Geophysical Corner

Phase Decomposition and Its Applications

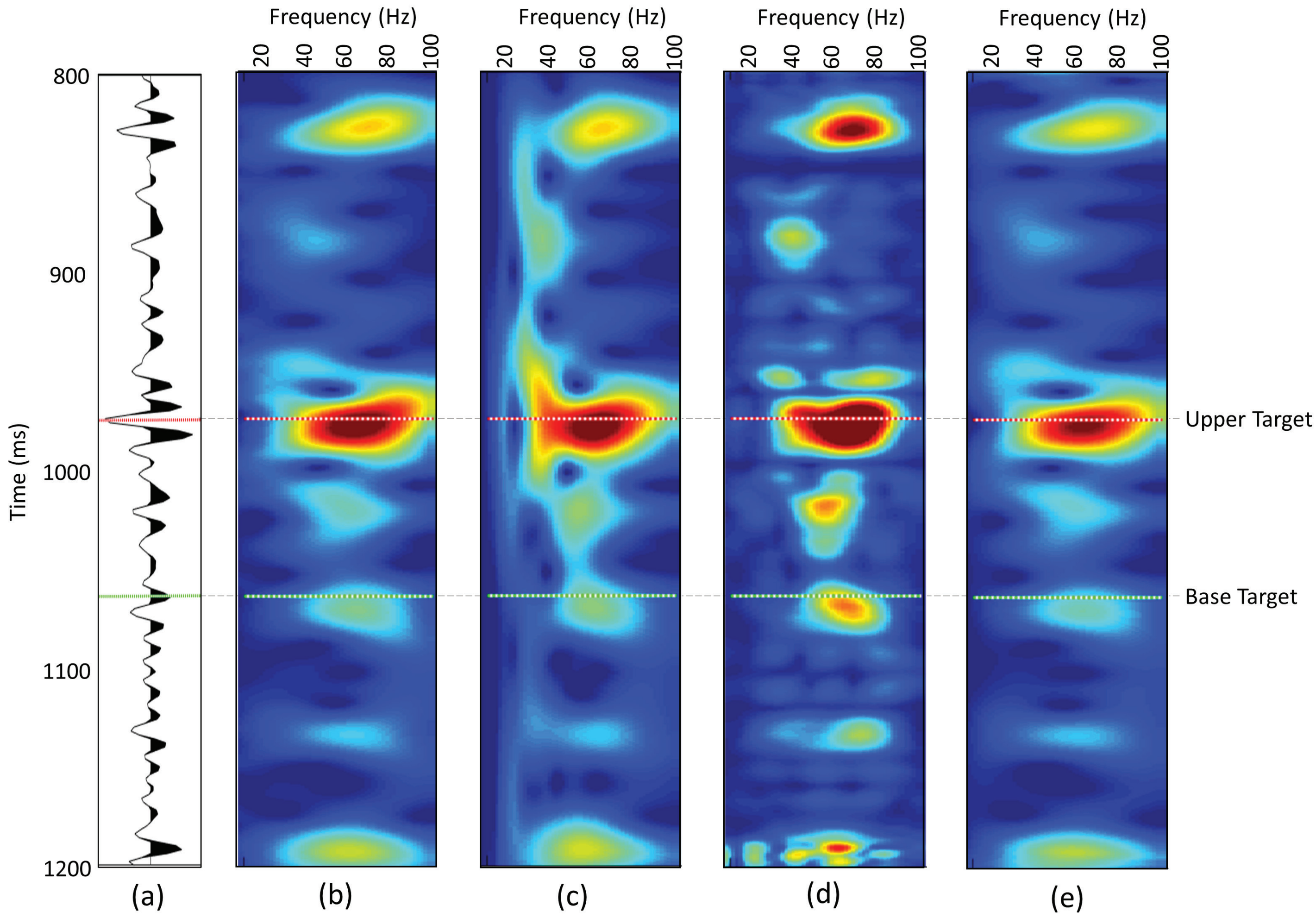

Figure 1: Spectral decomposition on a seismic trace in (a) with the generated amplitude frequency gathers using the (b) STFT (40 millisecond window), (c) CWT, (d) CLSSA (40 millisecond window), and (e) OGSA methods. The two horizontal dotted lines in red and green are the levels of the two markers shown for reference.

