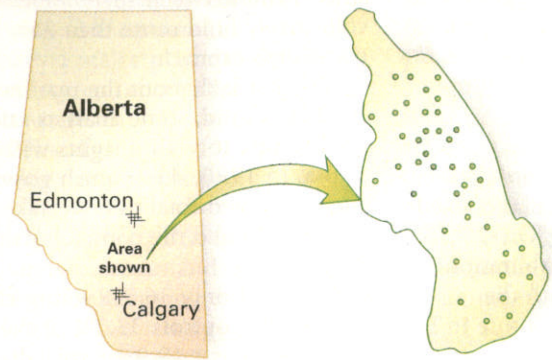
Enhancing seismic frequency bandwidth using VSPs—a case study

Satinder Chopra
Core Laboratories
Calgary

LOCATION OF WAYNE OIL FIELD Fig. 1



A new method for restoring high frequencies within the seismic bandwidth has been applied to a producing field in southern Alberta. This method is different from the conventional methods practiced in the industry and utilizes the frequency decay experienced at different VSP depth levels.

Once the frequency attenuation has been determined from downgoing VSP traces, the surface seismic data are compensated for that. The procedure is robust and yields better-defined stratigraphy leading to more confident interpretations.

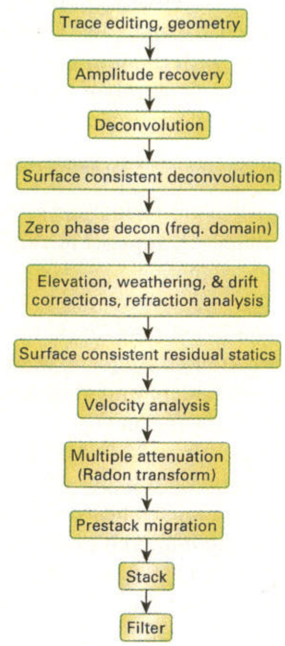
Wayne Nisku oil pool in the Wayne-Rosedale area is 15 km southwest of Drumheller in Alberta (Fig. 1).

The discovery well 4-24, drilled in 1993, started the process of development drilling, and the pool started producing in 1994. Presently, more than 20 wells have been drilled in the pool. The daily production from the area exceeded 1,000 cu m/day in 1996 and lately is 500 cu m/day.

The target reservoir is a Devonian Lower Nisku dolomite formation about 35 m thick. It was deposited as a widespread carbonate bank in a shallow, open marine environment. The porosity is primarily vuggy within the oil reservoir but ranges to intergranular beyond.

Overlying the Nisku reservoir rock are the primary dolostones and the laminated impermeable anhydrites formed in the subtidal to supratidal environment of a regressive often hypersaline shelf. Below the Nisku are the Ireton and Leduc formations. The Ireton, an argillaceous dolomite, is very thin in the area. It is underlain by thick, porous Leduc dolomite, which is generally regarded as a regional aquifer.

REPROCESSING SEQUENCE Fig. 2



The regional aquifer provides an adequate reservoir pressure support to most of the pool. However, production data suggest internal flow barriers within the reservoir. In addition, numerous small offset faults cut this formation that may act as conduits for hydrocarbons and/or water.

An integrated study was undertaken to update the pool development plan.

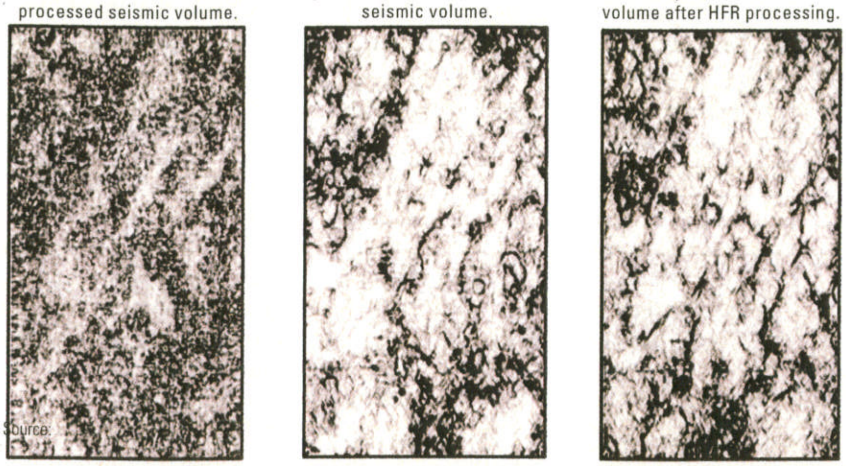
Time slices (1,210 ms) from coherence volumes

