Coordinated by Guillaume Cambois

# Integrating coherence cube imaging and seismic inversion

SATINDER CHOPRA, Scott Pickford, Calgary, Alberta, Canada

Despite the success of 3-D seismology, the geophysical community recognizes that these surveys contain more information than simply the structure or identification of isolated bodies in the subsurface. This conviction has led to new techniques to exploit the additional information. Amoco's development of coherence cube technology in the 1990s is an example. At about the same time, based on work by Roy Lindseth originally done in the 1970s, a plethora of 3-D poststack inversion algorithms arrived that delivered high-resolution information about the subsurface from seismic data.

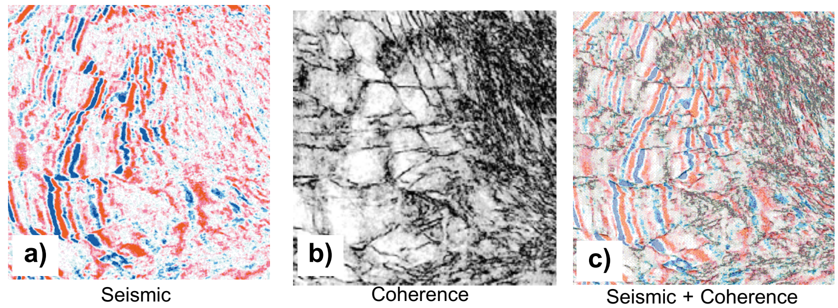


**Figure 1. Time slices from seismic and coherence volumes. Notice the clear fault and fracture detail on the coherence data.**

This paper describes the integration of coherence cube imaging and seismic inversion and the advantages that accrue from this combination.

Coherence cube imaging essentially generates a cube of coherence coefficients by calculating localized waveform similarity in both in-line and cross-line directions. The underlying assumption is that seismic traces cut by a fault generally have different seismic character than neighboring traces. As a result, there is a sharp discontinuity in local trace-to-trace "coherence." Similarly, stratigraphic features are associated with definite seismic waveform expressions. A time slice from a coherence cube would depict lineaments of low coherence along faults and other features like channels, reefs, salt edges, and unconformities.

Traditional seismic time slices are usually used for interpreting faults that run perpendicular to strike. However, in complex fault zones, faults running parallel to strike become more difficult to see as fault lineaments become superimposed on bedding lineaments. Because three-dimensionality is an essential ingredient of the coherence cube, faults or fractures in any orientation are revealed equally well. Radial and en-echelon faulting also are seen clearly. Furthermore, because features such as beaches and deltas are clearly defined by coherence cube, a better idea of progression and retreat is possible while trying to reconstruct the sequence stratigraphy of the area. Similarly, the remarkable detail of mud flows, submarine canyons, and depositional stratigraphy, that is unidentifiable on seismic reflection data even on close scrutiny, stands out distinctly.

Figure 1 is offshore Canada's east coast where NW-SE faults and fractures, apparently difficult to interpret on conventional data, show up clearly on the coherence slice. Overlaying a coherence slice on the seismic slice greatly helps interpretation (Figure 1c). Figure 2 illustrates that channel features and reefs show up distinctly on the coherence slices but not on conventional seismic.