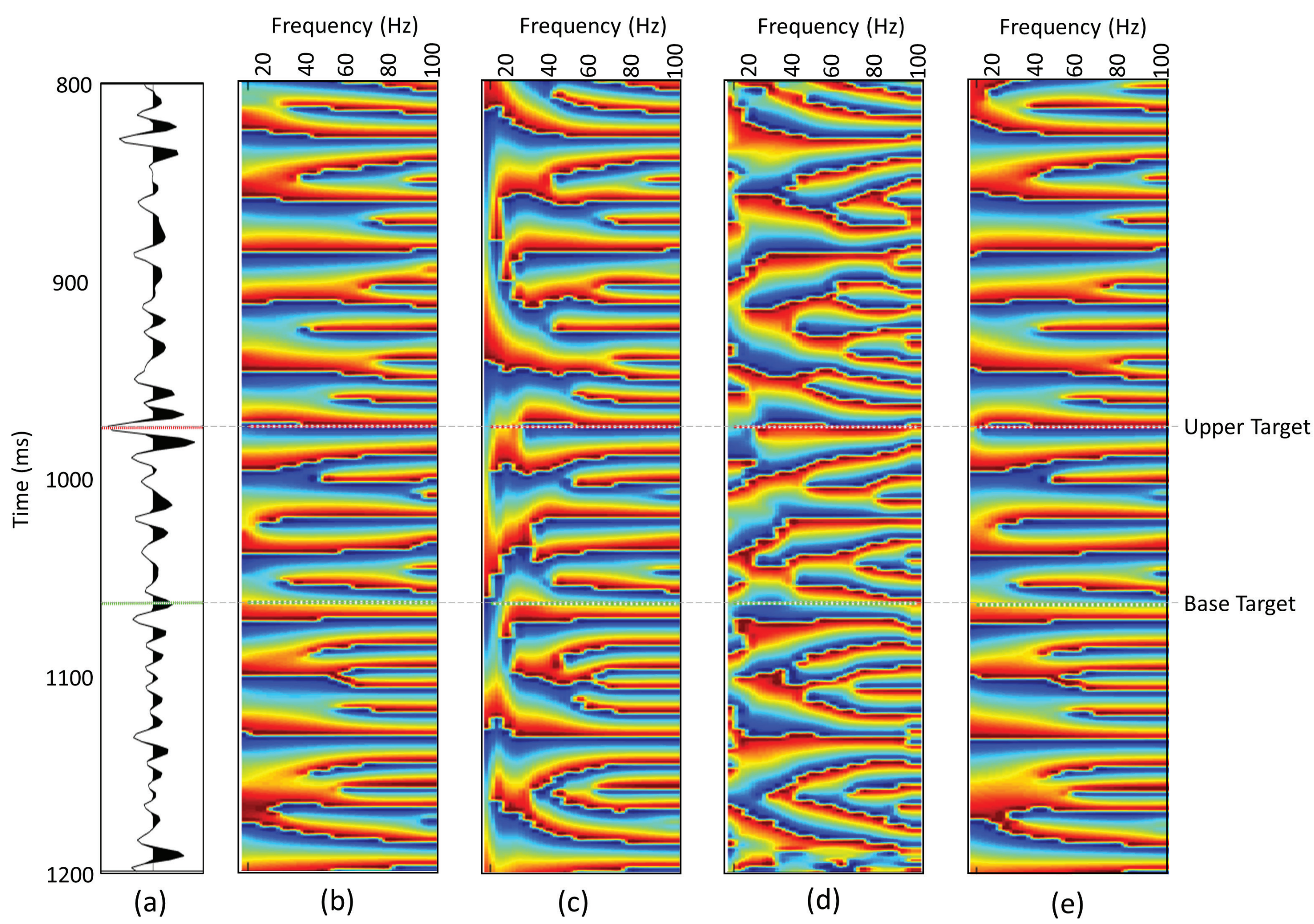

Figure 2: Spectral decomposition on a seismic trace in (a) with the generated phase frequency gathers using the (b) STFT (40 millisecond window), (c) CWT, (d) CLSSA (40 millisecond window), and (e) OGSA methods. The two horizontal dotted lines in red and green are the levels of the two markers shown for reference.

Phase decomposition is a novel technique that decomposes a composite seismic signal into different phase components, which can improve reservoir characterization. The technique is particularly useful in those areas where thin-bed interference causes the phase of the input seismic response to differ from the phase of the embedded wavelet in the data.

For a zero-phase wavelet in the data and thin low-impedance layers below tuning thickness, the waveform phase response generated after carrying out phase decomposition is found to be minus 90 degrees, which stands out as an anomaly. On the contrary, a corresponding high-impedance thin layer exhibits a similar (plus) 90-degree phase waveform response. By generating a synthetic response with use of well data and a zero-phase wavelet, such observations for thin reservoir layers can be understood with confidence and correlated with real seismic data. Phase decomposition can help immensely in direct interpretation of seismic data in terms of reservoir and non-reservoir zones, among other applications.

