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# Reservoir characterization with high frequency bandwidth seismic data and coherence processing

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**Summary**

Reservoir characterization is a crucial prerequisite to predict the economic potential of a hydrocarbon reservoir or to examine different production scenarios. Unfortunately, it is difficult to determine the exact reservoir properties at the required scale. Typical seismic data has a temporal resolution around 100 feet and a spatial resolution of about the same order. However, surface seismic is the only tool available to address the reservoir fields wide. Wells resolve the reservoir down to the inch scale, but only at single points in the field. A new method of enhancing the frequency bandwidth of seismic data and restoring high frequencies has been developed and can have a profound effect on better correlation with well logs and help bridge the scale gap. Referred to as Frequency Bandwidth Extension technologies (FBE), this method increases the limit of resolution of seismic data by exploiting the limit of resolution in the frequency spectrum. This is different from any of the conventional methods practiced in the industry. This approach (pentent pending) results in sharper wavelets capable of identifying thinner beds and subtle features.

The application of 3-D Coherence processing is an extremely powerful tool to efficiently exploit the wealth of structural and stratigraphic information encapsulated in the seismic waveforms of 3-D seismic data volumes. This tool provides the oil industry with technology that significantly improves productivity, interpretation accuracy, and extracts a vast amount of information from the 3-D seismic data volume that would otherwise be overlooked. This technique allows the geoscientist to rapidly identify both subtle structural and stratigraphic features throughout the field. In addition this technology is very powerful for recognizing subtle differences between 3D data sets processed with different parameters and technologies especially those which change the frequency of the waveform. Thus coherence is an excellent tool to evaluate both the structural and stratigraphic effects of increasing the frequency of seismic data as demonstrated here.

The resultant data cube is equally useful to geophysicists, geologists, and reservoir engineers to help build a more accurate picture of the subsurface, increasing the precision of reservoir modeling, and decreasing the risks associated with drill site selection. Processing geophysicists work closely with interpretation geoscientists to optimize the results of the coherence processing using the latest algorithms and parameters to focus on features of specific interest.

**Introduction**

Reservoir characterization methodology involves determining reservoir architecture, establishing fluid-flow trends, constructing reservoir model, and identifying reserve growth potential. Geophysicists are often frustrated at their inability to extract and understand the subtle stratigraphic detail contained in 3-D seismic volumes. Seismically, stratigraphic bodies with definitive shapes show up if they are encased in rocks with contrasting velocity. Low-porosity carbonate bodies associated with thin shales and encased in shaly carbonate rocks may not be seen on seismic data having a narrow frequency bandwidth. Often we come across examples where the initial processed 3-D seismic volume results in interpretations that sometimes are geologically suspect, e.g., cases involving complex faulted patterns or subtle stratigraphic plays. Similarly, postmortem analysis may cite small fault displacements or obscure seismic data as reasons for dry wells. In practice, more accurate stratigraphic interpretation is needed, but the available bandwidth of the data is inadequate to image or resolve the thickness of many of the thin targets seen in the wells. This problem can be addressed by having data of reasonable quality and augmenting it by some frequency restoration procedure that would improve the vertical resolution. Frequency restoration is necessary because seismic waves propagating in the subsurface are attenuated and this phenomenon is frequency dependent - higher frequencies are absorbed more rapidly than lower frequencies. Consequently, the highest frequency recovered on most seismic data is usually about 80 to 100 Hz. This enables confident mapping of subsurface horizons of interest, clarifies detailed geological settings and eventually leads to more profitable seismic exploration programs.

**Methodology**

The FBE approach to enhance the frequency bandwidth results in sharper wavelets capable of identifying thinner beds. Resolving thin beds from seismic data imply identifying individual reflections from the top and bottom of a bed, and the limit of resolution is defined as “the smallest bed separation that can be identified as two distinct events in seismic data”. Ricker (1953), Widess (1973) and Kallweit et al (1981) studied the limit of resolution more than two decades ago by convolving wavelets of known characteristics with two spikes, the distance (time interval) between the spikes representing the top and bottom of the structure under study. The procedure enunciated here is robust and helps to define trends better leading to more confident interpretations. Such applications could redefine prospects, which in some cases may have been declared unsuccessful based on interpretation of seismic data with poor bandwidth.

