplitude calibrated using a time window where only signals from interfaces not affected by production (top Cretaceous to base Cretaceous) are included.

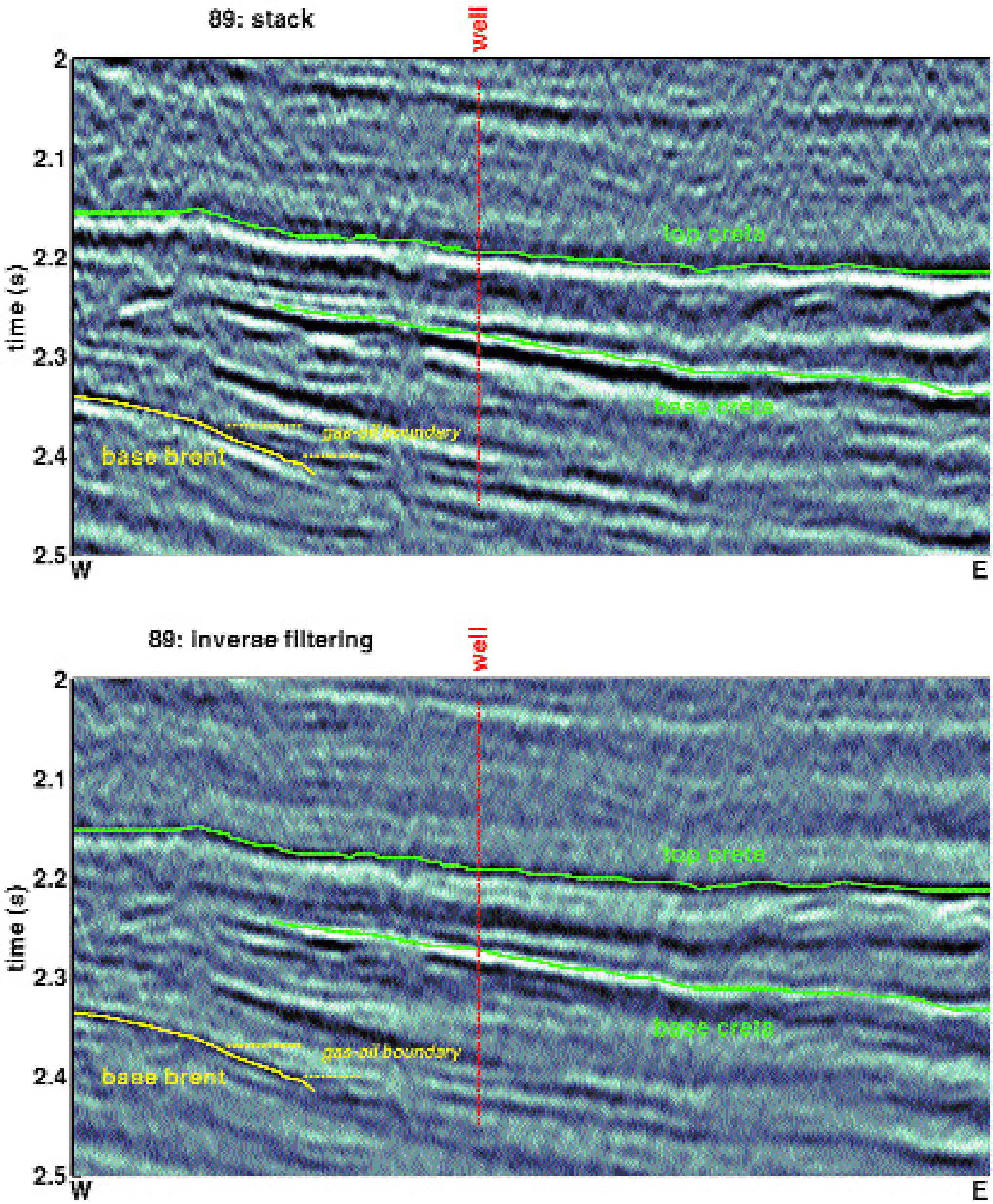

Fig. 5 - Comparison between 1989 stacks before (top) and after (bottom) deconvolution. The main reflectors are evidenced by green lines. The red dashed line represents the borehole projected on the acquisition plane. The base Brent (yellow) is the lower boundary of the reservoir. While the gas-oil boundary is pushed downwards during production, by injection into the gas cap, portions of the reservoir change from oil saturation to gas saturation and reduce their acoustic impedance.