Another important aspect is that the seismic waveform is amplitude, phase and frequency dependent. Consequently, for thin layers below tuning, the frequency content of the associated seismic response must be monitored for targets with variable thicknesses. Phase decomposition does not use well data for the generation of phase components, but the synthetic traces generated from well data can be used to establish the relationships between amplitude/phase/frequency that may be desirable for a given problem. In this context, application of spectral decomposition to a synthetic trace could produce a frequency gather and provide the required frequency-dependent behavior. Likewise, the application of phase decomposition to the generated synthetic gather will provide a set of phase component gathers. Thus, between the spectral and phase decomposition applications, the desired amplitude/phase/frequency information can be sought.

We begin this article with a brief description of some of the spectral decomposition techniques available in different commercial software packages, and then showcase their application to a seismic dataset under study. We take the discussion forward from there to the description of phase decomposition and its applications. Finally, we draw some convincing conclusions.

Spectral Decomposition

Spectral decomposition is an effective way of analyzing the seismic response of stratigraphic geologic features. It is carried out by transforming the seismic data from the time domain into the frequency domain. This can be done simply by using the short time window discrete Fourier transform (STFT), but there are other methods that can be used for the purpose, namely the continuous wavelet transform (CWT), S-transform, matching pursuit, constrained least-squares spectral analysis (CLSSA), particle swarm spectral decomposition (PSSD), and the optimal Gaussian spectral analysis (OGSA).

Some of these methods and their applications have been described in previous Geophysical Corner articles (December 2013, March 2014 and March 2015) and will not be repeated here.

Using any of the above spectral decomposition methods, the input seismic data volume can be decomposed into amplitude and phase volumes at discrete frequencies within the bandwidth of the data, which can then be displayed and interpreted. Alternatively, the output data can be sorted into time-frequency displays, also called gathers, for amplitude and phase.

Frequency gathers for amplitude and phase are generated with the application of the following methods:

- STFT: The discrete Fourier transform uses a time window for its computation, and this choice has a bearing on the resolution of the output data.
- CWT: The continuous wavelet transform depends on the choice of the mother wavelet, and usually yields higher spectral resolution but reduced temporal resolution at low frequencies.
- CLSSA: Uses an inversion-based algorithm for computing the spectral decomposition of seismic data and is performed by the inversion of a basis of truncated sinusoidal kernels in a short time window. The method results in a time-frequency analysis with excellent time and frequency resolution and with a time-frequency product superior to the STFT and the CWT.
- OGSA: This process uses a series of frequency domain Gaussian functions

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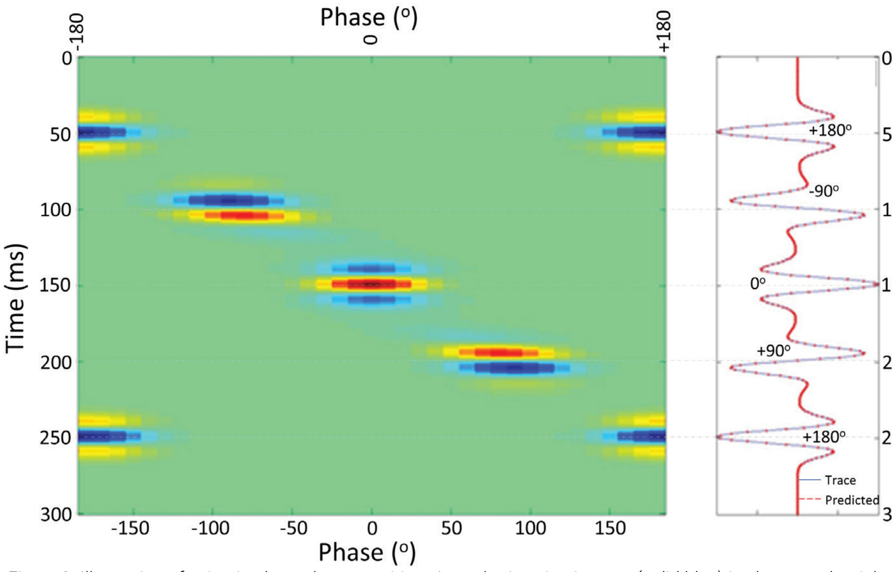

Figure 3: Illustration of seismic phase decomposition. A synthetic seismic trace (solid blue) is shown to the right and the generated time-phase panel or phase gather for it is shown to the left. When the time-phase panel is summed over phase, the original trace is reconstructed and is shown overlaid as dashed red on the solid blue trace to the right.

