PS Spectral Balancing of Seismic Data Using Spectral Decomposition*

Satinder Chopra[1] and Kurt J. Marfurt[2]

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[1]Arcis Seismic Solutions, TGS, Calgary, Canada (schopra@arcis.com)
[2]University of Oklahoma, Norman, Oklahoma

Abstract

The interpretation of discrete stratigraphic features on seismic data is limited by both its bandwidth and its signal-to-noise ratio. Unfortunately, well resolved reflections from the top and base of subtle stratigraphic geologic boundaries occur only for thick features imaged by broad band data. Seismically thin stratigraphic features approaching a quarter wavelength thickness give rise to composite or “tuned” seismic reflections. Different spectral decomposition methods provide an effective way of examining the seismic response of stratigraphic geologic features in terms of spectral components and so help in the interpretation. The phase components help with the interpretation of the discontinuity features as well as stratigraphic features such as onlap, offlap, and erosional unconformities.

In this study we first illustrate the applications of a newer attribute derived during spectral decomposition, called voice components, in terms of more accurate interpretation of the subsurface features. We follow this by describing an amplitude-friendly method for spectral balancing, which enhances the frequency content of the data and at the same time preserves the geologic tuning features and amplitudes. Spectral decomposition of seismic data that are spectrally balanced and interpreted in terms of the voice components leads to more accurate definition of the features of interest. We demonstrate some of these applications, and in particular the detailed definition of faults and fractures. Such discontinuity information can be interpreted better on coherence attribute displays in the zone of interest. Coherence attribute computation performed on spectral decomposition after spectral balancing yields higher detail with regard to the faults and fractures or other discontinuity features such as channels, reefs, etc.

Spectral balancing of seismic data using spectral decomposition

Satinder Chopra* and Kurt J. Marfurt+

*Arcis Seismic Solutions, TGS, Calgary, Canada; +The University of Oklahoma, Norman

Summary

In this study we first illustrate the applications of a newer attribute derived during spectral decomposition, called voice components, in terms of more accurate interpretation of the subsurface features.

We follow this by describing an amplitude-friendly method for spectral balancing, which enhances the frequency content of the data and at the same time preserves the geologic tuning features and amplitudes. Spectral decomposition of seismic data that are spectrally balanced and interpreted in terms of the voice components leads to more accurate definition of the features of interest.

We demonstrate some of these applications and in particular the detailed definition of faults and fractures. Such discontinuity information can be interpreted better on coherence attribute displays in the zone of interest.

Coherence attribute computation performed on spectral decomposition after spectral balancing yields higher detail with regard to the faults and fractures or other discontinuity features such as channels, reefs, etc.

Spectral decomposition

The **different spectral decomposition methods** including the following:

1. Traditional short window discrete Fourier transform,

2. The continuous wavelet transform (CWT),

3. The S-transform, and

4. The matching pursuit transform

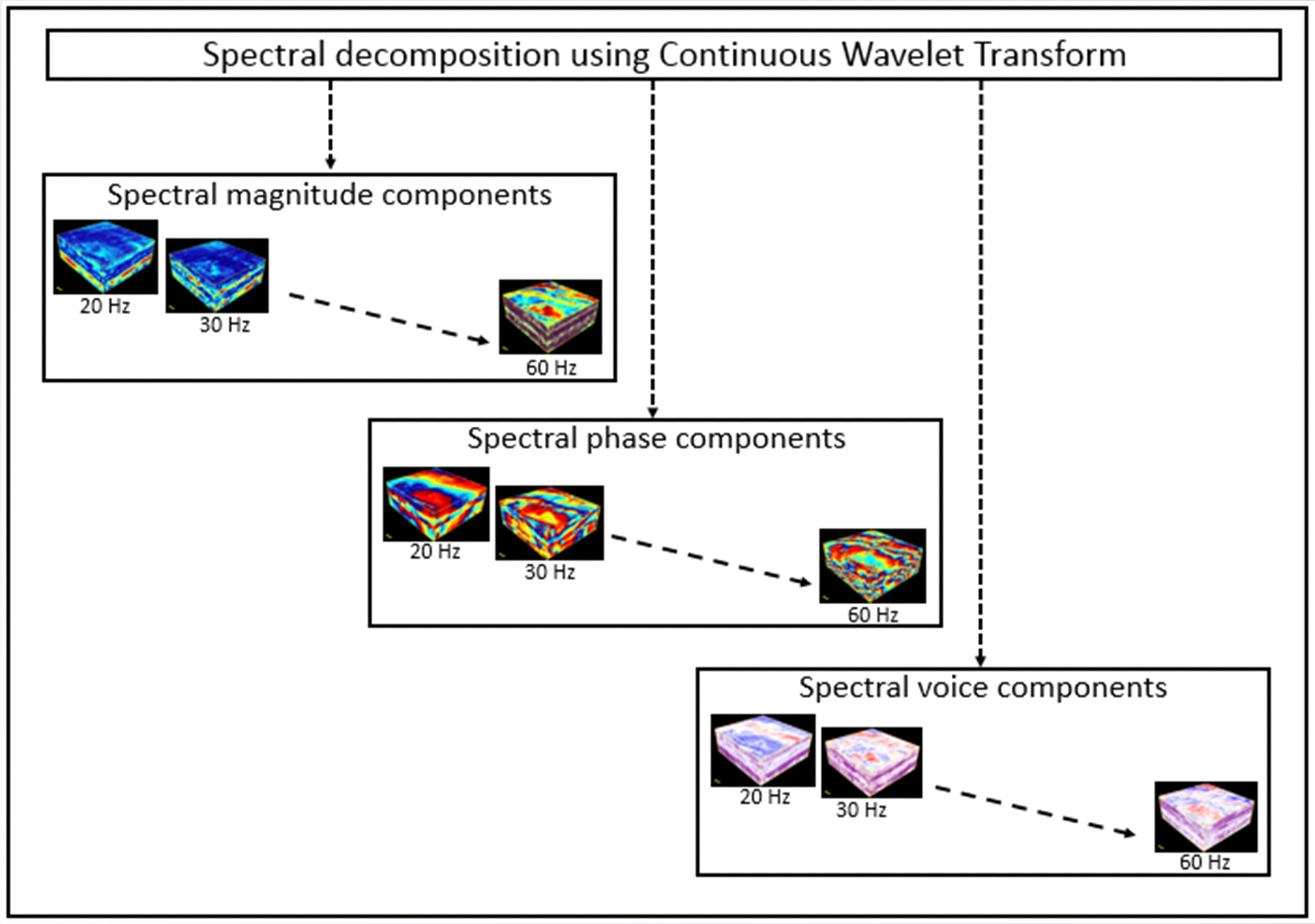
All these compute the spectral magnitude and phase components at every time-frequency sample. The analysis of such spectral magnitude and phase components is equivalent to interpreting the subsurface stratigraphic features at different scales (Figure 1).

The mother wavelet chosen for CWT spectral decomposition, e.g. the Morlet wavelet, is a complex function (Sinha et al., 2003) (Figure 2). As a result, the **spectral components obtained from CWT are also complex**. Thus when **spectral decomposition** is carried out on seismic data, it **yields the spectral magnitude and phase at each time-frequency sample**.

The spectral magnitude represents the energy that correlates with the trace, and the phase represents the phase rotation between the seismic trace and the Morlet wavelet at each instant of time.

Goupillaud et al. (1984) showed that the CWT process preserves the signal energy and is reversible

Thus the signal can be reconstructed from the CWT coefficients as a convolution along the scales used in the transformation plus an integration along time. In addition to magnitude and phase, one can readily compute the spectral voices (e.g. Marfurt and Matos, 2014), at every time-frequency sample.



Spectral decomposition using Continuous Wavelet Transform

Spectral magnitude components

Spectral phase components

Spectral voice components

Figure 1: Typical workflow for spectral decomposition carried out using the continuous wavelet transform method. The output includes spectral magnitude, phase, and voice component volumes.