Data are then compared in order to identify time lapse variations. This approach is based on the assumption that the seismic response from non productive horizons should not have changed in time. Equalisation of such events guarantees that residual differences between vintages are due to true variations in the physical properties of target layers.

Production in the Oseberg field started in late 1988. The gas injection into the cap of the

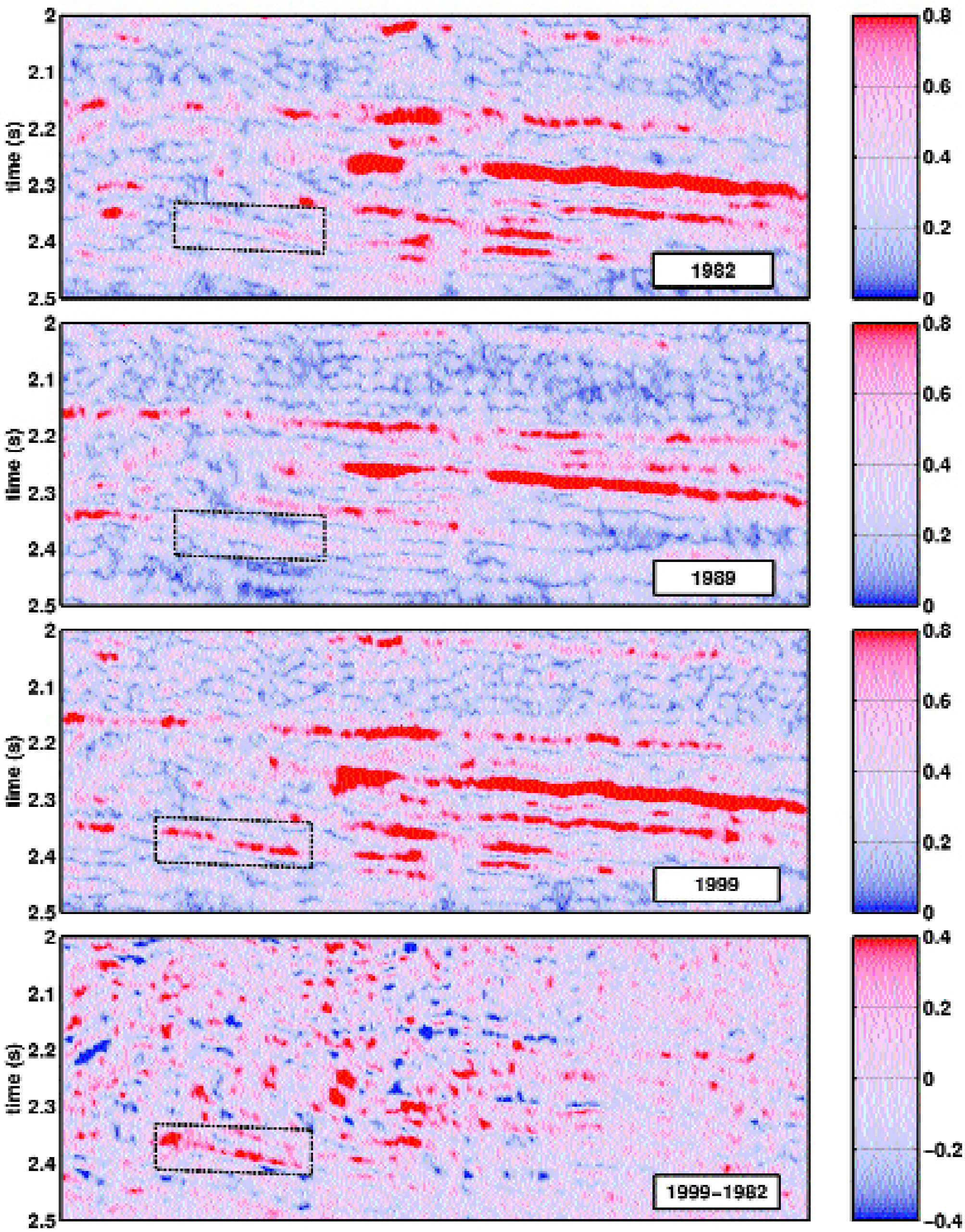

Fig. 6 - Envelope amplitudes of inverse filtered 10 deg. stacks for 1982, 1989 and 1999 vintages (top to bottom). Bottom panel: difference between 1999 and 1982 envelopes. Values are positive (red) when 1999 amplitude is bigger than in 1982. The region where the time lapse variation is detected is enclosed in black frames.

reservoir pushes the top of the oil layer downwards and towards the east (see the reservoir sketch in Fig. 5; please note that the position of the gas-oil interface is only qualitative because it was not recognised as a reflection on the data). Portions of the reservoir rocks change from oil saturation to gas saturation, reduce their acoustic impedance and increase their contrast with the underlying Dunlin Formation. Time lapse amplitude variations, due to oil-gas substitution, are then expected along the base Brent reflector, which is the west (east dipping) boundary of the reservoir. Fig. 6 reports amplitude envelopes of 1982, 1989 and 1999 data (1992 line is not shown because it is located some hundred meters south of the other lines). Frames enclose areas where reflection amplitudes from the base Brent increase from the pre production (1982 and 1989) to the latest 1999 data.

The bottom panel in Fig. 6 shows the difference between 1999 and 1982 envelopes. Values are positive (red) if 1999 amplitude is bigger than in 1982. Large, laterally coherent, positive peaks characterise the base Brent reflection. Such coherency does not hold in the response from non productive reflectors and, in particular, no peaks are present at all in the traces where the