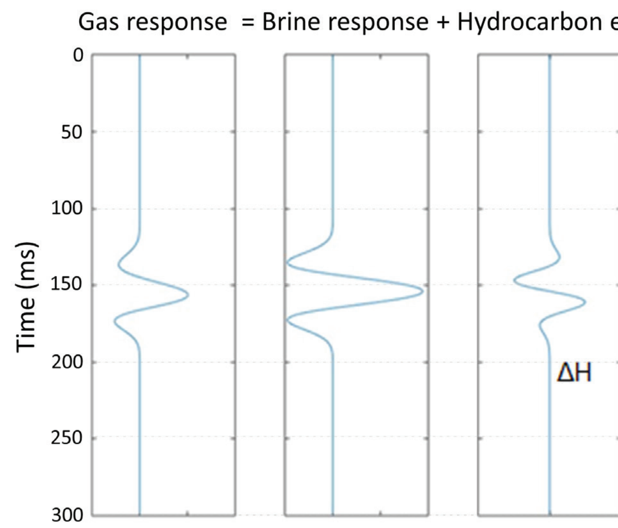

Figure 4: Synthetic waveforms for a seismically thin layer using a zero-phase wavelet resulting in a "dim spot" when gas is added. Both brine and gas-filled cases have impedance intermediate between the overlying and underlying impedances, yielding a zero-phase waveform for both cases. Notice the hydrocarbon effect, ΔH, has a minus 90-degree phase rotation with respect to the zero-phase wavelet.

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to decompose the spectrum of the data, which is carried out in the frequency domain. The result is the superposition of frequency domain Gaussian functions that are seen to better correlate or match the spectrum of the seismic.

In figure 1 we show the spectral amplitude gathers for a particular seismic trace shown to the left. We notice that these amplitude gathers generated with the application of some of the methods mentioned above are comparable, though differing in temporal and frequency resolution. However, we also notice that the equivalent phase gathers generated by the same set of methods and displays in figure 2 appear to be complicated in terms of their interpretative value.

Phase Decomposition

In 2016, Castagna and his team introduced an alternative approach for understanding the phase of the seismic trace by distributing the amplitude and phase spectra such that the amplitude can be expressed as a function of phase as well as frequency. In general, as stated above, the application of spectral decomposition on a seismic trace produces a time-frequency analysis, which when integrated over the data frequency range will recover the original trace. In this analysis it is possible to introduce phase as a third dimension such that a time-phase analysis, or a phase gather, can be generated, which essentially represents the amplitude as a function of time for individual phase components of the seismic trace. When integrated over the complete phase range, the original seismic trace can be reconstructed.

For an insight into this process, a synthetic seismic trace generated with the use of a few Ricker wavelets is shown in solid blue to the right in figure 3. To the left is the phase gather generated for the blue synthetic seismic trace, which exhibits a good correlation with the phase information indicated on the original seismic trace. On summing this time-phase panel over phase, the original seismic trace can be reconstructed and is shown as dashed red trace overlaid on the solid blue original trace.

An interesting observation is that any phase component of the seismic trace as seen on the phase panel can be extracted and reconstructed. A significant implication of this observation is that phase decomposition can be used as a powerful tool that may be put to use for accentuating or suppressing seismic events with specific spectral characteristics. This process is referred to as "phase filtering."

A unique observation mentioned in the introduction is that the difference in response between thin hydrocarbon-bearing reservoirs exhibiting low impedance and the same reservoir rock with 100-percent water saturation and higher impedance are found to occur on the phase component that is out of phase with the embedded zero-phase seismic wavelet.

Before going into the details of the phase decomposition method, we wish to demonstrate this. Figure 4 shows a zero-phase response representing a brine-filled thin layer with impedance intermediate between overlying and underlying half-spaces (middle) as well as the waveform associated with a similar layer bearing gas, also with intermediate impedance (left panel). For seismically thin layers, the gas response minus the brine response, called the "hydrocarbon effect" (right panel) is always minus 90-degrees phase rotated with respect to the zero-phase wavelet.

To get a feel for the benefits of phase decomposition, we can look at the synthetic example of an intermediate impedance thin layer (with layer time thickness equal to quarter of the dominant wavelet period) as shown in figure 5. The wavelet used for generating the seismic response is a zero-phase Ricker wavelet. The layer itself has a channel with reduced impedance relative to the inter-channel facies.