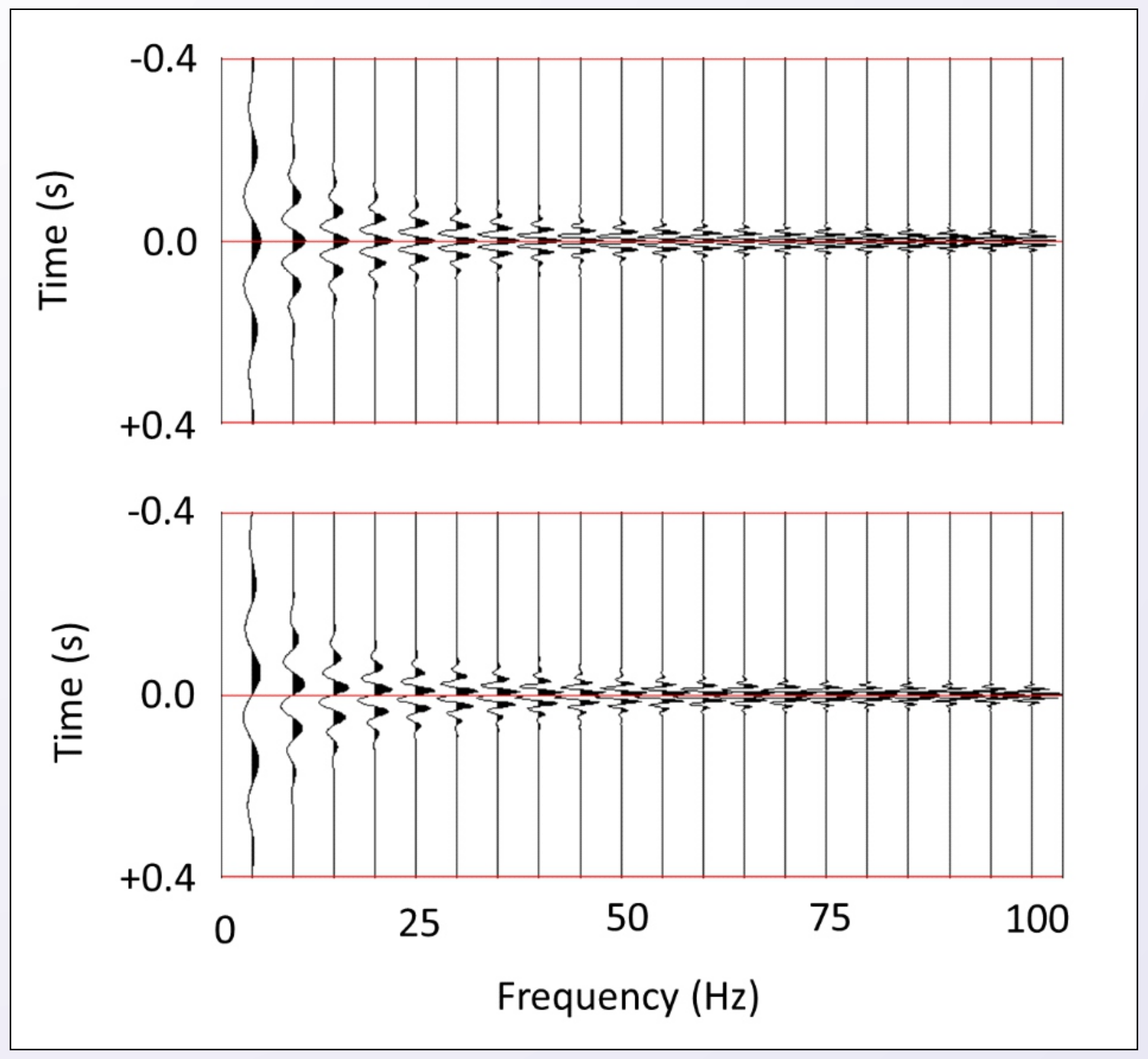


Figure 2: Complex wavelets used in the complex wavelet transform. The (top) real and (bottom) imaginary (or 90^0-phase rotated) wavelets are simply convolved with the input seismic trace about each sample to form $v(t,f)$ and $v^H(t,f)$. The convolution with the real wavelets provides the voices, $v(t,f)$, such as the 30 Hz voice shown in the next figure. The spectral magnitude, $a(t,f)$, is defined as $m(t,f)=\{[v(t,f)]^2+[v^H(t,f)]^2\}^{1/2}$ while the spectral phase is defined as $\varphi(t,f)=ATAN2[v^H(t,f),v(t,f)]$ and ranges between -180^0 and $+180^0$ (examples shown in Figure 4).