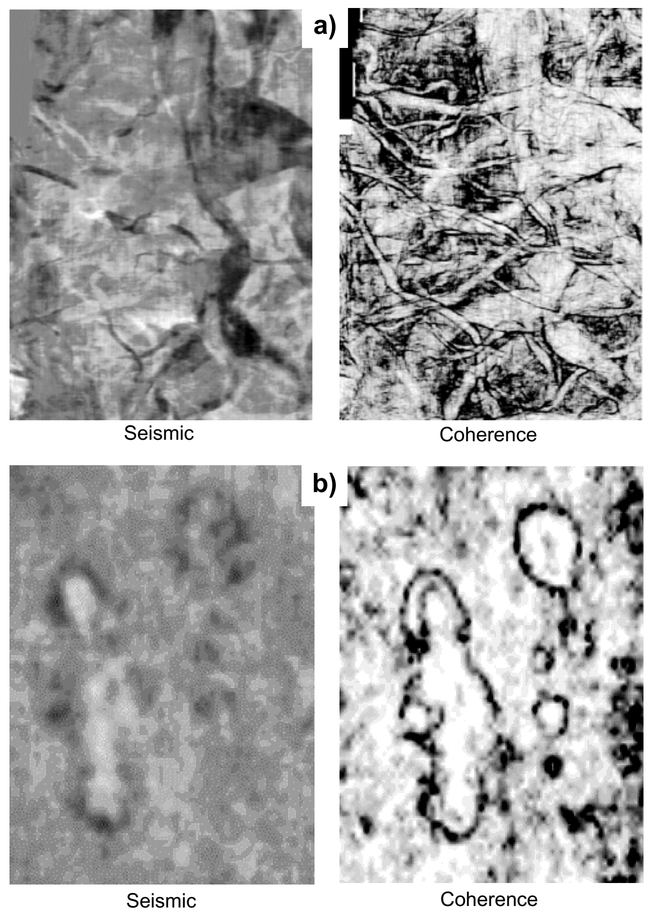


**Figure 2. Channels (a) and boundaries of reefs (b) are more distinct on coherence slices than conventional seismic time slices.**

**Seismic inversion.** Seismic impedance inversion is widely used today mainly due to the ease and accuracy with which impedance data can be interpreted. Also, inversion of seismic data to acoustic impedance allows an integrated approach to geologic interpretation. (This article uses "inversion" to mean transformation of poststack seismic reflectivity traces into acoustic impedance data.)

Seismic reflection data represent an interface property—i.e., reflection events are due to relative changes in acoustic impedance of adjacent rock layers. The observed amplitude changes, however, do not indicate whether the amplitude changes relate to lithology variations above or below an interface. Acoustic impedance (the product of density and velocity) is a physical rock property. Well logs measure both these entities directly so, by dividing the density log by the sonic log, the acoustic impedance log is obtained. Thus acoustic impedance is a layer property. Because seismic amplitudes are attributes of layer boundaries, quantitative interpretation of seismic data in terms of thin stratal interval properties (impedance) should rely on inversion. Acoustic impedance simplifies lithologic and stratigraphic identification (being a layer property) and may be directly converted to lithologic or reservoir properties such as porosity, fluid fill, and net pay. In such cases, inversion allows direct interpretation of 3-D geobodies. Inversion plays an important role in seismic interpretation, reservoir characterization, time-lapse seismic, pressure prediction, and other geophysical applications.

Because inversion transforms seismic amplitudes directly into impedance values, special attention needs to be paid to their preservation. This ensures that the observed amplitude variations are related to geologic effects. Thus, the seismic data should be free of multiples, acquisition imprint, have a high S/N ratio, be zero-offset migrated, and without any numerical artifacts. Due to the band-limited nature of seismic data, the lack of low frequencies will prevent the transformed impedance traces from having the basic impedance or velocity structure (low-frequency trend) crucial to making a geologic interpretation. Also, the weak high-frequency signal components or their absence from the seismic data will find the impedance sections wanting in terms of resolution of thin layers. Both these aspects are taken care of during impedance inversion.

The low-frequency trend of acoustic impedance is usually derived from well logs or stacking velocities and used as a priori information during inversion. This helps enhance the lateral consistency of the resulting impedance data. The weak high-frequency signal components indicate notches or roll-offs on the higher end of amplitude spectra of seismic traces. Processing steps that tend to broaden the spectral band are usually adopted so that data input to inversion has an enhanced effective frequency bandwidth. Time-variant spectral whitening is one such process that flattens the amplitude spectra of the traces without altering the phase. Wavelet processing is another attractive option. A wavelet-processed section is one wherein the embedded wavelet is zero phase. The wavelet-processed section has better resolution and provides a more accurate indication of reflector time. Also, it makes the comparison of the seismic section with a well log simpler. These reasons suggest, and rightly so, that a wavelet-processed section should be input for seismic inversion.

Several different techniques/methodologies are commonly used to perform acoustic impedance inversion.