The synthetic seismogram shows a peak corresponding to the plus reflection coefficient. The slight changes in amplitude caused by the channel change the reflection coefficients slightly, but the lateral variation in the amplitude caused by the channel is small enough and may not be recognized on conventional seismic data. This implies that any amplitude or phase anomaly that we may expect due to the channel will be weak and may not be detected on the seismic traces.

The minus 90-degree phase component shown in figure 5c exhibits a prominent anomaly in that what is almost invisible in figure 5b is seen nicely in figure 5c. Thus, for thin layers the change in waveform corresponding to an anomalously low impedance is expected to show up on the minus 90-degree phase component, and conversely, the change in waveform caused by an anomalously high impedance will occur on the plus 90-degree phase component. Intermediate impedance changes as well as lateral impedance changes are visible on both the minus and plus 90-degree phase components. Both these phase components (minus 90 degrees and plus 90 degrees) could be added to produce an output that may be referred to as the odd component; similarly, the 0-degree and 180-degree phase components could be summed to produce what could be referred to as the "even component." Such observations suggest that phase decomposition could serve as a tool for direct interpretation of data in terms of impedance variations.

Likewise, phase decomposition can be used as a reconnaissance tool when hydrocarbon anomalies associated with a range of thicknesses are expected to be seen on seismic data. The resolved reflections on the different phase

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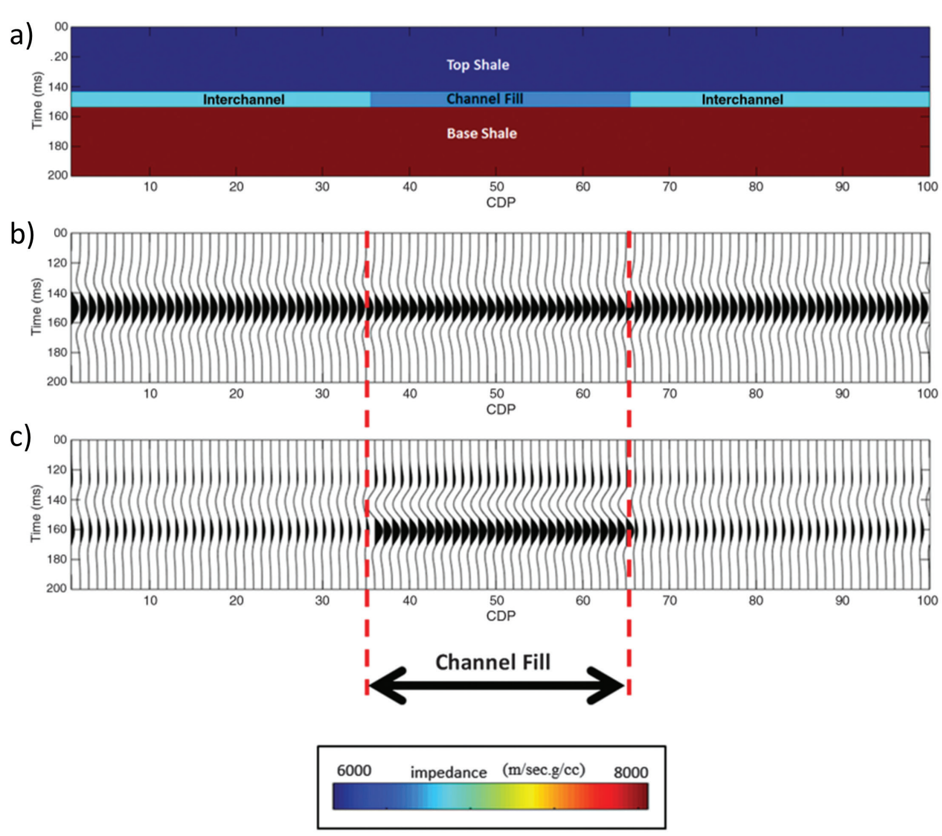

Figure 5: The amplitude anomaly due to the change in impedance in the thin layer containing the channel, though not very apparent on the synthetic seismogram, causes a strong amplitude anomaly on the minus 90-degree phase component. (Castagna et al., 2016)

Ritesh Kumar Sharma is with Calgary-based SamiGeo. He has vast experience of working with 2-D/3-D, land, and marine seismic data with different applications such as AVO analysis, rock-physics analysis, frequency enhancement of seismic data, simultaneous inversion, extended elastic impedance inversion as well as geostatistical inversion. He is an active member of SEG and CSEG.