Analyses done in the late 1970's and 1980's show that the limit of resolution (thinnest bed that can be resolved) is a function of the wavelet's characteristics (breadth or frequency information). Since then, noise reduction and deconvolution techniques are routinely applied to field data with the objective of maximizing resolution through the optimization of the useable bandwidth and shaping of the amplitude spectrum of the data; with the premise that, once the optimum spectrum has been obtained within the usable bandwidth, it cannot be further extended to include frequencies not recorded in the field or for which the signal-to-noise ratio (S/N) is too low. The Frequency Bandwidth Extension is a non-conventional technique which works in the frequency domain where the limit of resolution is smaller than in the time domain. FBE takes the optimally processed seismic data and increases resolution considerably by extending the wavelet's spectrum up to the maximum usable bandwidth.

In practice, the extension of the frequency bandwidth by padding is imperfect and results in wavelets that are not white and, for this reason, do not honor Kallweit's time limit of resolution; nevertheless, time limit of resolution is still reduced by 30% by making $f_{UE}$ (New and extended maximum frequency) larger than $1.4f_U$ (maximum frequency of a broadband wavelet). By padding amplitudes between $f_U$ and $f_{UE}$, where there is no seismic signal, the wavelet becomes sharper with the resultant decrease of the limit of resolution. Since no real signal exists from $f_U$ to $f_{UE}$, it will be impossible to see the effect of beds thinner than $T_{RN}$ on the extended spectrum and the resultant tuning curves will have different characteristics than those observed in the usual case. Namely, amplitudes will not increase for wavelets convolved with thinner beds than the new limit of resolution, and thickness and amplitudes around the original limit of resolution will be in error as observed by comparing.

The coherence analysis is an innovative process, patented by Amoco (Bahorich and Farmer, 1988 and 2000, Marfurtt, et al, 1996 and 1999). It brings a renewed excitement to seismic interpretation and removes a significant amount of guesswork. The process provides accurate maps of the spatial change in the seismic waveform that can readily be related to geologic features and depositional environments. Faults and fracture systems can now be spatially imaged and directly mapped from the coherence data without the tedious task of drawing faults on each vertical section and proceeding blindly without the knowledge of their spatial position in the early crucial phase of the interpretation. Stratigraphic features can now be readily detected in the volume, relieving the interpreter of the tedious task of locating them, thus freeing up time for detailed analysis (Maione, 1999).

The coherence algorithms used are typically referred to as C1, C2 and C3. The methodology originally patented by Bahorich and Farmer in 1994 describes a correlation technique as part of the approach for providing the numerical similarity of a cube of seismic traces. This resulted in the C1 algorithm. Further work performed by Bahorich et al produced the superior C2 based semblance algorithm. In 1996, Gersztenkorn and Marfurt announced the Eigen structure algorithm (C3) with, in most cases, a significant response improvement over the semblance based formulation. Eigen solution (C3) has proved to be highly successful with increased robustness in revealing both subtle faults and stratigraphy in one execution. These results are far superior to the Correlation (C1) and Semblance (C2) solutions used in the passed and available on the workstations.

The Eigen algorithm is a multi-trace Eigen decomposition process that is more robust with higher resolution than previous algorithms. Consider two seismic traces whose amplitudes are crossplotted sample by sample on the Cartesian coordinate system. The distribution of the general shape of the plotted points can be represented by an ellipse and the pattern formed by these points is governed by the coherence of the two input traces plotted. The ellipsoidal shape is not a measure of the individual samples but more a measure of the overall waveform shape being input.

An additional improvement was added which gives an option to remove the structural effect from the technique caused by the instability of the zero-crossing on the seismic trace. This is achieved by a higher fidelity dip/azimuth search. Recently a major breakthrough was accomplished by introducing a gradient response which produces a significant lift in the sensitivity resulting in higher resolution features especially in the textural background. This capability called High Resolution Eigen makes even the most subtle waveform changes visible to the eye with both faulting and stratigraphic detail. 3-D seismic coherence is computed by measuring waveform similarity within an aperture which includes traces and time samples within a user specified space and time window control. The waveform similarity is measured along all possible planes within the dips specified. User defined criteria are used to output similarity measurements. Faults can be identified by their low similarity measurement when the aperture is straddling the fault location. Subtle changes in the seismic waveform which show the extent and internal details of stratigraphic features can also be identified by using the technique.

**Data Examples**

The frequency restoration procedure described above has been run on a 3-D seismic data set from an onshore oilfield in southwest China, and convincing and promising results have been obtained. Figures 1 and 2 show the application of FBE on the migrated 3-D seismic data using the approach discussed above. The FBE process has increased their bandwidth from 40 Hz or less to over 100 Hz using this patent pending new technique. The geologists can redefine thin beds, pinchouts, small faults, and new prospects using these high frequency seismic sections with higher confidence.