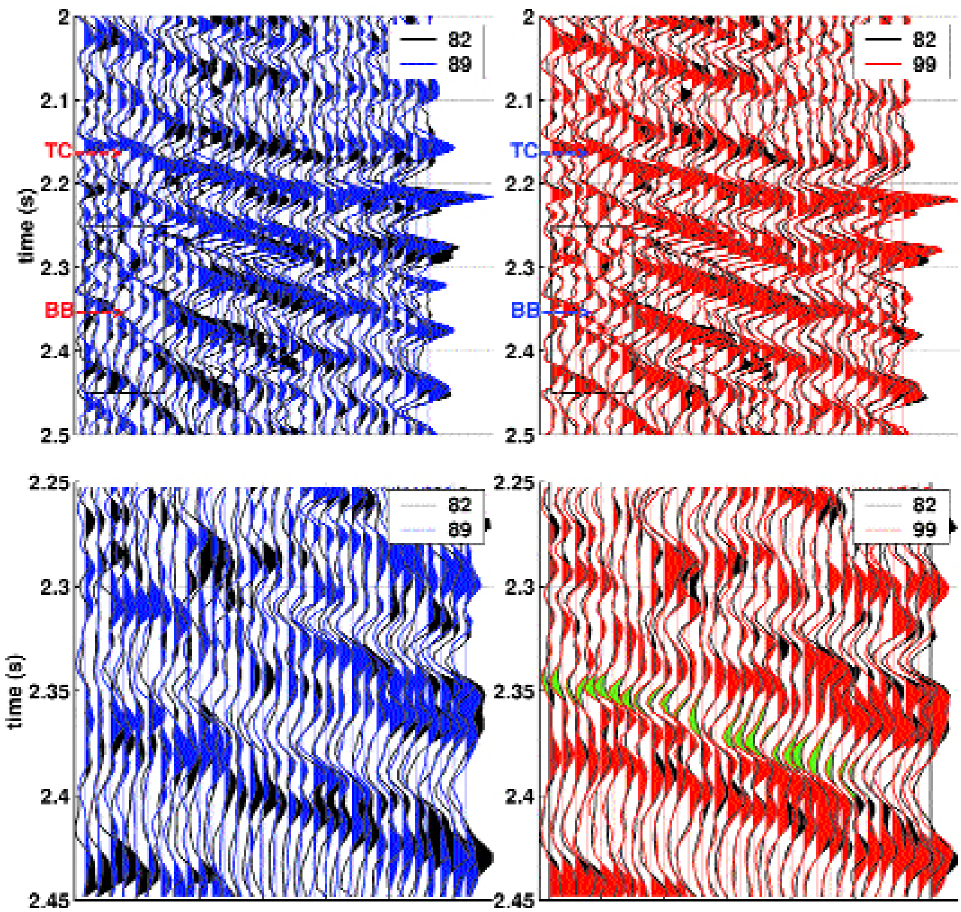

Fig. 7 - Pseudo acoustic impedance curves for 1982, 1989 and 1999 vintages. The area enclosed in frames in the top panels is enlarged in the bottom panels. Responses from top Cretaceous (TC) and base Brent (BB) are evidenced by arrows. In the lower right panel, the impedance gap area between 1982 and 1999 is evidenced by green fill. One trace every ten is plotted in the top panels, one every two in the bottom panels.

time lapse effect is encountered.

After bandwidth expansion by means of inverse filtering, pseudo acoustic impedance is calculated by inversion of Eq. 1 for ρ_{i+1} (Oldenburg et al., 1983). Pseudo impedance curves (Fig. 7) demonstrate a general good match between data from 1982 and 1999 vintages; less so between 1982 and 1989 and between 1989 and 1999. Nevertheless, the trough just above the base Brent impedance raise is deeper in 1999 data than in 1982 and 1989 (green filled areas in lower frames of Fig. 7). This can again be interpreted as the time lapse variation due to fluid substitution.

3.2. Pre stack wavelet processing

NON ZERO OFFSET REFLECTIVITY. - Pre stack reflectivity series are calculated according to the physical properties and geometry of the 1D layered model provided by borehole data. Ray kinematics is calculated by iterative solution of 1D parametric equations for travel times and offsets. Propagation at shallow depths, not covered by well log data, is described by an equivalent layer whose velocity is provided by seismic velocity analysis. Amplitude of reflection coefficients is obtained using the complete Zoeppritz equations, based on P and S velocity and density data.

The results of kinematic calculations, superimposed on the actual modelled CMP gather, are reported in Fig. 8. The output is finally converted to time and resampled, in order to match the sample rate of seismic data.

