Application of spectral decomposition to detection of dispersion anomalies associated with gas saturation

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For many years geophysicists have attempted to exploit attenuation measurements in exploration seismology, because attenuation is perhaps the seismic property most closely related to the saturating fluid. The routine application of such ideas has proven elusive, however, largely because of the difficulty experienced when we attempt to measure attenuation in reflection data. Recent developments in the application of spectral decomposition methods to seismic data have opened the possibility of making further progress in this direction.

It is certainly the case that a wide range of evidence suggests that hydrocarbon zones are associated with abnormally high values of seismic attenuation and, in view of the Kramers-Kronig relations, we might expect that this attenuation would be associated with significant velocity dispersion. Consideration of the "drift" between velocities measured in VSP and log data over thick sections of the earth's crust has suggested that velocity dispersion in seismic wave propagation is generally small, but this still leaves the possibility that certain zones, such as hydrocarbon reservoirs, exhibit significant magnitudes of velocity dispersion and attenuation. Consideration of indirect dispersion measurements, particularly the frequency dependence of shear-wave splitting and other anisotropic attributes, further suggests that this is the case.

It can be difficult to explain the link between fluid saturation and attenuation using poroelastic models; straightforward application of the Biot equations will lead to attenuation values which are far too small. A recent paper (Chapman et al., 2005) showed how to implement ideas from squirt-flow theory to model hydrocarbon-related attenuation anomalies. Abnormally high attenuation can be produced as result of gas saturation, but this attenuation must be accompanied by significant velocity dispersion in the reservoir layer. This leads naturally to the view of the reservoir as a "dispersion anomaly" and under these circumstances the reflection coefficient becomes strongly frequency dependent. Synthetic modeling suggests that this effect is rather important and would usually dominate the traditional effect of attenuation thought of as a continuous and cumulative loss of energy during propagation. The nature of the frequency response depends strongly on the AVO behavior at an interface.

The effect of the frequency-dependent reflection coefficient is essentially instantaneous in character. This makes modern instantaneous spectral analysis techniques the ideal tool for detecting such variations. Such an approach has a number of potential advantages over the traditional methods which rely on the comparison of the spectral properties of two windows separated in time, and which inevitably contain different combinations of events.

This article applies the spectral decomposition techniques to two field data sets in an attempt to detect the type of dispersion anomalies suggested by the modeling. Within the context of a standard AVO analysis, we find that reflections from the hydrocarbon-saturated zone appear to display systematic frequency anomalies. These anomalies can be reproduced with synthetic reflectivity modeling which is also consistent with the AVO analysis. In general, the study leads us to believe that the study of systematic frequency variations can potentially help provide additional information on fluid saturation.