Figure 3 comparies the FBE processing result from 500 ms to 2,000 ms section. The FBE procesing has significantly increased the frequence bandwidth, sharpened the wavelet, and enhanced the reflection image for much easier and more confident interpretation in the reservoir zone. Figure 4 shows the time slice at 1,000 ms with significant high frequency features and great details after FBE processing.

Figure 5 is the comparison of time slice (1,680 ms) of seismic data (left) and the coherence data (right) using Adaptive High Resolution Eigen method. There are fracturing zones on the top of the structure and small faults developed along the major fault zone on the Coherence processing time slice, which can not be identified from the time slide seismic data.

Figure 6 comparies the time slices (1,680 ms) of coherence processing result before and after FBE processing. Here a direct comparison of the results can be evaluated. The FBE process reveals subtle features more clearly throughout the structure leading to a more accurate understanding of the subtleties of the field.

The FBE processing has significantly improved and increased the resolution of the seismic data. Much more detailed geological features can be easily indentified and interpretated (red line surrounding area) from the coherence data after the FBE processing. These plots have significantly helped geologists and reservoir engineers to understand and interpret fluid distribution, subtle reservoir structure, and conduct reservoir characterization with great confidence.

**Conclusions**

The FBE method described in the abstract increases the limit of resolution of seismic data by exploiting frequency spectrum of seismic wavelets and increasing the time limit of resolution to a higher part of the spectrum. This results in sharper wavelets capable of identifying thinner beds. A by-product of extending the frequency spectrum is the shifting of the tuning effect of thinner beds to the new limit of resolution ($T_{RN}$). When tuning curves before and after the process are compared, it is observed that although different, the differences are minuscule and insignificant compare to the benefits coming from being able to resolve thinner beds. The procedure enunciated here is robust and helps to define trends better leading to more confident interpretations. Such applications could redefine prospects, which in some cases may have been declared unsuccessful based on interpretation of seismic data with poor bandwidth.

Coherence processing examines the spatial change in the seismic waveform, by mathematically comparing a window of a seismic trace with its neighbors. This processing is aimed at identifying the discontinuities. Subtle changes in a reflecting horizon’s character will show as a sharp discontinuity in relation to the local waveform. Thus Coherence can be considered the complement of the conventional seismic, in one hand we see the reflections and on the other the discontinuities.

By combining the power of the frequency bandwidth extension techniques and the coherence processing as an evaluation tool a new dimension in understanding subtle reservoir information can be achieved. Both subtle structural and stratigraphic features can now be revealed which add significance to better understanding of the reservoir.

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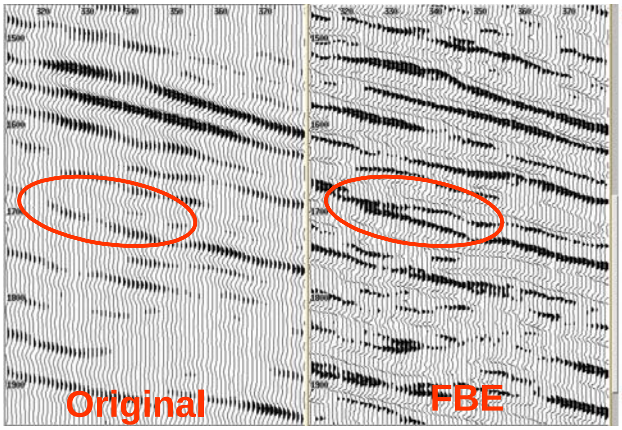


Figure 1 Stacked section before (left) and after (right) FBE processing. Many detailed subtle stratigraphic features can be seen on FBE data (green line interpretation).

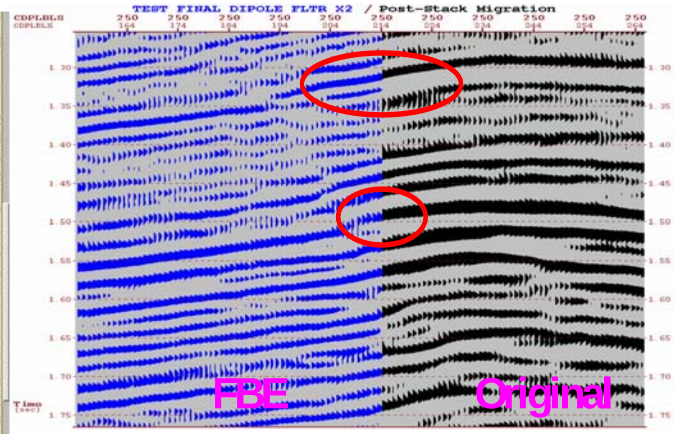


Figure 2 Direct merge of seismic section before FBE (right) and after FBE (left) processing. Additional small reflectors can be identified in red circle areas on FBE data.