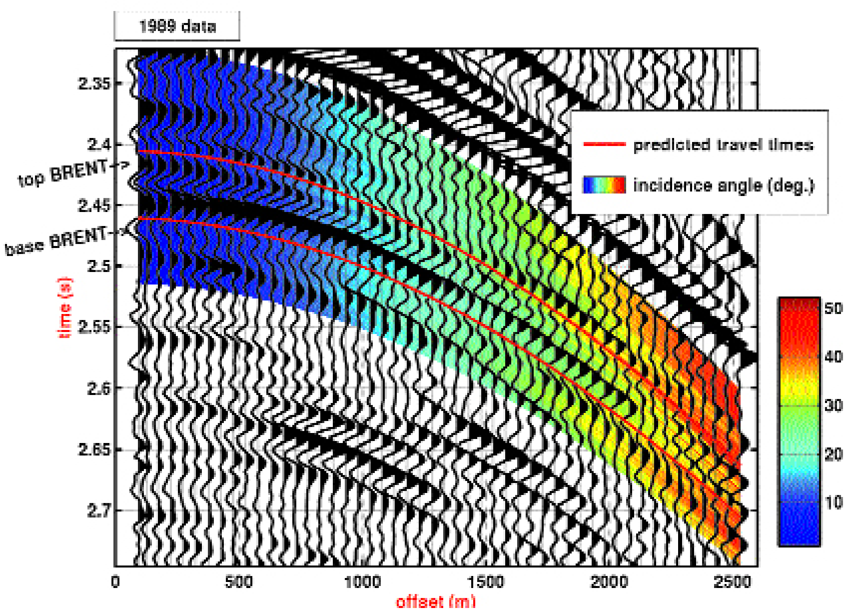

Fig. 8 - Travel times and incidence angles of seismic rays are predicted according to the 1D Earth model provided by borehole data. Colour represents incidence angle at the reflecting interface. Solid red lines show the predicted travel times for top and base Brent reflectors.

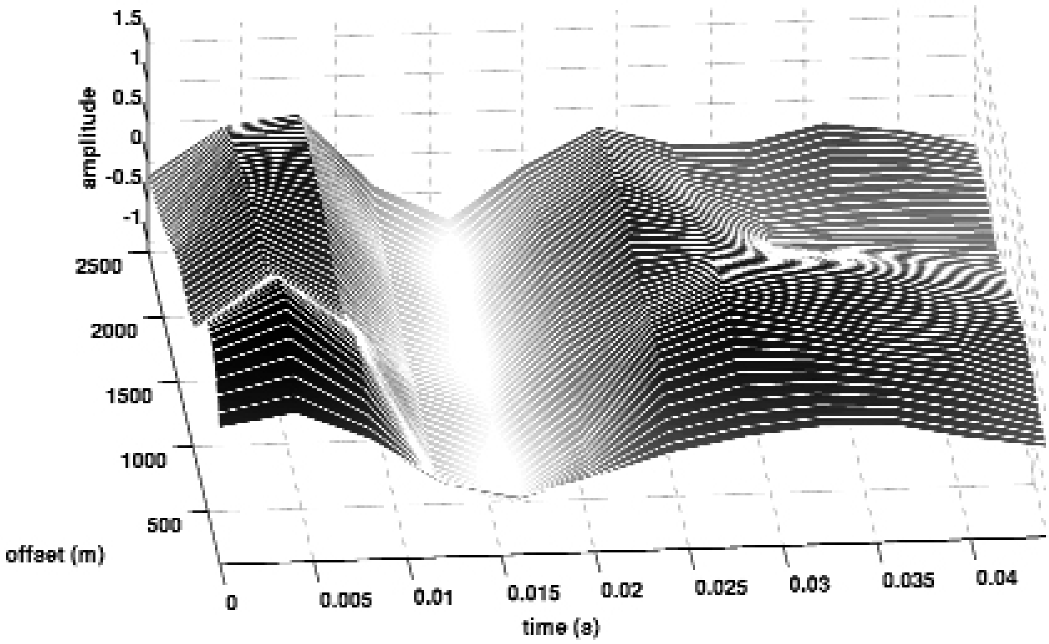

Fig. 9 - Pre stack wavelets, bandpass filtered both in time and offset domains.

WAVELET EXTRACTION. - After an accurate residual time alignment, wavelets are designed as 80 ms least square filters. The filter inputs are the angle-dependent reflectivity series and the desired outputs are the appropriate intervals of seismic traces from the best matching CMP gather. Results, bandpass filtered in time and offset domains, are shown in Fig. 9.

Offset dependent wavelets describe with appropriate accuracy the phase and amplitude variations that can be encountered along one event. Nevertheless, in this preliminary attempt, offsets are limited to 2500 m in order to avoid too noisy traces and the complication of critical reflections.

INVERSE FILTERING. - Fig. 10 shows the effect of inverse filtering on a CMP gather from 1989 vintage, both with and without normal move out applied. Solid red lines show the predicted travel times for some reference horizons. The deconvoluted gathers on the right show higher temporal resolution, as a consequence of the bandwidth increase. The amplitude peaks are also positioned at their predicted travel times. The obtained wavelet compression allows more accuracy in the estimation of optimal stacking velocities, also for closely spaced interfering events. This is apparent in the velocity semblance panels represented in Fig. 11.