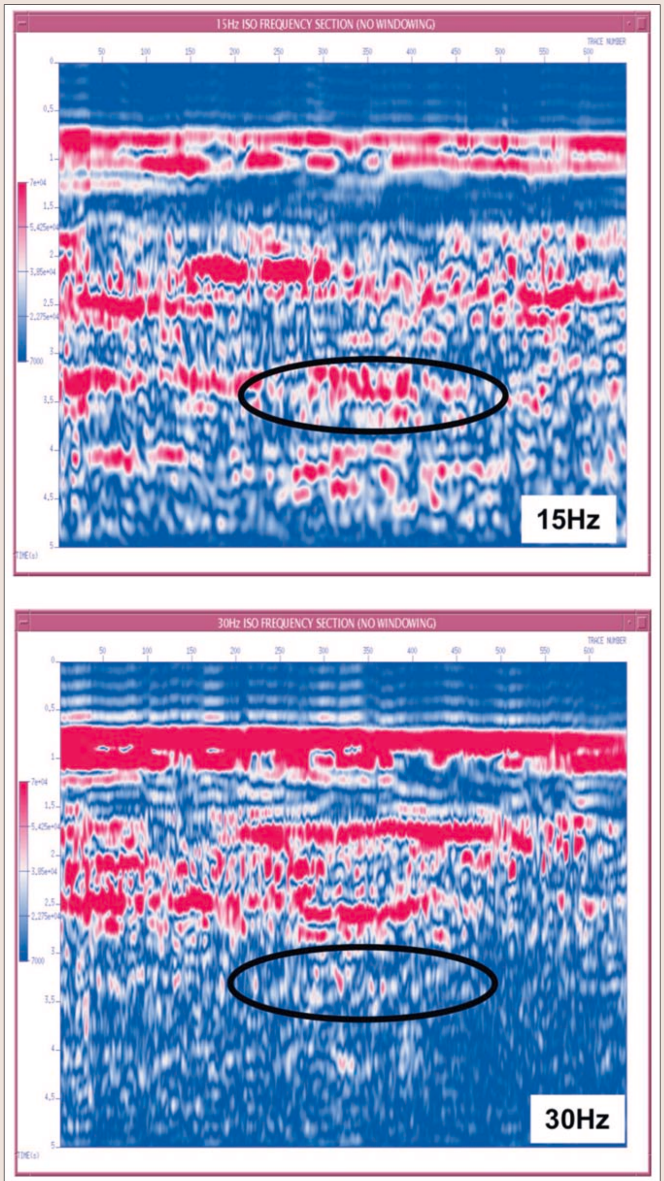


Figure 1. Isofrequency stacked sections for example 1 for 15 Hz and 30 Hz. The reservoir zone, indicated, is bright at the lower frequencies but cannot be observed on the higher frequency sections.

Spectral decomposition and balancing. Spectral decomposition techniques help us to understand scale and frequency-dependent phenomena, essentially by allowing us to study the data one frequency at a time. Specifically in this paper, given a trace *f(t)*, we form the Stockwell, or S-transform:

$$Sf\left(u,\omega\right)=\frac{1}{2\pi}\int_{-\infty}^{\infty} f(t)\frac{|\omega|}{\sqrt{2\pi}}e^{-\frac{(u-t)^2\omega^2}{8\pi^2}}e^{-i\omega t}dt,$$

which mean that, for each choice of frequency, we have a new trace corresponding to that particular frequency. With such a concept and given a collection of traces we can form a "frequency gather," consisting of each trace's representation at the specified frequency. While such an arrangement may seem beguiling, it is very important to remember that perfect spectral decomposition is a logical impossibility on account of the Heisenberg uncertainty principle.

When we wish to compare the traces at different frequencies, we should expect to find markedly different amplitudes because neither the source nor the earth's reflectivity have white spectra. The procedure for compensating for these effects is to use spectral balancing. In our synthetic data, because we know the input wavelet, we can balance the different traces exactly, a step which is similar to deconvolution. In real data we attempt to equalize the average amplitudes between the various traces across a particular time window, or reference horizon. Our preference is to balance over a wide time window, because this makes local frequency anomalies particularly clear.

The main use of spectral decomposition has been in delineating tuning phenomena. Nevertheless, there have been suggestions that it can be used for direct hydrocarbon detection. This paper attempts to develop this aspect of the technique in conjunction with rock physics modeling.

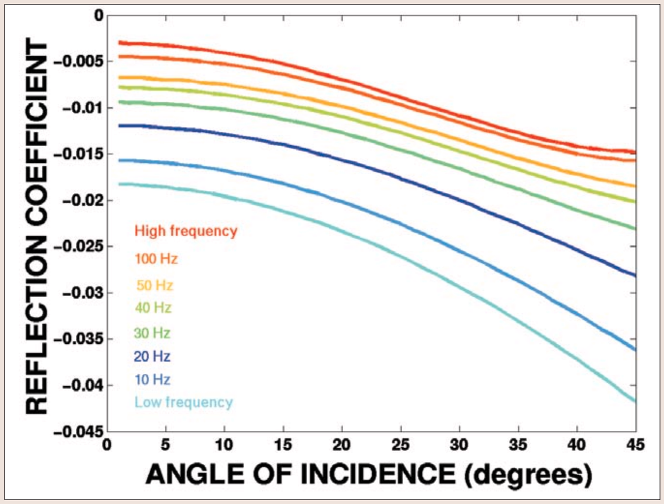


Figure 2. AVO curves for various frequencies for our first model, under gas saturation. The low-frequency curve corresponds to the traditional Gassmann case.