John Castagna holds the Sheriff chair in geophysics at the University of Houston. His main research interest is the quantitative interpretation of seismic data.

Oleg Portniaguine is the co-founder and senior vice president for research and development at Lumina Technologies, Inc., the principal author and lead developer of many Lumina's proprietary algorithms and software. He is the author of more than 50 publications and two patents.

Gabriel Gil is the chief geophysicist at Lumina Technologies, Inc., and has more than 15 years of experience in reservoir geophysics. His areas of expertise are data processing and conditioning, AVO analysis, rock physics, seismic inversion, spectral decomposition analysis, spectral inversion, seismic interpretation and quantitative interpretation.

Kenneth Bredesen works as a geophysicist at the Geological Survey of Denmark and Greenland. He has previously worked as a quantitative interpretation geophysicist at Spike Exploration and as a postdoctoral researcher at Aarhus University. His core competencies are quantitative seismic interpretation, rock physics modeling, seismic attributes and amplitude analysis.

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components might not show any difference from the zero-phase input seismic data. But the bright spots associated with thin low-impedance gas sands may exhibit a strong anomaly on the minus 90-degree phase component.

Real Data Application

The seismic data used for the phase decomposition application is a 3-D seismic volume from Denmark shot over a natural gas storage structure. Natural gas has been injected and stored in this structure since 1989, where the reservoir occurs within a domal subsurface structure and is covered by a tight caprock. The "Gassum target interval" bounded by Upper Target and Base Target markers (figure 7a), approximately 140 meters thick consists of interbedded sandstones and mudstones and is the reservoir where natural gas is stored by displacing formation water. The upper 40 meters are divided into five gas storage zones segregated by thin shale beds. Overlying the Upper Target marker is the 300-meter thick Lower Jurassic sandstone formation (not shown), which consists of marine mudstones and shales, and is the regional caprock. Below the Base Target marker are the impermeable mudstones of older formations (not shown), at approximately 2,800 meters below the surface.

In figure 6 we show the same seismic trace shown in figure 1 together with the frequency gather generated using the CWT method and the corresponding odd and even component gathers. The equivalent phase gather is shown to the left of the seismic trace. We notice a prominent anomaly seen on the frequency gather, the phase gather, and which is also prominently seen on the odd frequency gather, but not on the even component.

Finally, in figure 7a we show a segment of an inline from the seismic data volume. A prominent amplitude anomaly is seen in the middle of the section and its extent is indicated with the yellow block arrows. Figures 7b and c show the equivalent even and odd sections generated after phase decomposition was carried out on the input seismic data. Notice how no significant anomaly is seen on the even component but stands out clearly on the odd component.