Fig. 3

A. Coherence volume generated from earlier processed seismic volume.

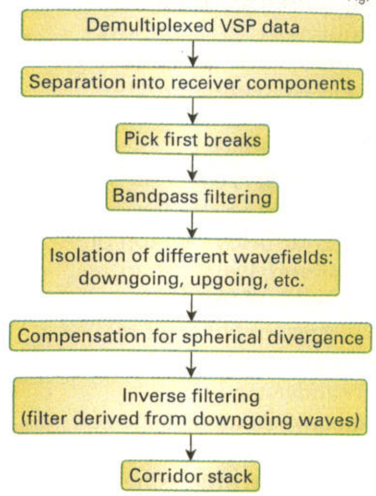
B. Coherence volume generated from reprocessed seismic volume.

C. Coherence volume generated from reprocessed seismic volume after HFR processing.



Processing sequence for VSP

Fig. 4



As part of this study, it was decided that the available 3D seismic data over the field be re-examined and integrated with other relevant data.

The goal of the seismic study was to better image and map the subtle faults that may impact flow in the reservoir. A second goal of the reprocessing was to provide a broadband, zero phase data cube for inversion processing.

Wavelets extracted from the previously processed volume were significantly non-zero phase and were nonstationary, exhibiting an apparent phase change along the trace. A revised seismic interpretation and inversion were to be used to constrain a revised reservoir model for the pool which is to be used for simulation and infill planning.

Improvement evaluation

The available 3D seismic data were reprocessed.

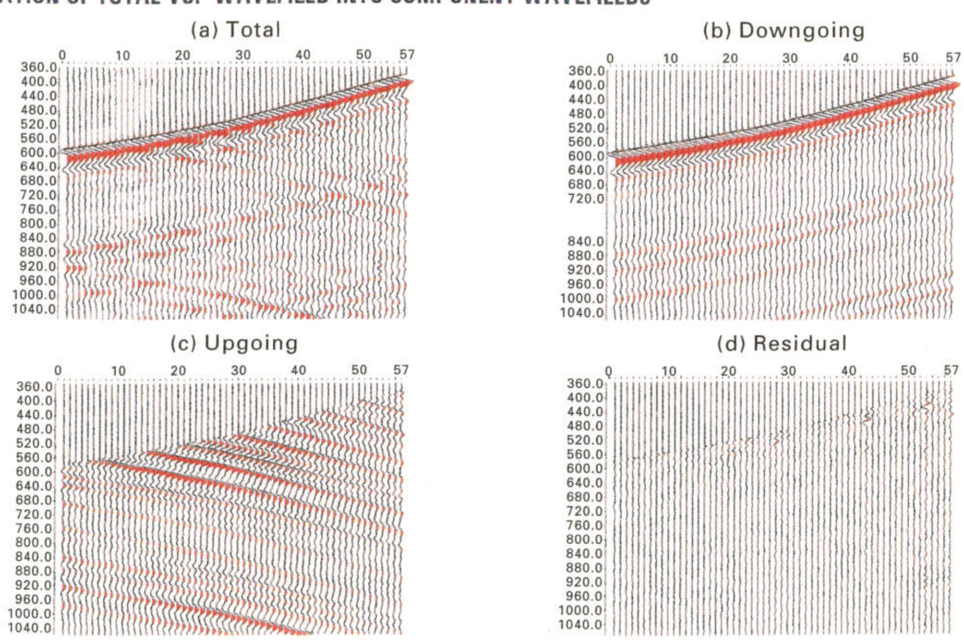
The processing flow used is shown in Fig. 2 and was aimed to improve the quality of the post-stack data and to gain higher resolution and better signal-to-noise ratio at the main target level or interval. Prestack migration and surface consistent deconvolution, we believe, partly helped to achieve this objective.