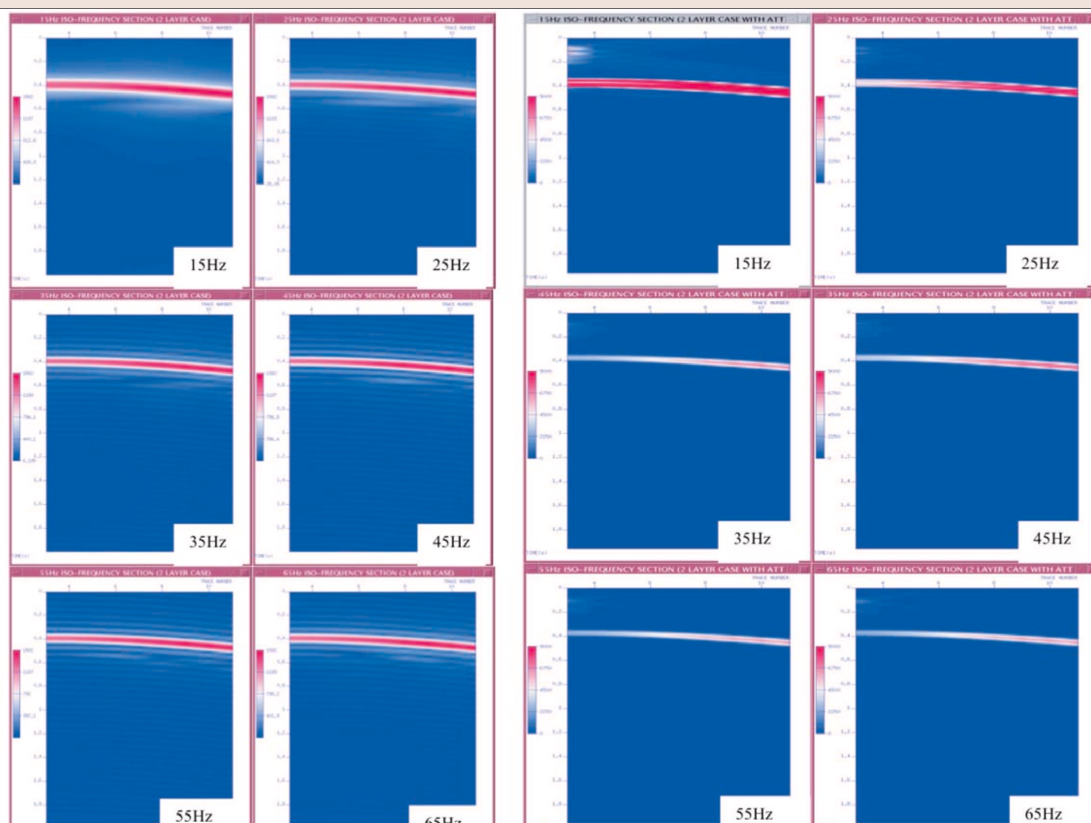
Example 1. Our first example is a 2D line of streamer data from a gas field in the North Sea. The main point of our approach is that interpretation has to begin with a standard AVO analysis. Such an analysis indicated that the data showed zones of strong class III AVO anomalies at the reservoir level; this was confirmed by gradient and intercept crossplotting as well as consideration of product, fluid-factor, and scaled Poisson ratio stacks.

Following the work of Castagna et al. (2003), we formed "isofrequency sections" from the stacked data. From these it is immediately apparent that significant frequency anomalies are associated with the class III AVO anomalies at the reservoir level. Figure 1 highlights such a region, which is bright on a 15-Hz section, but no bright spot is visible on the 30-Hz section. The effect was consistent for other frequencies; the reservoir was bright at low frequency, but did not stand out on the higher frequencies. This highlights the fact that in practice the concepts of amplitude and AVO anomalies are typically frequency-dependent phenomena.