In this study, **we discuss the value of such spectral voices in subsequent attribute calculation.**

Another traditional use of time-varying Fourier transforms is spectral balancing. Trace by trace time-varying spectral balancing improves vertical resolution but destroys relative amplitudes.

We d**iscuss an amplitude-friendly method for flattening the amplitude spectra of the input data and show its applications as well.**

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Voice components from CWT spectral decomposition

addition to the spectral and phase components, Goupillaud et al. (1984) introduced another component, alled the voice component, which is a simple function of spectral magnitude, m, and phase ϕ, at each me-frequency sample and is given by

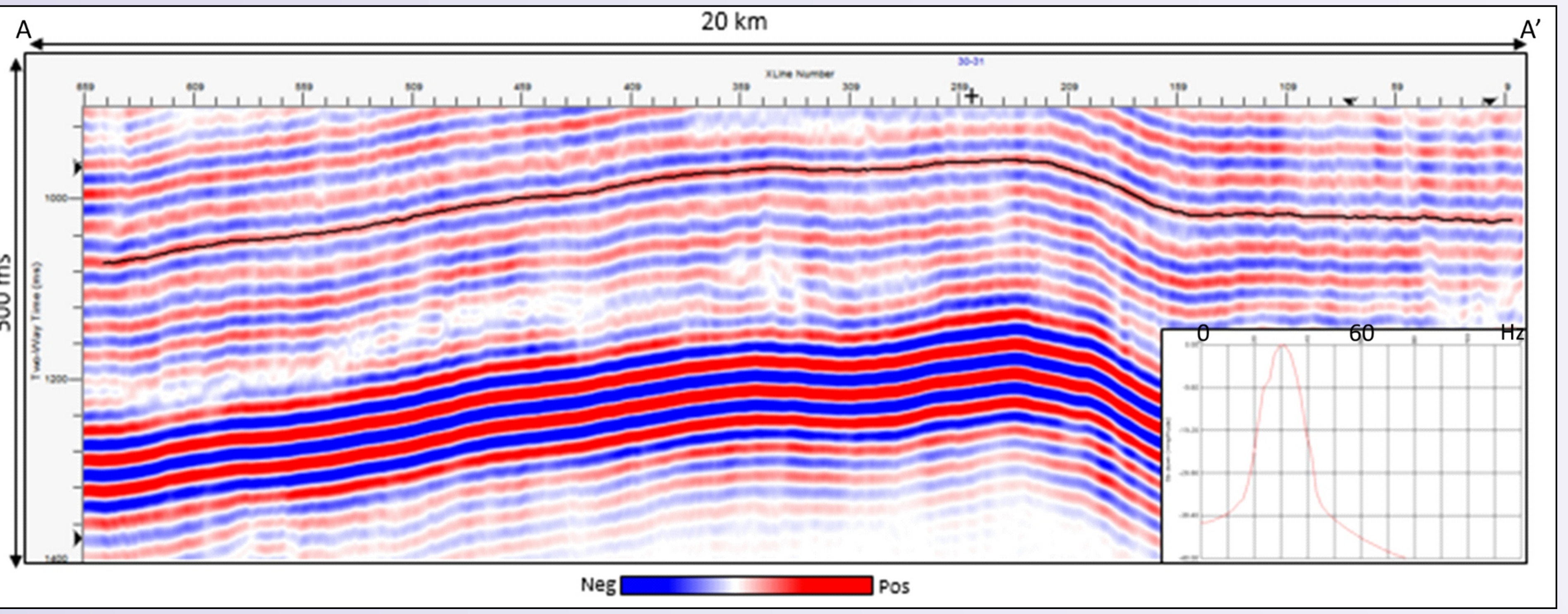
$$v(t,f) = m(t,f)\exp[-j\phi(t,f)].$$

he real part of the sum over all frequencies, f, of all these voice components reconstructs the original ace. Since the voice components are band-pass filtered versions of the original seismic data (Fahmy et ., 2008) application to map subtle hydrocarbon features can be viewed as analysis of the spectral voices.

fter choosing an appropriate mother wavelet (Chopra and Marfurt, 2015) the scaled members of the avelet family are defined by simple scaling and shifting of the mother wavelet.

ross-correlating the member wavelets with the original seismic trace generates the spectral voice omponents.

or the continuous wavelet transform, the voice components are equivalent to narrow bandpass filtered ersions of the input seismic data. We show the 30 Hz voice component section in Figure 3 along with the agnitude spectrum of the 30 Hz wavelet.



igure 3: A vertical slice through the 30 Hz voice component after spectral decomposition with spectral balancing and its amplitude spectrum. Notice the frequency width on both sides of the amplitude maxima seen at 30 Hz. *(Data courtesy: Arcis Seismic Solutions, TGS)*

uch voice components offer more information that can be subsequently processed and interpreted.