As elaborated in the next section, advantage was taken of the higher resolution of VSP data to enhance the bandwidth of the post-stack seismic data. The frequency enhancement of the seismic data was evaluated by running coherence cubes on the seismic volumes. The coherence cube is an excellent tool for imaging faults and stratigraphic features in 3D seismic data volumes.[1-4]

The time or horizon slices are useful for following faults and stratigraphic features in map views which are not biased by the interpreter. Fig. 3 shows time slices from the coherence volumes run on the earlier processed seismic volume and the

Separation of total VSP wavefield into component wavefields

Fig. 5



reprocessed volume. The signal-to-noise ratio is higher, random noise levels are low, and some of the faults are seen clearly with their NE-SW trend.

Zero offset VSP

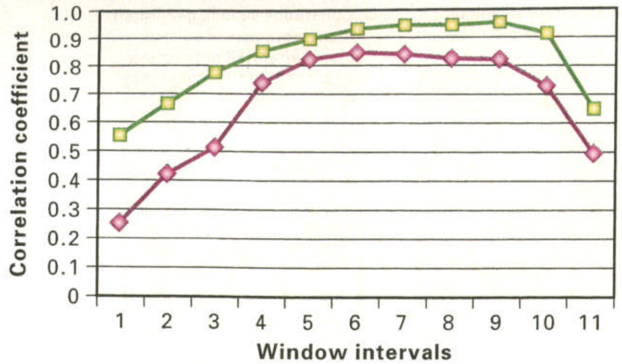
Seismic interpretation in the interval below the top of the reservoir, i.e. 1,100 to 1,300 ms, is difficult due to the absence of coherent reflections.

To understand this prospective strata better, a zero offset VSP recorded in well 4-24 was processed. The processing sequence adopted is shown in Fig. 4.

The separation of the combined VSP wavefield into component wavefields was effected by a nonlinear optimization separation method.[5] Fig. 5 shows the total wavefield separated into the downgoing, upgoing, and residual wavefields.

As the corridor stack trace is a zero-offset trace that represents the wavefield recorded along the wellbore, it can be compared directly to well logs in time. VSP first arrival times were used to compute and apply drift corrections. A correlation analysis was carried out between a generated synthetic VSP trace (using logs) and the real corridor stack trace before and after drift correction. Enhanced correlation between the two traces can be seen after drift correction (Fig. 6).

CORRELATION COEFFICIENT ANALYSIS Fig. 6



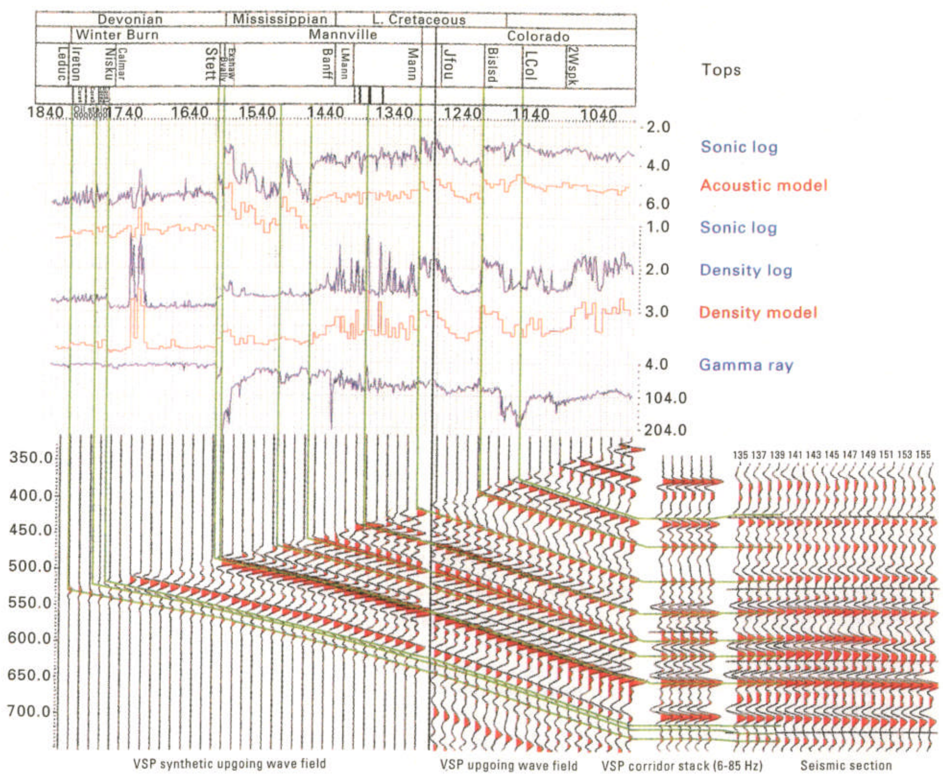
As the next step, a synthetic VSP was generated to identify the multiple activity in the broad zone of interest and also understand the path followed by the source pulse to generate the multiple.[6] Apart from this, amplitude variations due to transmission effects could also be studied.