*Recursive inversion* is the most basic type of inversion and also the earliest methodology. It essentially assumes that seismic amplitudes are proportional to reflection coefficients and transforms input seismic traces to acoustic impedance traces. Input data are usually wavelet-processed. This does not fully satisfy the basic assumption, as the wavelet is not removed. Consequently, tuning and wavelet sidelobe effects are not reduced. Also, the results are produced within the seismic bandwidth, so that the method does not offer a significant advantage relative to conventional interpretation.

A broadband reflectivity series can be obtained by removing the embedded wavelet from the seismic trace. However, the removal of the wavelet from the trace to arrive at a suitable reflection coefficient series is not unique (i.e., more than one solution exists). To overcome this mathematical limitation, some inversion methods adopt constraints for the possible solution and get a correct inversion volume within the seismic bandwidth.

*Blocky inversion* models the subsurface as layers or blocks in terms of acoustic impedance and time. The starting model is defined by a few 3-D main time horizons. Well logs tie the main time horizons to the seismic data and define the impedance bounds for each model layer. The impedance within each layer may vary laterally and vertically. The impedance bounds are set to keep the optimized model laterally smooth and within given limits. The nonuniqueness is taken care of by restricting the number of layers relative to the number of seismic samples. The starting model is compared to the seismic data and iteratively updated to better match the seismic data.

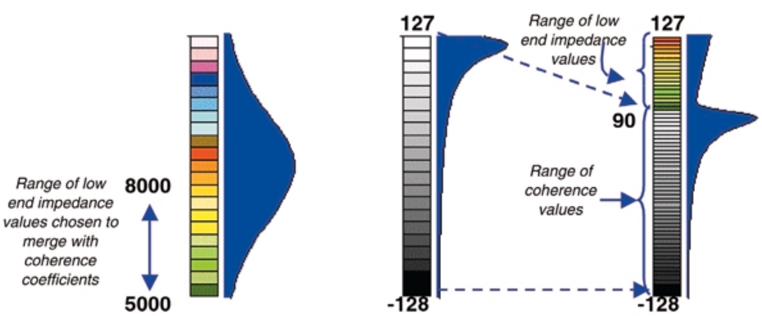


**Figure 3. Mechanism of composite displays.**

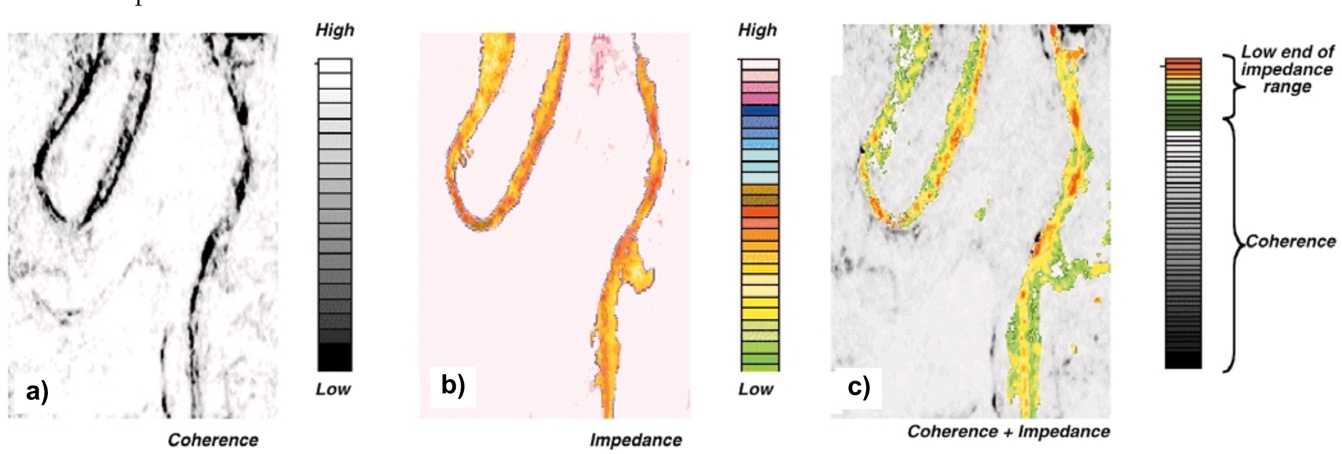


**Figure 4. Time slices from different kinds of data volumes.**

*Sparse spike inversion* estimates the reflectivity series that would approximate the seismic data with a minimum number (sparse) of spikes. Nonuniqueness is taken care of by applying the sparse reflectivity criterion. Maximum likelihood deconvolution (Chi et al., 1984) and L1 norm (Oldenburg et al., 1983) algorithms are commonly used.