We performed an extensive synthetic modeling study to determine if the frequency and AVO anomalies could be systematically related to gas saturation. We used a commercial reflectivity code (ANISEIS) which permits the use of materials with frequency-dependent velocities and attenuations. Our interest had three components; the simple Gassmann effect, the Gassmann effect with tuning, and the full dynamic modeling with attenuation and associated dispersion.

When we considered the simple single-layer case, it was

Figure 3. Reflections from the single interface for our model under gas saturation. Left diagrams are for the Gassmann case; right diagrams are the dispersive case. Spectral balancing based on the input wavelet has been carried out. For the Gassmann case, similar energy appears on each isofrequency section. In the dispersive case, the low-frequency sections have markedly more energy.



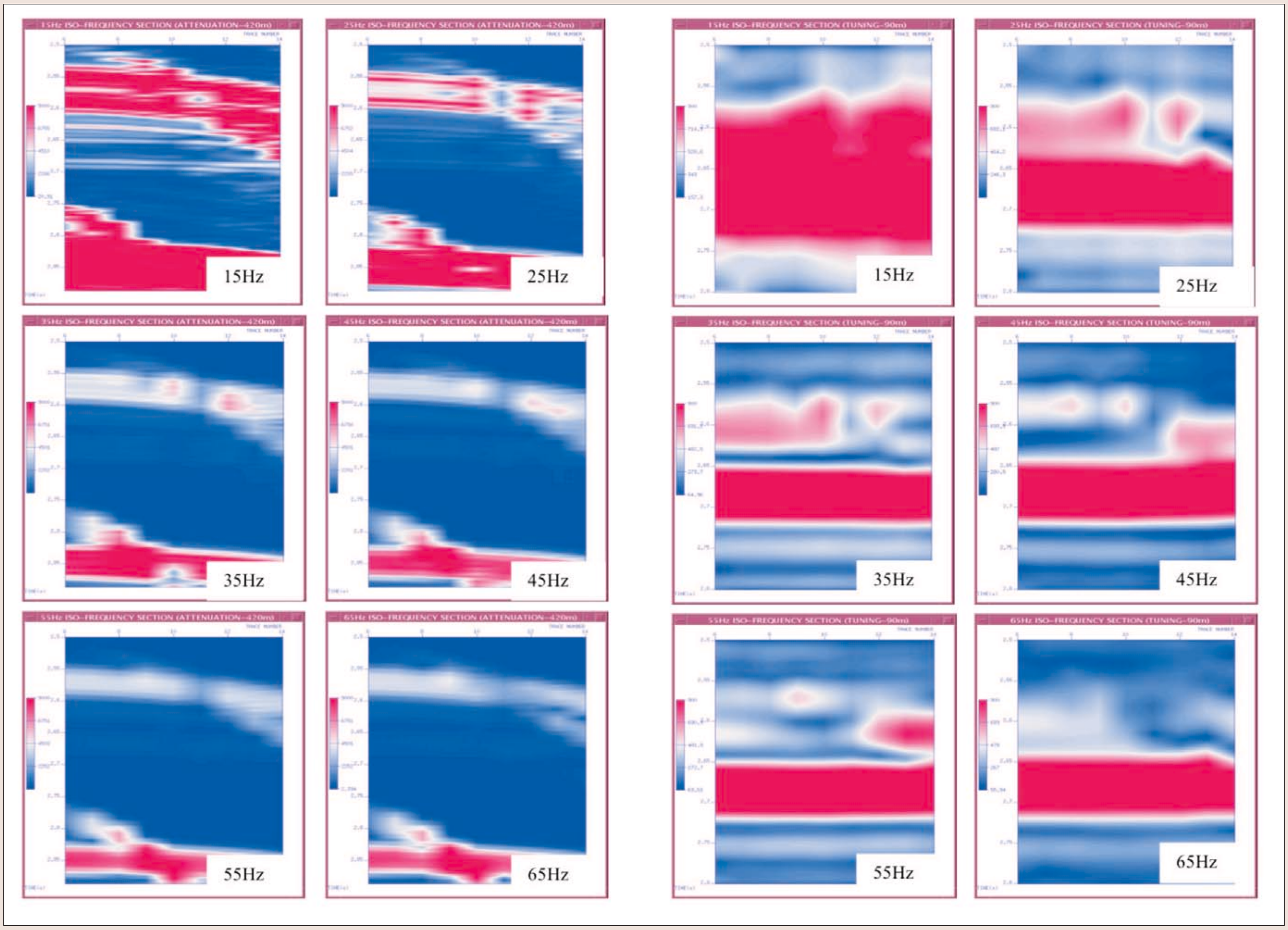


Figure 4. *Isofrequency sections from the multilayer model. Left diagrams correspond to the dispersive case, but with a thick reservoir layer of 420 m for which no tuning occurs. Right diagrams are for the Gassmann case, but with a thin reservoir of 90 m which is close to the tuning thickness. Spectral balancing has been applied in both cases, but the lower-frequency sections appear brighter.*