Objectives

1. To introduce a newer attribute derived during spectral decomposition, called voice component, that proves useful for accurate interpretation of the subsurface features.

2. Describe an amplitude-friendly method for spectral balancing, which enhances the frequency-content of the seismic data.
3. Demonstrate applications in terms of detailed definition of faults and fractures.

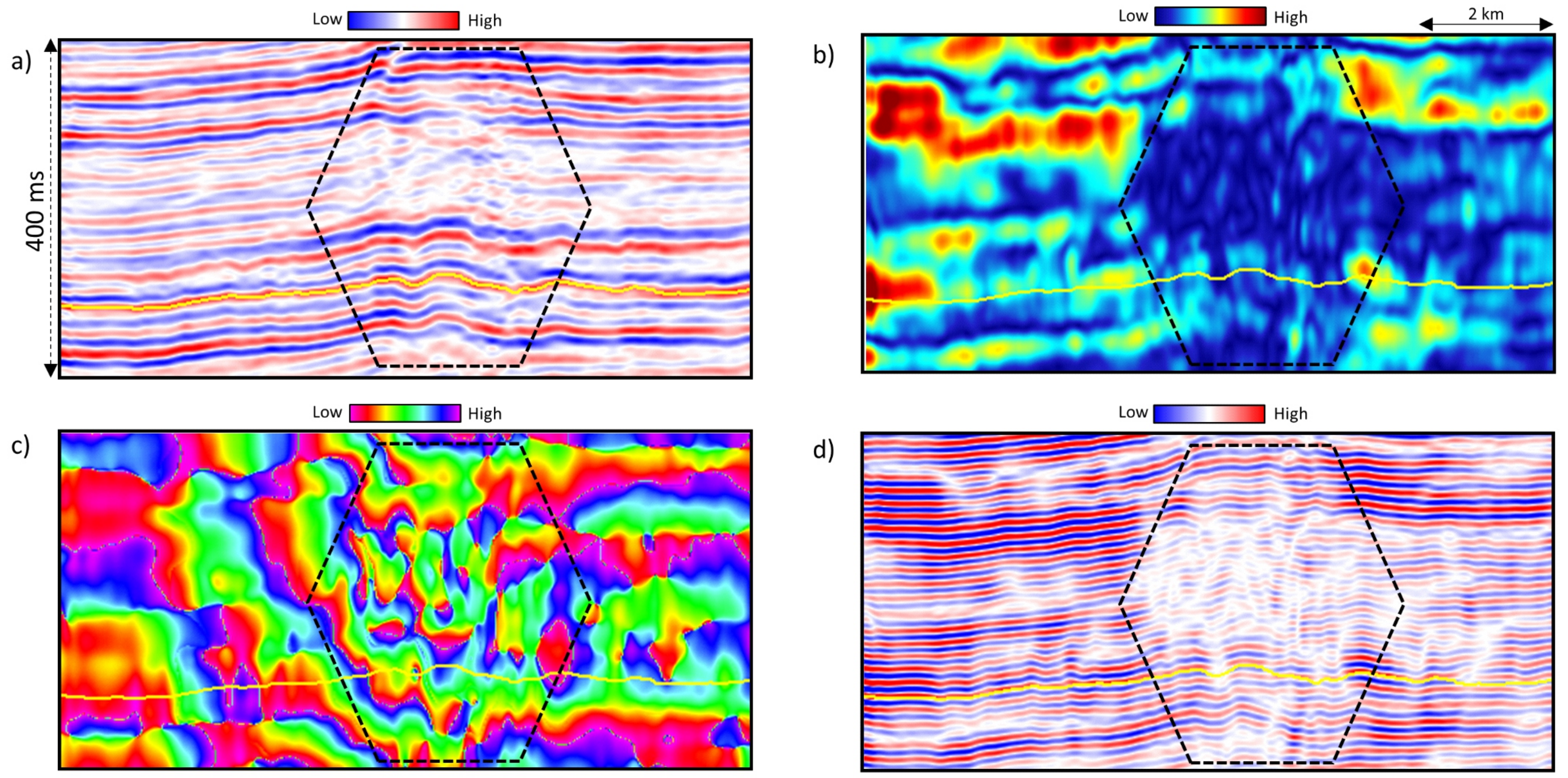


Figure 4: Vertical slices through (a) original 3D seismic amplitude and corresponding 65 Hz (b) spectral magnitude, (c) spectral phase, and (d) spectral voice component volumes. **Notice the vertical discontinuities in the highlighted portion are poorly seen in the original broadband data, are not seen in the spectral magnitude component, but are clearly seen in the spectral phase and voice components.** The voice component has the advantage that it can be easily interpreted and processed (e.g. using coherence) as one would the original seismic amplitude data. *(Data courtesy: Arcis Seismic Solutions, TGS)*

In Figure 4a we show a vertical slice through a 3D seismic volume from northern-central Alberta, Canada. The equivalent slices through the spectral magnitude, phase, and voice components at 65 Hz are shown in Figures 4b, c and d that highlights fault discontinuities not seen in the original broadband data (or in most of the lower spectral components). Notice that the vertical discontinuity information is not clearly seen on the spectral magnitude, but rather on the phase component. **The voice component combines both attributes and nicely delineates the discontinuities.** This observation could be exploited to our advantage by either interpreting the discontinuity information as such or by running a discontinuity attributes such as coherence on the voice component volume.

Spectral balancing of seismic data in an amplitude-friendly wa