As sparse-spike inversion tends to remove the embedded wavelet from the data, the inversion results are broadband for the higher frequencies, maximizing vertical resolution and minimizing the tuning effects.

*Stratigraphic inversion* attempts to construct a stratigraphic model from seismic data. These methods often introduce complex spatial stratigraphic relationships (e.g., conformity, angular unconformity, baselap) between layers.

*Geostatistical inversion* combines geostatistical data analysis and modeling with seismic inversion. Geostatistical analysis generates spatial statistics; vertical variograms are generated from well bore measurements, and horizontal variograms are estimated from the acoustic impedance values afforded by starting impedance model generated from seismic data, e.g. recursive inversion. Starting from the well log control points, geostatistical modeling simulates data at grid points. While carrying out the inversion, the simulated points are modified so as to agree with both well and seismic data.

All the model-based inversion methods belong to a category called *local optimization methods*. A common characteristic is that they iteratively adjust the subsurface model in such a way that the misfit function (between synthetic and actual data) decreases monotonically. In the case of good well control, the starting model is good, and local optimization methods produce satisfactory results. For sparse well control or where the correlation between seismic events and nearby well control is made difficult by fault zones, thinning of beds, local disappearance of impedance contrast, or the presence of noise, these methods do not work satisfactorily. In such cases, *global optimization methods* (e.g., simulated annealing) are needed. Global optimization methods employ statistical techniques and give reasonably accurate results.

But no matter what inversion approach is adopted, the acoustic impedance volumes so generated have significant advantages. These include increased frequency bandwidth, enhanced resolution, and reliability of amplitude interpretation through detuning of seismic data and obtaining a layer property that affords convenience in understanding and interpretation.

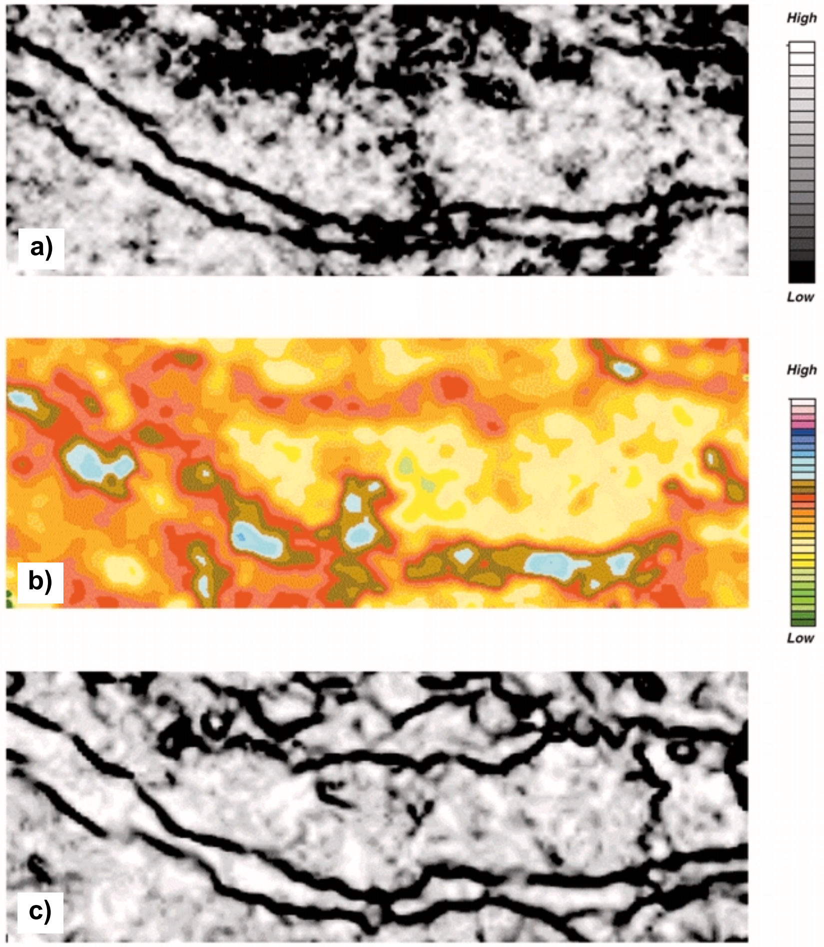

**Figure 5. (a) Time slice from coherence cube on seismic data and (b) from impedance volume. (c) The same time slice from coherence cube run on impedance volume.**