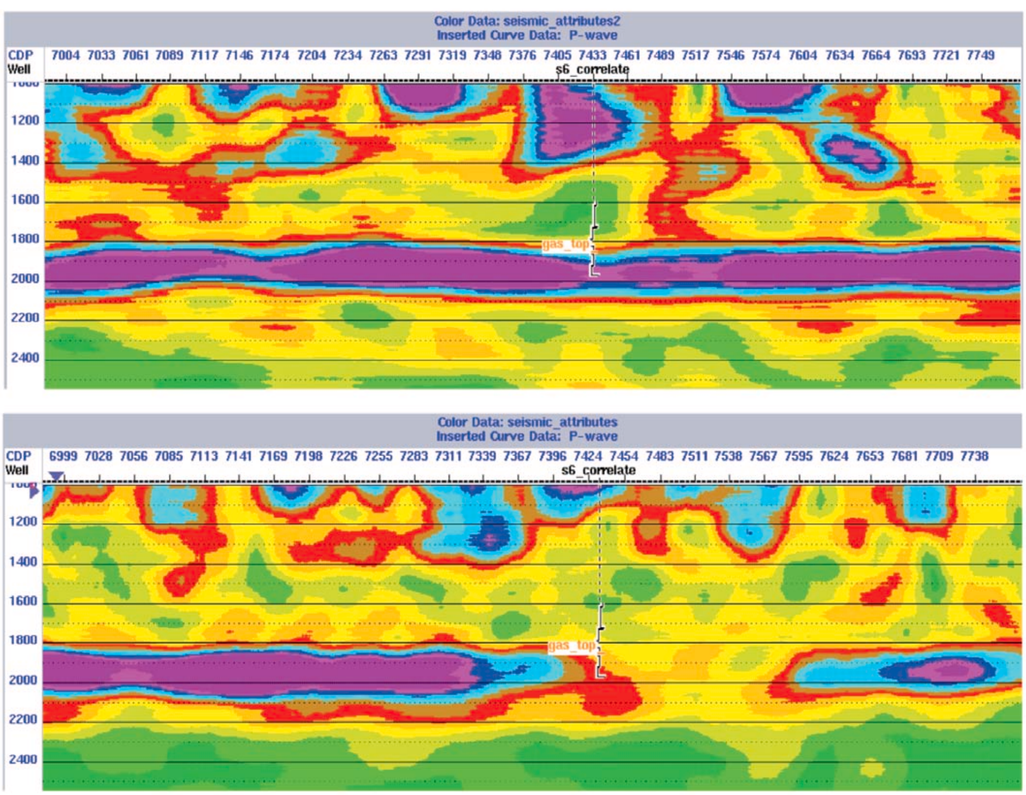


Figure 5. *PP stacked sections from example 2, band-passed into low- (top) and high- (bottom) frequency sections. Note how the reservoir level (around 2 s) appears dim in the high-frequency section but not in the low-frequency section.*

easy to model the standard AVO attributes with Gassmann, under straightforward assumptions. We performed spectral decomposition to produce balanced isofrequency sections. As might be expected, these sections showed similar energy in each isofrequency section, and so we could not model the effect seen in the data with a simple one-layer model. When we introduced dispersion into the reservoir layer, however, the frequency dependence of the reflection implied that the isofrequency sections were no longer balanced, and the low frequencies appear to have much more energy. Figure 2 shows the gas-saturated reflection coefficients for a range of frequencies for the model while Figure 3 shows a comparison between the balanced isofrequency sections for the single-layer case, assuming both the purely elastic case (left) and the case with a dispersive reservoir layer (right).