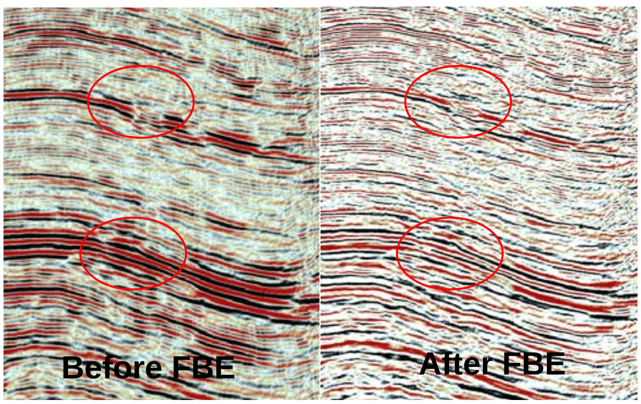


Figure 3 Comparison seismic section from 500 ms to 2,000 ms before (left) and after (right) FBE processing.

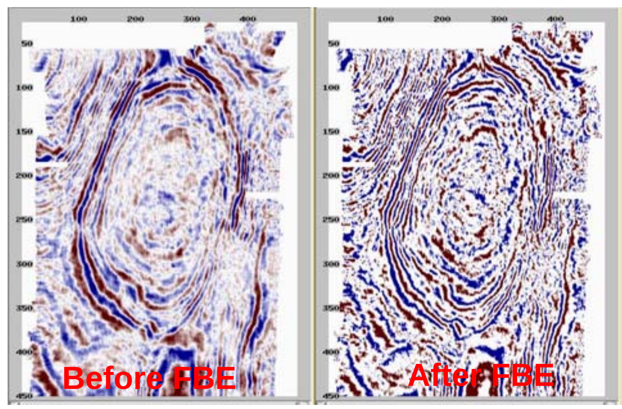


Figure 4 Time slide (1,000 ms) of seismic data before FBE (left) and after FBE (right) processing.

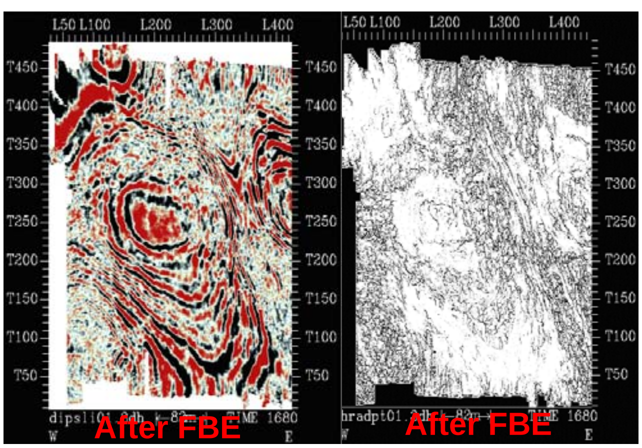


Figure 5 Time slide (1,680 ms) of seismic data (left) and time slide (1,680 ms) of Coherence Cube data (right) comparison.

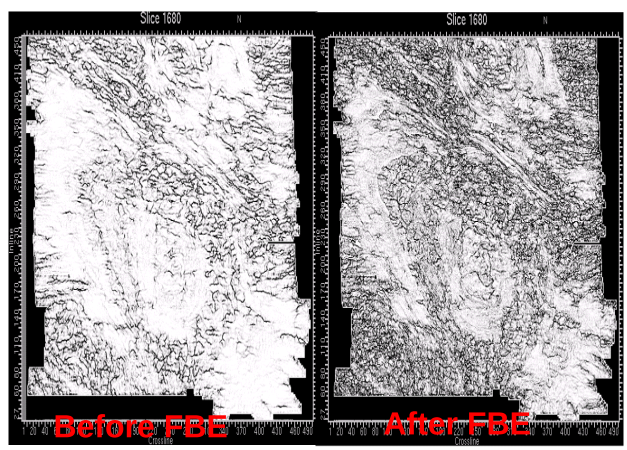


Figure 6 Time slice (1,680 ms) of the Coherence Cube data before FBE (left) and after FBE (right) processing.

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