**Integrating coherence cube and inversion.** The coherence cube offers a high resolution unbiased image of the variations within the volume, wherein geologic features and faults are enhanced. As stated earlier, the inverted seismic volume exhibits an improved image of the impedance variations, which can be used for lithologic and stratigraphic interpretations. By integrating the coherence and impedance volumes, acoustic impedance changes can be readily identified within sedimentary systems, resulting in unparalleled detail of subtle sedimentary depositional features. Acoustic impedance results may be numerically combined with the coherence results to produce a volume that would allow interpreters to display the stratigraphic images from the 3-D seismic data and examine the acoustic impedance contrast across them. For example, sand deposition within a channel that is gas charged would exhibit low impedance. So, a range of low impedances representing the gas sands may be selected and merged with the coherence cube. The composite merged volume may again be sliced through to see low impedance (in color) displayed within the boundaries of the channel.

Figure 3 illustrates how the low end of the impedance range of values is cut off from the impedance volume and merged with the coherence volume.

Channel sand reservoirs are difficult to develop efficiently, but often they have excellent production characteristics. The depositional mechanisms involved in channels can create sand bodies whose thickness and quality can vary rapidly over short distances. Such rapid variations make it difficult to use conventional seismic data successfully for mapping. Impedance inversion helps in such cases.

Figure 4a shows a coherence slice depicting two channels that stand out clearly in a high coherence background. The impedance slice (Figure 4b) indicates low impedance within the channels implying the presence of hydrocarbon bearing sands. A composite volume may be generated wherein the low end of the impedance amplitudes is merged with the coherence coefficients. When stretched over a suitable color scale (Figure 4c), the variation within the low end of the range of the impedance values chosen is clearly seen within the boundaries of the channel.

Such composite plots can define precise reservoir and nonreservoir facies boundaries and reservoir compartments.

**Coherence cube and inverted volumes.** Applying the coherence cube technique to seismic data gives the spatial waveform coherence measurement in place of the amplitude measurement. However, it is possible to apply this technique to the inverted volume—i.e., run coherence cube processing on the acoustic impedance volume. In such a case, rather than measuring local waveform similarity, the search is focused on acoustic impedance matching. The output volume is still coherence but of acoustic impedance rather than of seismic data. Because the inversion volume has a higher vertical resolution than the input seismic data and enhanced S/N ratio, the coherence resolution from acoustic impedance data is significantly superior to the coherence process applied to seismic data. Figure 5 compares time slices (at 1044 ms) from coherence cubes run on seismic (Figure 5a) and the corresponding inverted volume (Figure 5c). Constrained inversion (blocky) was carried out on the input seismic volume, and the time slice at 1044 ms is shown in Figure 5b. Notice in Figure 5c how the distinct boundaries of another channel emerged in addition to the low coherence features in 5a.

As mentioned earlier, reflection is an interface property, and impedance is a layer property; so there is an inherent phase difference between the two attributes. It could be argued therefore that the coherence slice in Figure 5c, though at the same time, may not be comparable to the coherence slice in Figure 5a. However, the fact that coherence on inversion affords a better image could still be verified by comparing a coherence slice with a succession of slices from the coherence volume of Figure 5c.

Figure 6 shows such a succession. Each slice confirms the conclusion stated above.