The sonic log was used to derive the acoustic boundaries and then simulating the zero offset VSP geometry, the synthetic VSP was generated using a ray-tracing package.

As seen in Fig. 7, the events corresponding to the main formation tops on the sonic log seem to tie very well with the real VSP corridor stack. This suggests that the corridor stack chosen for stacking was a good choice and that no multiple activity is included.

The corridor stack can now be confidently correlated with the seismic. Fig. 8 shows the correlation of logs, the aligned upgoing wavefield, the corridor stack, and a segment of the seismic section. This plot shows a general agreement between VSP and surface seismic data.

CORRELATION OF LOGS, SYNTHETIC VSP, REAL VSP, CORRIDOR STACK, AND SEISMIC Fig. 7



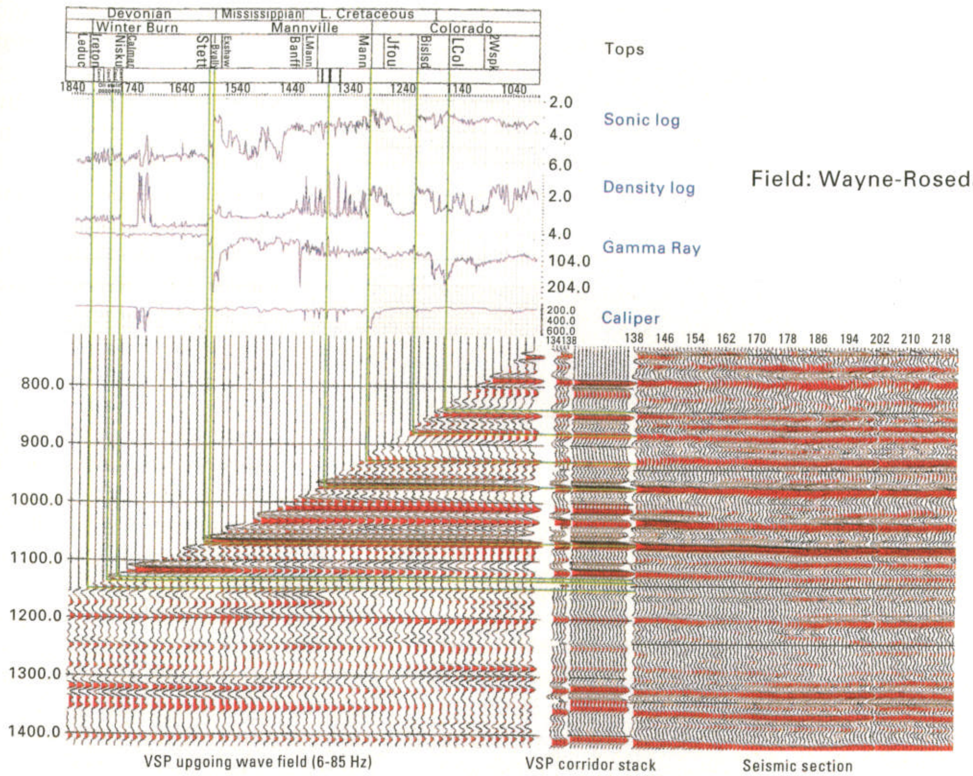
Enhancing bandwidth

High frequency restoration (HFR) is a method used for restoring high frequencies in the bandwidth of the surface seismic data and is different from any of the conventional methods practiced in the industry.[7]

It utilizes the frequency decay experienced at different VSP depth levels in a well. For VSP downgoing signals recorded at different depth