In practice we know that we never deal with reflections from single layers; tuning and multiples are always important issues. To address these issues, we formed a blocked model with 10 layers from velocity data from the field in question. We also varied the thickness of the reservoir layer to simulate tuning phenomena, and we did this both for the simple Gassmann modeling as well as the modeling with dispersion. In general we found that the dispersion effect is still strong even in the multilayer case, but, for certain reservoir layer thicknesses, tuning can give a similar effect to that arising from the dynamic modeling. Figure 4 shows a comparison for the multilayer case between a dispersive reservoir layer without tuning and an elastic reservoir layer with tuning. We conclude that without detailed information on the velocity model it can be difficult to distinguish between the effects of dispersion and tuning.

Example 2. We applied similar ideas to a gas field from Ordos Basin, onshore China. The potential reservoirs in the area are primarily in the fluvial sandstone in the Permian. The subsurface has a flat-layered structure with gas reservoirs typically below 3000 m. The targeted gas beds are thin and have a small P-wave velocity difference between the gas sand and the overlaid shale, giving rise to a weak amplitude on the

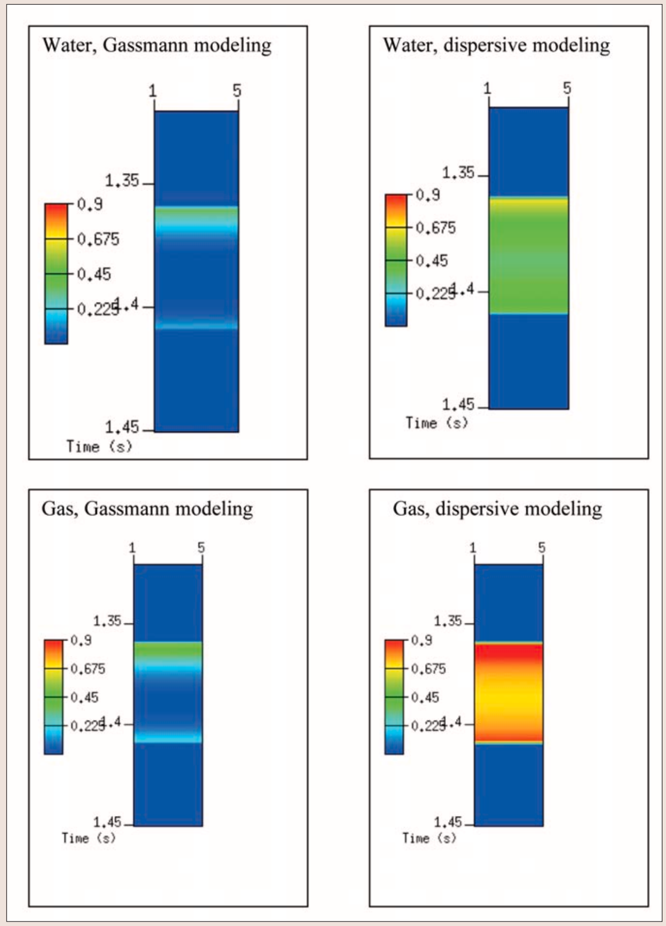
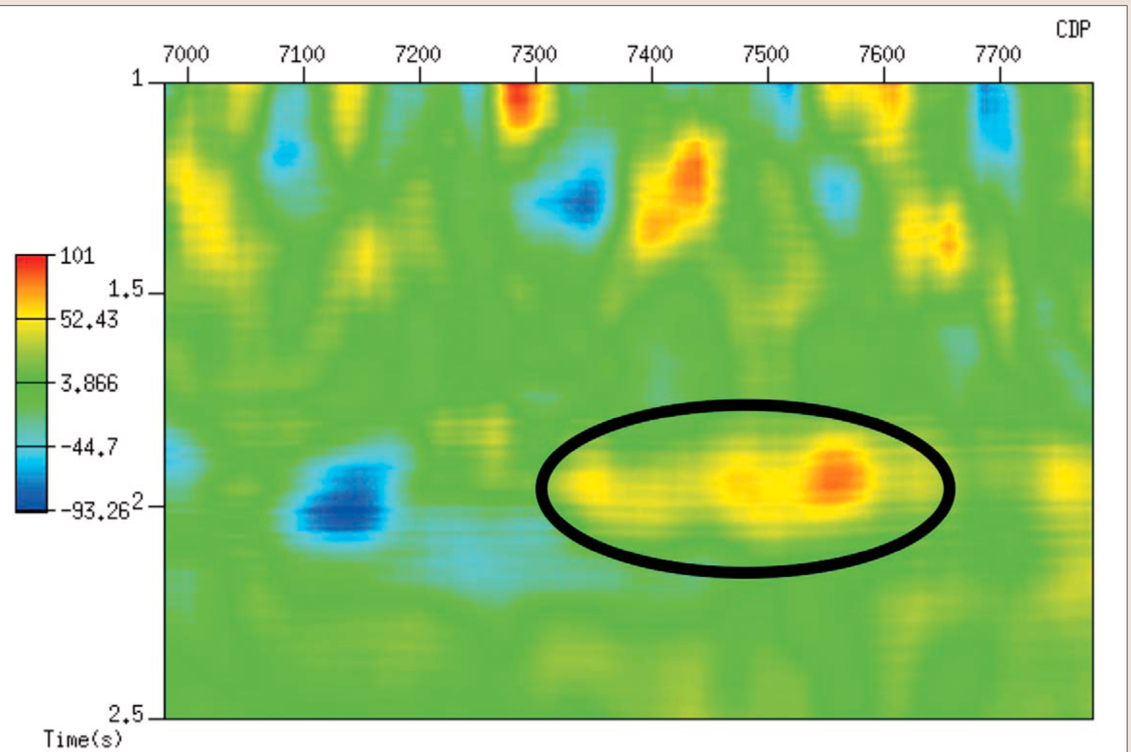