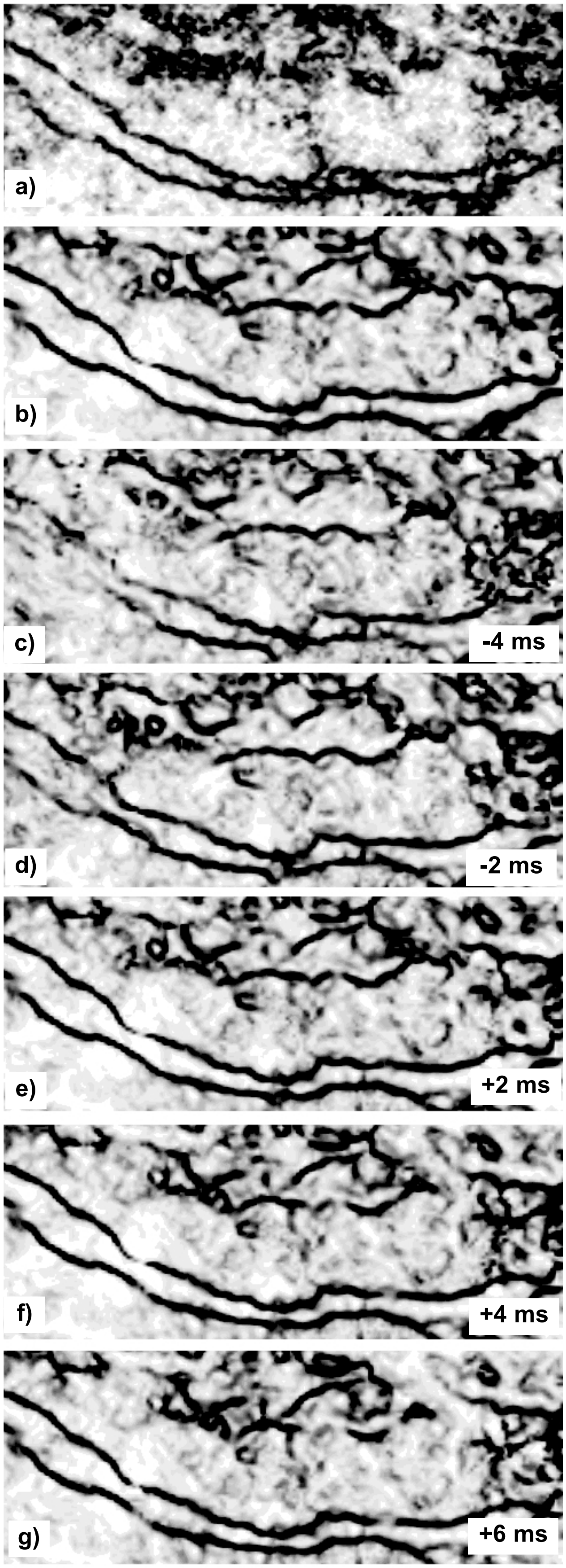


**Figure 6. Horizon slices from coherence cubes run on seismic data (a) and impedance data (b-g).**

**Suggested reading.** "Coherency calculations in the presence of structural dip" by Marfurt et al. (Geophysics, 1999). "Fault interpretation—The coherence cube and beyond" by Chopra and Sudhakar (*Oil and Gas Journal*, 2000). "Azimuth based coherence for detecting faults and fractures" by Chopra et al. (*World Oil*, 2000). "An interpreter's guide to understanding and working with seismic-derived acoustic impedance data" by Latimer et al. (*TLE*, 2000). "Geostatistical inversion—A sequential method of stochastic reservoir modeling constrained by seismic data" by Haas and Dubrule (*First Break*, 1994.) "A computationally fast approach to maximum likelihood deconvolution" by Chi et al. (Geophysics, 1984). "Recovery of the acoustic impedance from reflection seismograms" by Oldenburg et al. (Geophysics, 1983). *Introduction to Seismic Inversion Methods* by Russell (SEG, 1988). *Reservoir Geophysics* edited by Sheriff (SEG, 1992). LE

*Acknowledgments: Thanks to Scott Pickford for permission to publish this paper. The term Coherence Cube is a trademark of Core Laboratories.*

*Corresponding author: S. Chopra, schopra@scopica.com*

*Satinder Chopra obtained his master's degree in physics (1978) from Himachal Pradesh University. He joined India's Oil and Natural Gas Corporation in 1984. His experience is in the fields of seismic processing and interpretation, specializing in depth imaging, inversion, and AVO analysis. He is a member of SEG, CSEG, and EAGE.*