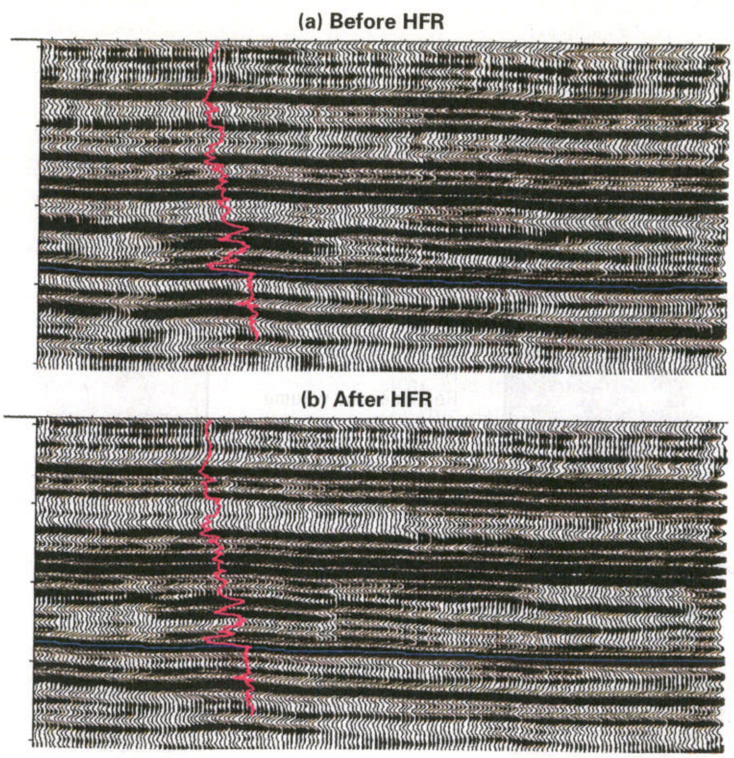
Correlation of logs, aligned upgoing wavefield, corridor stack, and seismic

Fig. 8



Segments of a seismic line*

Fig. 9



*Note the enhanced frequency content and the continuity of the reflection events.

levels, the ratio of change in frequency of the first arrivals at successive depths would describe the decay of frequency components between those observation points. This fact is utilized to first determine the amplitude decay resulting from frequency attenuation from downgoing VSP traces and then try and restore those frequency components that have been attenuated in the data.

The change in the amplitude and length of the wavelet on the first arrivals at successive depth levels is used to estimate the change in the frequency components. An inverse operator (in time domain) is designed to compensate that.

For application to seismic data, first the time window of application needs to be determined. For this purpose, the VSP upgoing wavefield is correlated with the CDP section so that each depth level point is seen in terms of two-way time where the determined operator needs to be applied. This way the node points for all the different operators are determined.

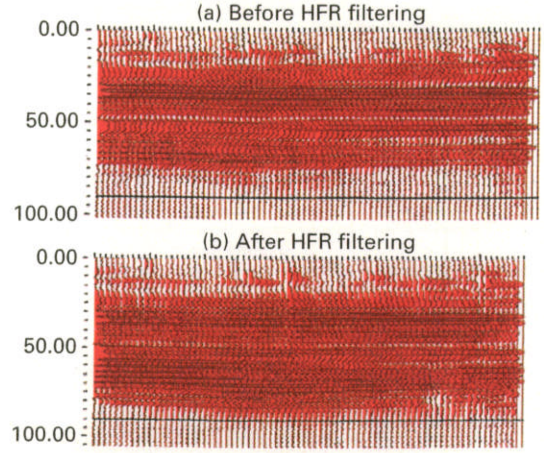
Thereafter, the filter application is run as convolution (time domain) on the seismic data. As inverse operators are applied continuously at every sample of the stacked data, windowing is avoided.

The HFR procedure when run on the seismic data has an effect similar to a time variant attenuation correction, resulting in a compression of the embedded wavelet. This generally results in slight changes in the phase, though still preserving the phase of the wavelet it started with. Usually, a small phase rotation of the seismic data after the frequency restoration process shows a good correlation match.

Fig. 9 shows a segment of seismic section with and without frequency restoration or filtering. Notice the improvement in resolution. The reflection events now exhibit more continuity.

Fig. 10 shows sectional amplitude spectra for a seismic line out of the 3D volume before and after HFR filtering. The frequency bandwidth of the data has been enhanced by more than 20 Hz.

AMPLITUDE SPECTRA IN ZONE OF INTEREST Fig. 10



*Notice the enhancement in the frequency bandwidth.

Evaluating improvement in frequency enhancement

Coherence cube was run on the reprocessed seismic volume before and after filtering to examine the differences that may have come about after frequency restoration.