4. Conclusions

In the post stack approach, wavelet processing based on well log reflectivity has proven an effective tool to enhance the quality of the stack image. This is due to the increase in temporal resolution, which also has a positive effect on the recognisance of polarity. The removal of

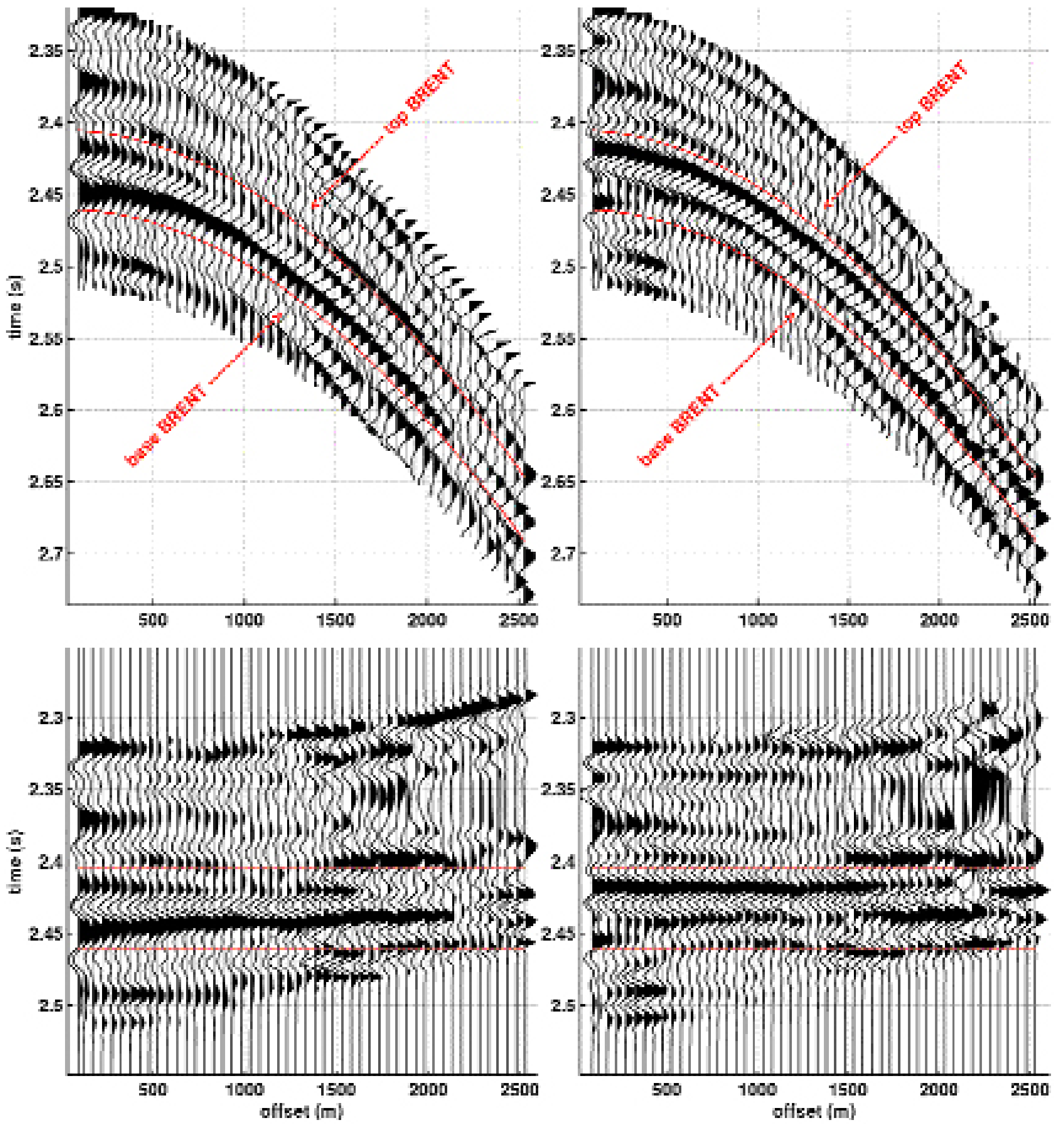

Fig. 10 - Comparison between 1989 vintage pre stack data before (left) and after (right) inverse filtering and with (bottom) and without (top) nmo correction. Solid red lines show the predicted travel times for top and base Brent.