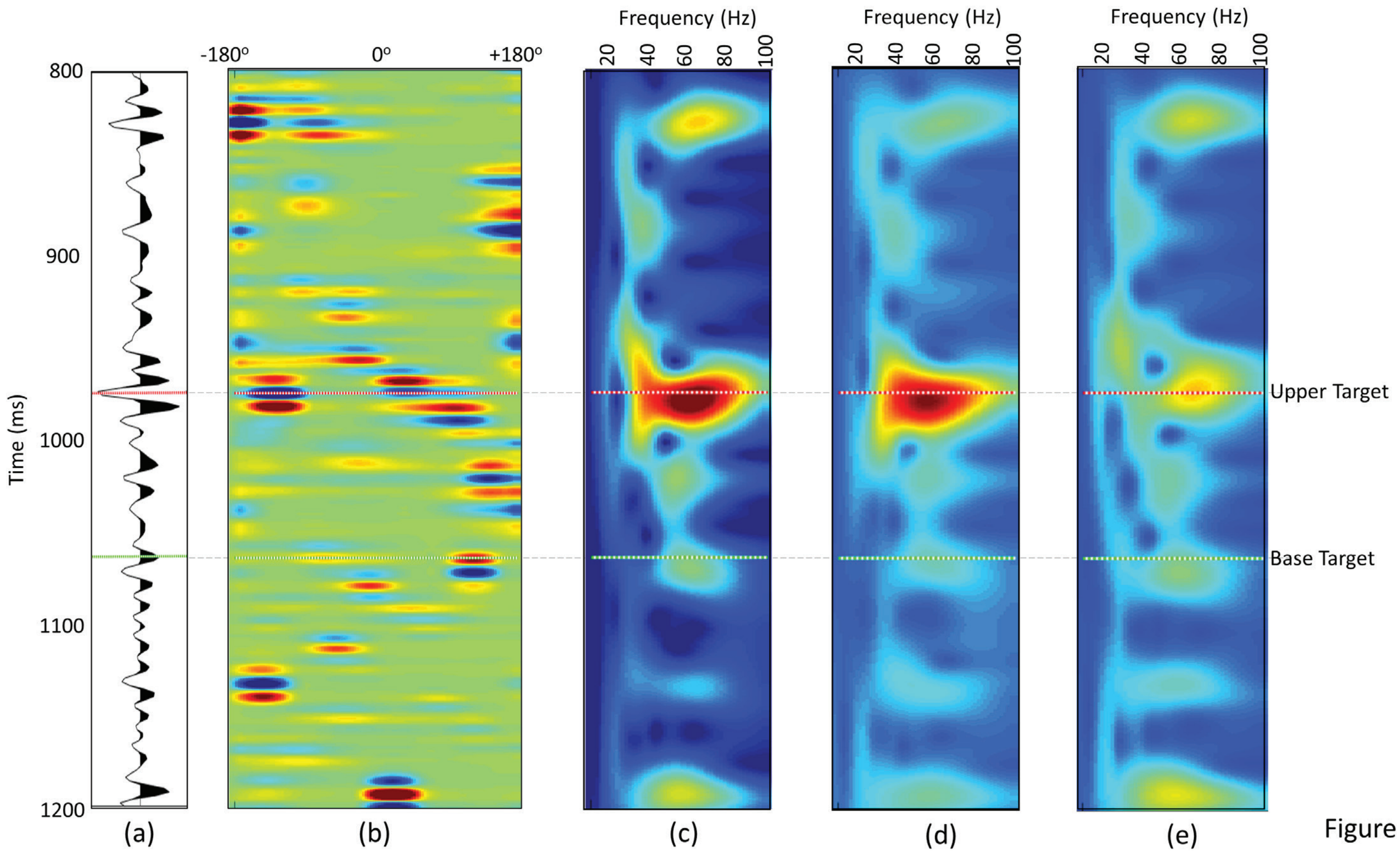

Figure 6

Figure 6: (a) A trace from a 3-D seismic volume from Denmark. (b) Phase gather generated for the seismic trace in (a). (c) Frequency gather generated for the seismic trace in (a) using the CWT method, with the computed odd and even component gathers shown in (d) and (e). The two horizontal dotted lines in red and green are the levels of the two markers shown for reference.