Fig. 3 showed time slices at 1,210 ms. An important thing to note here is that these patterns are seen as more distinct, yielding a clearer image for interpretation. One can see the NW-SE fault and fracture patterns in the center of the image apart from other E-W and NE-SW trends that can be interpreted as shown in (c). These trends are not so obvious on the slice in (a) or (b). The frequency restoration has helped define trends better.

Similarly, Fig. 11 shows time and horizon slices from different coherence volumes. Fault patterns are seen to have crisp and definite shapes and so lead to a more confident interpretation.

Evaluating effects

Acoustic impedance inversions were performed on the final prestack time migrated seismic volumes, both before and after HFR processing.

Inversion algorithms generally assume a stationary wavelet in the convolutional model of the seismogram. This is often satisfactory if the time-window of the inversion is not too long.

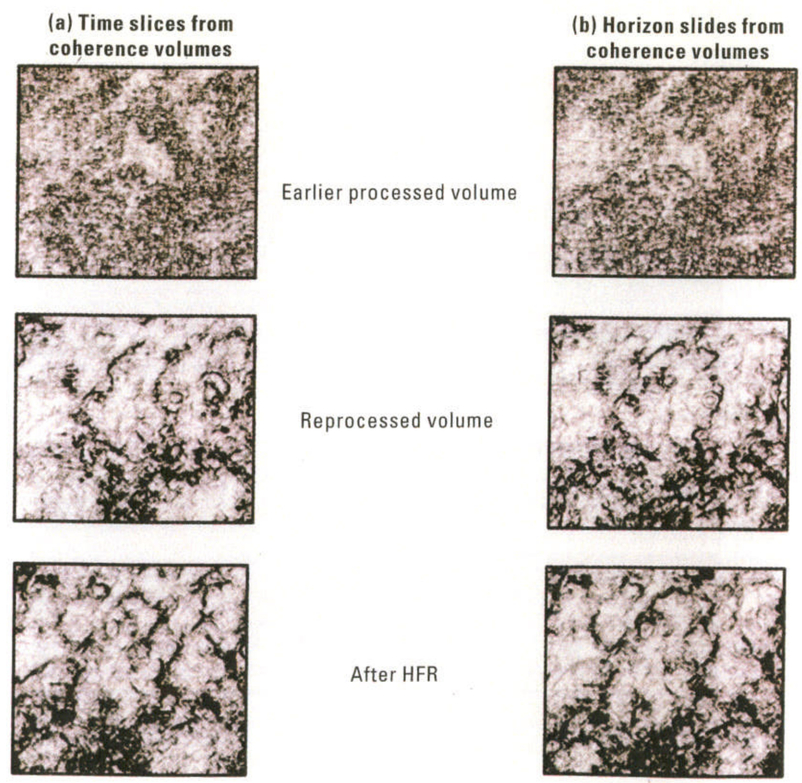
One might expect that any processing that can remove the predictable time-varying wavelet decay due to earth transmission processes should contribute to the stationarity of the wavelet, though it is not always the case. Wavelets were extracted from different time windows of a seismic line after HFR processing. As seen in Fig. 12 these wavelets are all zero phase, very similar to one another and hence stable.

The size of time window for the wavelet spectrum estimation and the accuracy of the resulting phase estimate are two aspects contributing to the nonuniqueness of the inversion result. With HFR processing it is possible to control these variables in a physically reasonable way.

Fig. 13 shows the impedance inversion segments from the seismic profile shown in Fig. 9. Fig. 13a is the impedance section generated from seismic migration, and Fig. 13b is the impedance section for seismic after HFR.

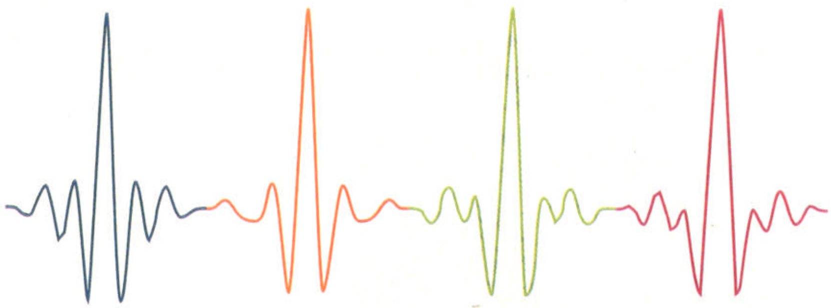
There are obvious differences in the inversion that stem from the greater stability of the seismic wavelet. In the indicated intervals, now there are distinct low impedance changes after HFR and the high impedance event to the right is seen resolved into two separate high impedance events. Such events