system-dependent effects enables to carry out the time lapse comparison between data sets from different vintages. Amplitude envelopes and pseudo acoustic impedance have been derived from deconvoluted angle limited stacks. Both of these evidence variations between the pre production (1982 and 1989) and latest data (1999).

Up to now, the pre stack approach has been inextensively tested on a single CMP gather extracted from the 1989 data set. Pre stack wavelets have been successfully extracted and the results of inverse filtering have proven that a significant enhancement in the resolution of velocity analysis is achievable. Further tests are possible, also including pre stack spectral calibration of time lapse data sets. The time matching between reflectivity and seismic data has proven to be a very delicate job, requiring direct control by the user.

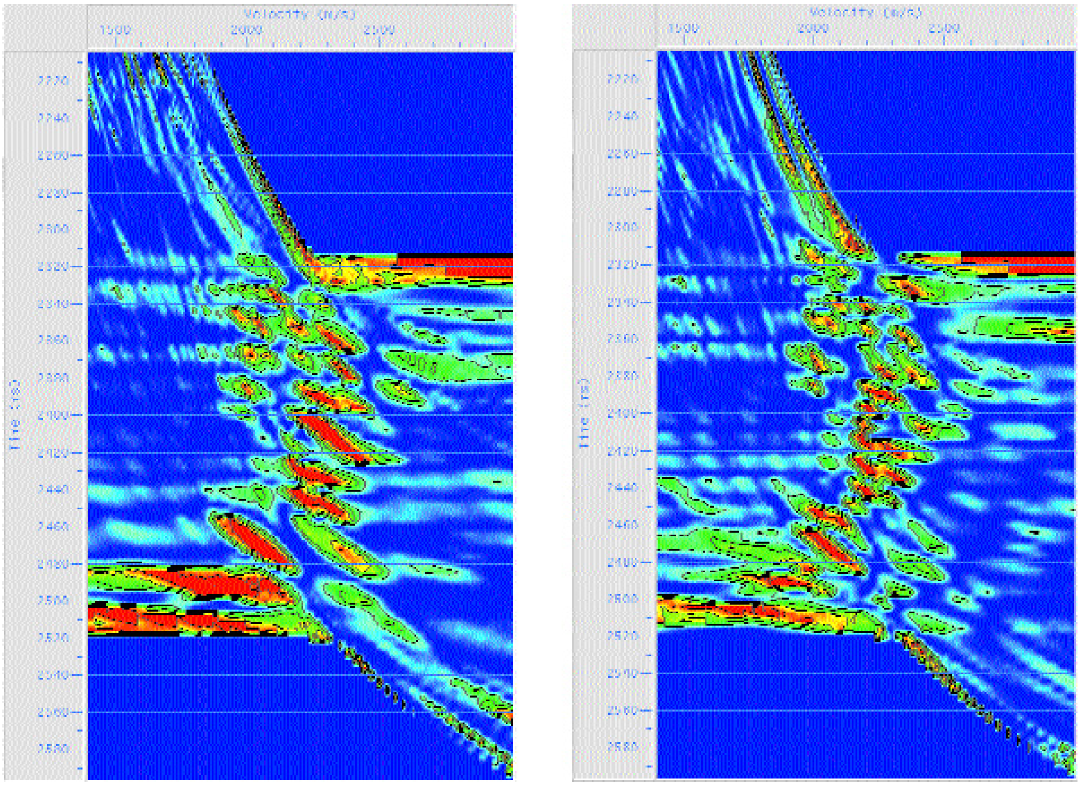

Fig. 11 - Semblance panels for pre stack '89 vintage data before (left) and after (right) inverse filtering.

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