In this method, the data are first decomposed into time frequency spectral components. The power of the spectral magnitude $P(t, f) = m(t,f)^2$, is averaged over all the traces $(j= 1,\ldots K)$ in the data volume spatially and in the given time window, which yields a smoothed average power spectrum, given by $\boldsymbol{P_{avg}(t, f)}$.

Next, the peak of the average power spectrum, $\boldsymbol{P_{peak}(t)}$, is also computed.

Both the average spectral magnitude and the peak of the average power spectrum are used to design a single time-varying spectral balancing operator that is applied to each and every trace in the data.

$$a_j^{bal}(t,f) = \left[\frac{P_{peak}(t)}{P_{avg}(t,f)+\varepsilon P_{peak}(t)}\right]^{\frac{1}{2}} m(t,f),$$

where ε is the prewhitening parameter.

Such spectral balancing is amplitude-friendly since a single time-varying wavelet is applied to the entire data volume.

Figure 5 shows vertical slices through a seismic amplitude volume before and after spectral balancing. The spectra were computed at 5 Hz intervals ranging from 5 to 120 Hz. The balancing was computed using a value of ε =0.04. The individua amplitude spectral before and after are shown as insets. Notice that after spectral balancing the seismic section shows highe frequency content and the amplitude spectra is flattened.

Encouraged with the higher frequency content of the data, we run energy ratio coherence (Chopra and Marfurt, 2008) on the input data as well as the spectrally balanced version of the data. The results are shown in Figures 6a, and b, where we notice better definition of the NNW-SSE faults as well as the faults/fractures in the E-W direction on the coherence run on spectrally balanced version.

Finally, we run the spectral decomposition on spectrally balanced version of the input seismic data, and put the voice components through to energy ratio coherence computation.

In Figures 6c, d, and e we show equivalent time slices computed from the 65, 75 and 85 Hz voice component volumes. Notice the clarity in the definition of the discontinuities on the displays. **Such data lead to better interpretation of the discontinuities than carrying out the same exercise of the input data.**