FAULT PATTERNS THAT LEAD TO CONFIDENT INTERPRETATIONS Fig. 11



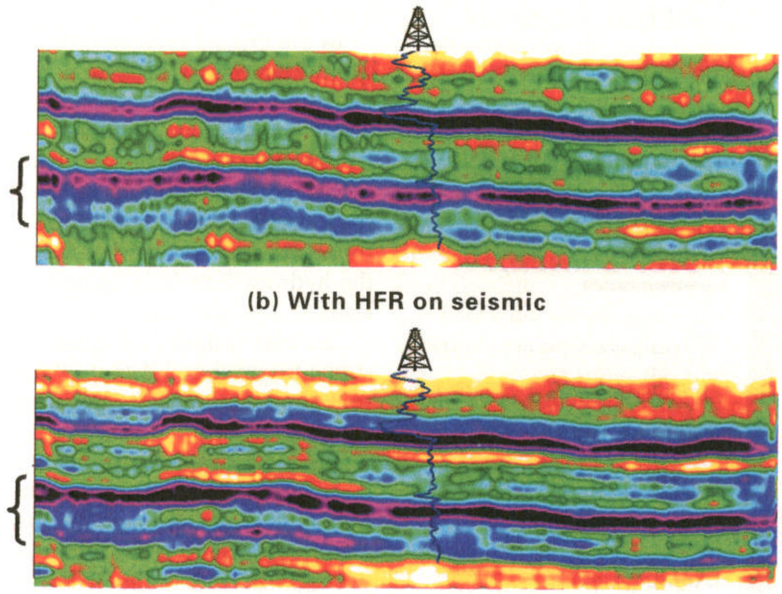
Wavelets from different time windows appear to be stable

Fig. 12



Impedance sections

Fig. 13



could make the difference between interpreting high and low porosity pockets.

Improved data

A procedure was devised to determine the decay in amplitude from the downgoing first arrivals from successive depth levels in a VSP and then apply the inverse decay function to surface seismic data. This application has illustrated the usefulness of the procedure. The poor reflection zone on the seismic shows up greater reflection detail and continuity which matches better with the corridor stack.

The ease and quality of wavelet estimate obtained using the HFR processed data has reduced the scope of nonuniqueness in the seismic inversion. The frequency restoration of the seismic data was evaluated by running coherence cubes on the seismic volumes before and after filtering. By integrating the VSP and surface seismic processing we have added information that has improved the fidelity of the final data volume.

Acknowledgments

We thank Core Laboratories for permission to offer this article for publication. Coherence cube and HFR are trademarks of Core Laboratories. ✦

References.

1. Bahorich, M., and Farmer, S., "The Coherence Cube," The Leading Edge, Vol. 14, No. 10, 1995, pp. 1,053-58.

2. Chopra, S., and Sudhakar, V. "Fault interpretation—the coherence cube and beyond," OGJ, July 31, 2000, pp. 71-74.

3. Chopra, S., Sudhakar, V., Larsen, G., and Leong, H., "Azimuth based coherence for detecting faults and fractures," World Oil, September 2000, pp. 57-62.

4. Chopra, S., "Integrating coherence cube imaging and seismic inversion," The Leading Edge, Vol. 20, No. 4, 2001, pp. 354-362.

5. Blias, E.A., and Katkov, U.B., "Optimization algorithms for selecting three components VSP wavefield," Automated System of Geological-Geophysical Data Acquisition and Processing, Riga, 1990 (in Russian).

6. Wyatt, K.D., "Synthetic vertical seismic profiles," Geophysics, Vol. 46, No. 6, 1981, pp. 880-891.

7. Chopra, S., Alexeev, V., and Sudhakar, V., "High frequency restoration of surface seismic data," The Leading Edge, Vol. 22, No. 10, 2003.

The author

Satinder Chopra (schopra@corelab.ca) specializes in coherence cube processing and inversion at Core Laboratories in Calgary. He has 18 years of experience in the fields of seismic processing and interpretation, specializing in depth imaging, inversion, and AVO analysis. He obtained his MPhil degree in physics from Himachal Pradesh University and joined Oil & Natural Gas Corp. Ltd. of India in 1984.