Figure 6. "Difference traces" formed by stacking the synthetic data, performing spectral decomposition, consistent spectral balancing, and subtracting the 30-Hz trace from the 15-Hz trace. The reservoir layer is 10-m thick, and we consider water and gas saturation in both the dispersive and Gassmann cases. Note that the Gassmann modeling gives small absolute values, but that gas saturation is associated with a strong positive amplitude when we perform dispersive modeling.

Figure 7. The results of balancing and differencing the sections from Figure 5. Notice that the gas reservoir shows as a positive anomaly (ringed) in accordance with our synthetic modeling.



PP-wave reflection.

Standard AVO analysis suggested that the top of the reservoir was in principle a class III interface, but that the reservoir reflection itself was a composite event, which led to an apparent negative reflection coefficient whose absolute amplitude declined with increasing angle of incidence, resembling the behavior of a class IV interface. Based on log data, we created an idealized multilayer model, with a 10-m thick gas sand and 10-m thick shale layer encased in a half space of higher impedance. This arrangement was able to effectively model the observed AVO behavior within the reservoir.

Application of spectral decomposition techniques to the stacked field data revealed an unexpected anomaly. Figure 5 shows the results of filtering the final stack into low- and high-frequency bands. It is clear that in the high-frequency section the reservoir appears as a low-amplitude anomaly, but this is not the case in the low-frequency section. Because the reservoir is only 10-m thick, it proved difficult to model this effect as being due either to a traditional attenuation mechanism or fluid-related changes in the tuning-thickness. To explain the behavior, we turned to our dispersive modeling.