Acknowledgements

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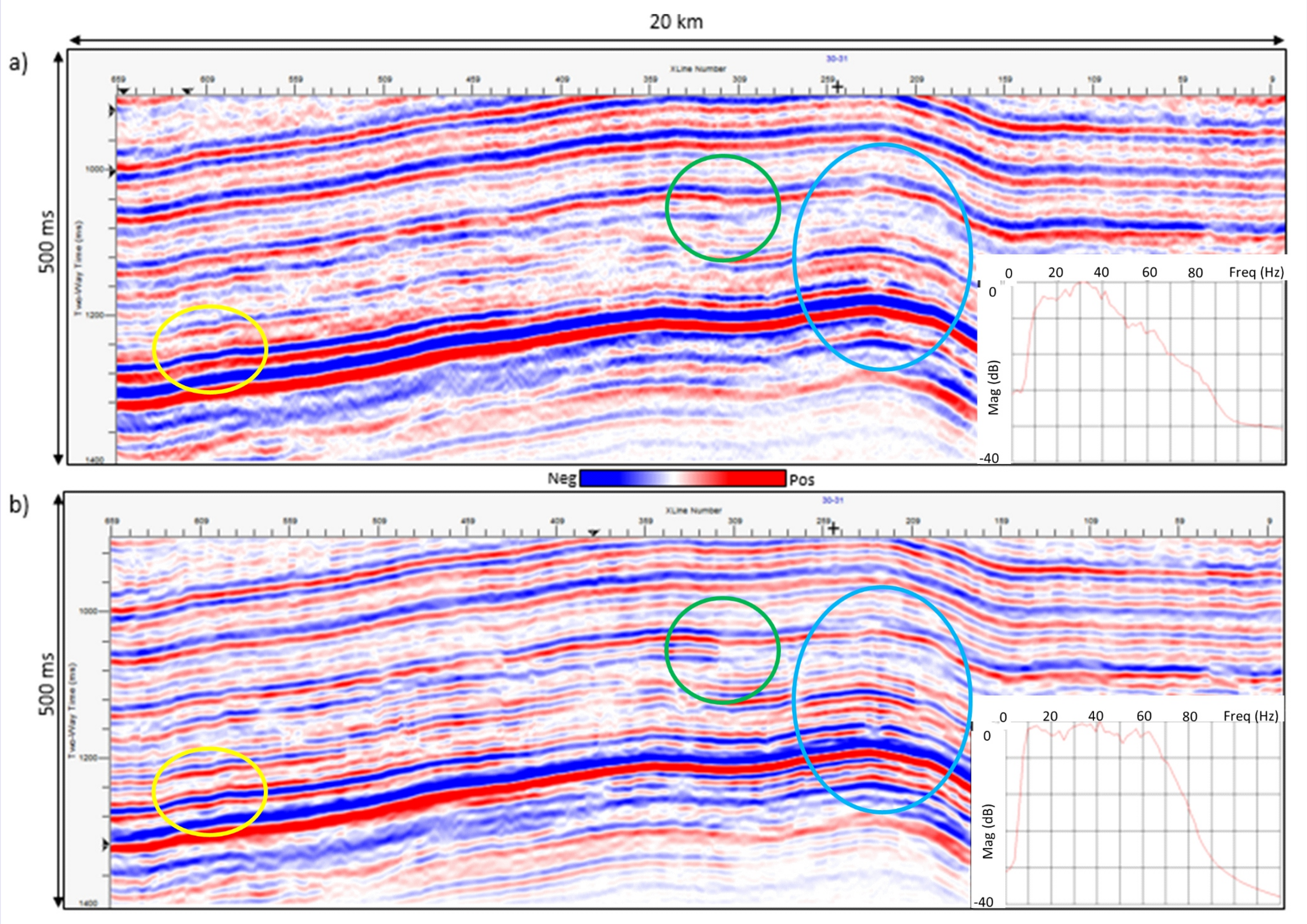

Figure 5: A vertical line through a seismic amplitude volume (a) before, and (b) after spectral balancing. Note the small channel (yellow circle) and clear edge (green circle) and improved vertical resolution (cyan ellipse). *(Data courtesy: Arcis Seismic Solutions, TGS)*