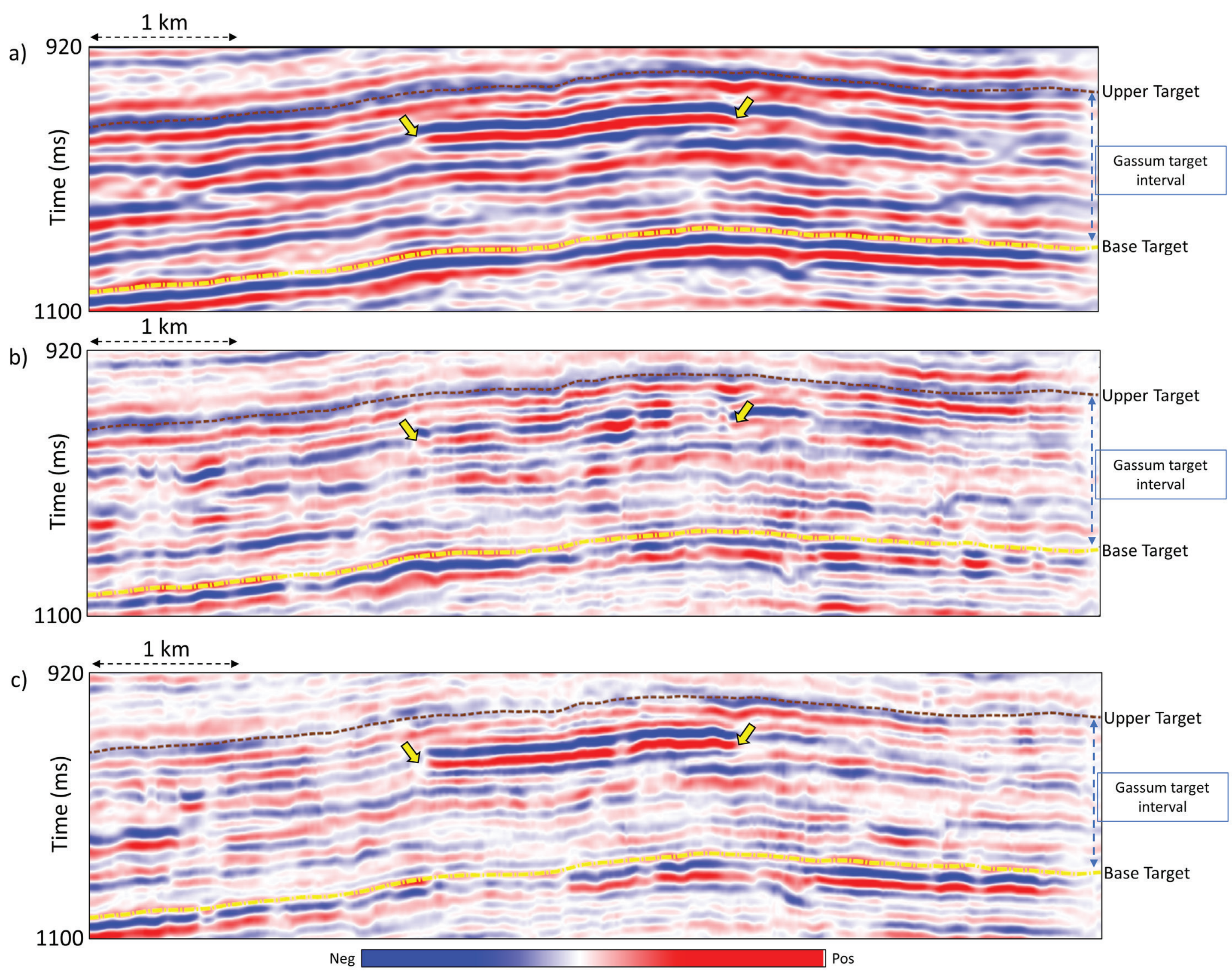

Figure 7: (a) An inline section from the PSTM stacked volume showing a shallow high-amplitude gas anomaly indicated with a yellow block arrow. (b) Equivalent inline section from the even phase (combination of 0-degree and 180-degree event phases) component volume. (c) Equivalent inline section from the odd phase (combination of minus 90-degree and plus 90-degree event phases) component volume.

Conclusion

Phase decomposition could serve as a tool for direct interpretation of data in terms of impedance variations as well as a reconnaissance tool. For doing these interpretations, not only the phase gathers but the individual phase components can also be generated, the ones at 0 degrees, 180 degrees, minus 90 degrees and plus 90 degrees appearing to be more useful. The first two phase components can be combined into an even component volume, and the latter two into an odd component volume. Thin-bed seismic anomalies associated with hydrocarbons can be conveniently analyzed by interpreting these two data volumes.

In many regions around the world, the production is expected from thin sandstone or carbonate reservoirs. Because the seismic waves are band-limited with low-frequency content, a thin reservoir implies that the thickness of the reservoir is at or less than a quarter wavelength of the seismic waves. In such thin reservoirs the reflection response would comprise interference of reflections from the top and the base of the thin layers. Exercises aimed at characterizing thin reservoirs frequently neglect such interference effects, resulting in inaccurate reservoir characterization. The phase decomposition discussed above finds useful applications, subject to some caveats, in that the seismic data being considered have a zero-phase embedded wavelet, the thicknesses of the zones of interest are at or below tuning at the CWT frequency used and the seismic response has absence of interference from adjoining reflectors. The application of phase decomposition to data that may not have one or more of the above conditions satisfied might not yield optimum results. If the seismic wavelet is not zero phase, the phase component where specific responses are expected, should be modified accordingly. For example, if a minus 90-degree signal is expected with a zero-phase wavelet, that response would be found on the minus 60-degree component if the wavelet phase were plus 30 degrees. If the layer of interest is above seismic tuning, low-pass filtering (for example by stacking low CWT frequencies) can be used to lower the frequency content and push the layer of interest below tuning. This is called "seismic thinning."

Attempts should be made to alleviate such problems and could include wavelet shaping of the embedded wavelet if it is not zero phase, using CWT spectral decomposition with a Ricker wavelet at higher frequency (but not high enough to go above tuning), and finally the phase decomposition analysis could be carried out on the required phase as read off from the phase gather, or what may be referred to as "phase filtering." Though not discussed here, some of these issues will be discussed in future articles. E

(Editors Note: The Geophysical Corner is a regular column in the EXPLORER, edited by Satinder Chopra, Founder and President of SamiGeo, Calgary, Canada, and a past AAPG-SEG Joint Distinguished Lecturer.)