As before we ran two sets of models, the standard elastic Gassmann case as well as the dispersive modeling, and found that as expected, for a class III interface, the gas saturation was associated with a systematic boost to the low frequencies relative to the high frequencies in the dispersive case. To illustrate this point we ran four models corresponding to water and gas saturation for both Gassmann and the dispersive case, stacked the data, formed isofrequency traces, and performed consistent spectral balancing on each trace. We then subtracted the resulting 30-Hz trace from the 15-Hz trace, and windowed around the main arrival to compensate for the different time durations of the signals. The results are illustrated in Figure 6. For each Gassmann trace there is little residual energy, implying that the traces were well balanced. In the dispersive case there was residual energy for both saturations, but it was much stronger in the gas-saturated case. A similar procedure was carried out on the data shown in Figure 5. The two sections were balanced and a difference was taken; Figure 7 shows the result. As can be seen, in the vicinity of the reservoir we have a response very similar to the gas response we saw in our synthetics.

Discussion. In this paper we have applied the spectral decomposition techniques to reflection data from hydrocarbon-saturated zones. Sharp changes in the spectral behavior associated with gas saturation have been noted elsewhere; the novelty of this paper lies in the attempt to model the behavior in terms of well-defined poroelastic effects. The understanding of such effects builds on the standard AVO analysis, since our interpretation is within the extended Rutherford-Williams classification outlined by Chapman et al. (2005). We emphasize that our work is an adjunct to the standard AVO methodology; we do not believe that it is possible to robustly interpret the spectral response in the absence of a thorough AVO analysis.

In our data examples, the gas saturation can be associated with a clear spectral signature, and the effect can actually be modeled in terms of a simple single-layer model, provided we account for velocity dispersion. Nevertheless, we know that in practice we always deal with more complicated geologic models. In particular, tuning is always present to a certain degree. When we perform fluid substitution with Gassmann in such a thin-layer case, we change the velocity and hence the effective tuning thickness. This provides a natural explanation as to why gas-saturated zones should appear as spectral anomalies. In our first example, we cannot discriminate whether the observed spectral anomaly is caused by tuning or dispersion, but in the second example the reservoir is only 10-m thick, and the tuning effect is not sufficient to produce a significant spectral response for such thin reservoirs at seismic frequencies.

Paradoxically, the fact that spectral anomalies often occur for such very thin reservoirs has often been cited as a reason why attenuation cannot be the responsible mechanism, because it was thought that attenuation, being primarily a propagation phenomenon, could only accumulate a significant impact for waves traveling over longer distances. Our emphasis on the frequency-dependent reflection coefficient arising from the attenuation-related dispersion anomaly provides an explanation to this point. The framework also answers another common argument against attenuation mechanisms being responsible for spectral anomalies which is that the high frequencies are commonly observed to return for reflections from below the reservoir, which would be impossible if we viewed attenuation as a simple cumulative loss during transmission mechanism. This phenomenon is reproduced in our synthetics. The deeper reflections occur at interfaces which are not associated with a strong attenuation and dispersion contrast and so are governed by a relatively frequency independent reflection coefficient. The spectral properties of such reflections therefore are those of the background trend, with the energy loss associated with passing twice through the attenuating layer being generally only a secondary effect.

Unfortunately, many processing and other artifacts can give rise to spectral anomalies which correlate with gas saturation, as has been eloquently pointed out by Ebrom (2004), and we are consequently conscious of the danger in overinterpreting such observed features. The purpose of this paper is simply to show that it is in fact possible to quantitatively model observed spectral anomalies in seismic data associated with gas saturation in terms of dispersion. Whether in fact velocity dispersion is the true cause of the spectral anomalies must be considered an open question; but nevertheless if the success of the modeling is maintained in other data sets, then it may be possible to develop an extension of the current AVO methodology which will include consideration of the dispersion effect and might give better access to fluid-saturation information.

Suggested reading. "Instantaneous spectral analysis: Detection of low-frequency shadows associated with hydrocarbons" by Castagna et al. (*TLE*, 2003). "Direct detection of oil and gas fields based on seismic inelasticity effect" by Rapoport et al. (*TLE*, 2004). "The influence of abnormally high reservoir attenuation on the AVO signature" by Chapman et al. (*TLE*, 2005). "Application of spectral decomposition to gas basins in Mexico" by Burnett et al. (*TLE*, 2003). "The low-frequency gas shadow on seismic sections" by Ebrom (*TLE*, 2004). TLE

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