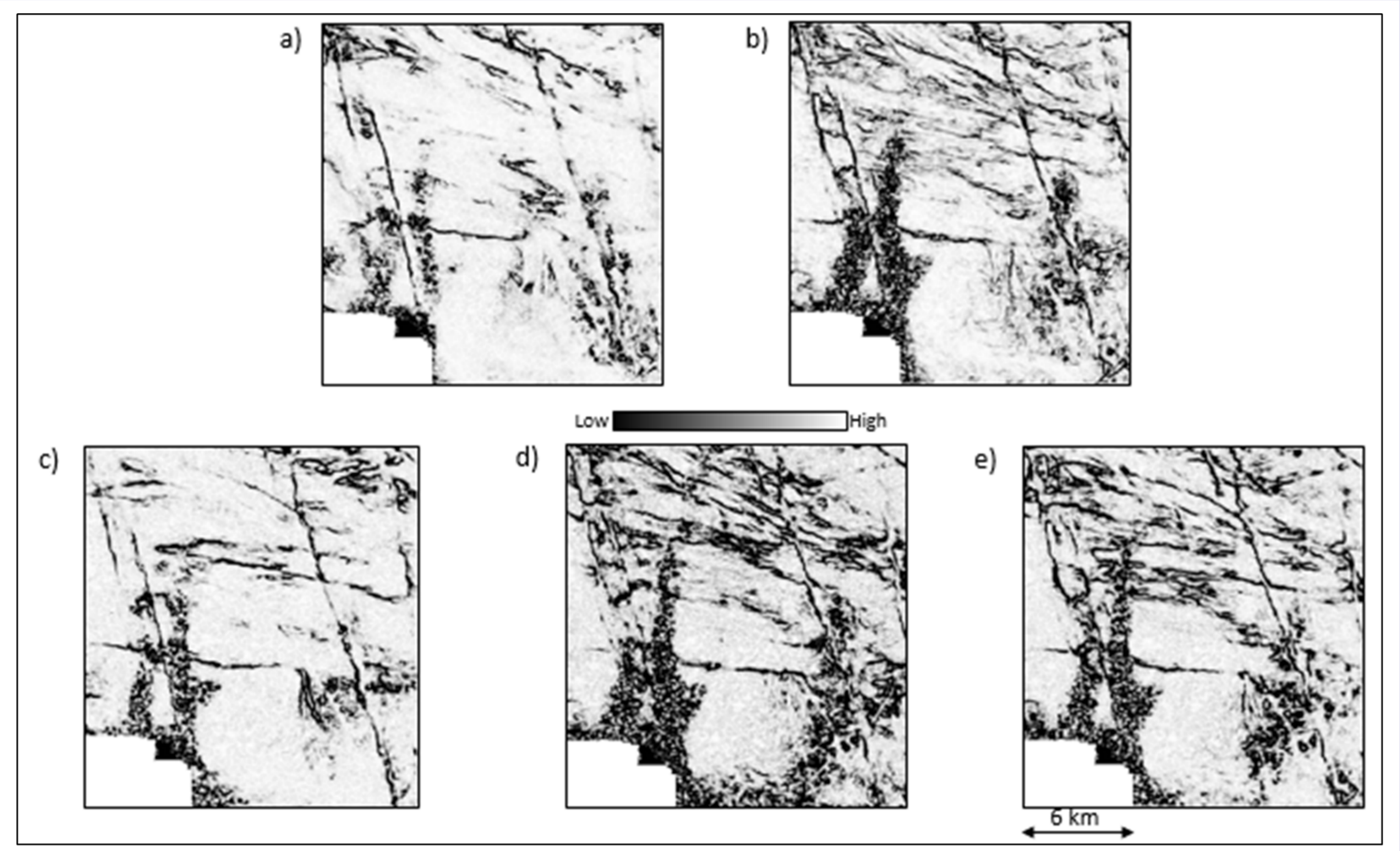

Figure 6: Time slices at 1322 ms through coherence computed from seismic data (a) before and (b) after spectral balancing, and from the (c) 65 Hz, (d) 75 Hz, and (e) 85 Hz voice components. Coherence computed from the 65, 75, and 85 Hz components clearly shows the lineaments corresponding to the faults and fractures. *(Data courtesy: Arcis Seismic Solutions, TGS)*

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Conclusions

We conclude that

(1) Voice components derived from spectral decomposition of input seismic data **furnish detailed and crisp information at specific frequencies that is amenable to more accurate interpretation**.

(2) S**pectral balancing of seismic data when performed in an amplitude-friendly way leads to broader band data**, which in turn exhibits detailed definition of faults and fractures.

3) Such discontinuity information can be interpreted better on coherence displays in the zone of interest.

4) **Coherence attribute computation performed on spectral voice components after spectral balancing yields higher detail with regard to the faults and fractures** or other discontinuity features such as channels, reefs, etc.