Seismic Attenuation for Reservoir Characterization

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Selecting the Synthetic Seismic Program

RSI has access to two synthetic seismic programs: Osiris seismic modeling system provided by Odegaard (Osiris) and synthetic seismic program, developed by SRB, implementing the Kennett method for normal incidence.

Osiris

Osiris is the seismic modeling program developed and marketed by Odegaard. This program implements the reflectivity method for seismic media representing a stack of visco-elastic transversly isotropic homogeneous layers. It provides a variety of source models and receiver geometries as well as several velocity dispersion models. This program computes the full elastic wave field, containing all of the multiples, AVO effects, reflection losses, refracted, inhomogeneous and converted waves and other physical phenomena describing the interaction of a seismic wave with "cake-layered" earth model. In other words, the synthetic seismic field is almost as complex as the real seismic measurement.

SRB's Kennett code

The SRB's Kennett code is an implementation of the Kennett method of seismic modeling for the special case of normal incidence plane seismic waves in a stack of homogeneous plane visco-elastic layers. The computed synthetic field contains all of the effects occurring at the normal incidence (i.e., multiples, transmission losses, etc.), but nothing else. There are no converted waves, AVO, head waves, etc. The resulting wave field is even simpler than zero-offset real seismic: no spherical diversion, inhomogeneous waves, etc.

Comparison

Ideally any synthetic computation program needs to be calibrated by comparing the synthetics it produced with a controlled laboratory experiment. A cheaper alternative would be to compare the output of two independent, significantly different, synthetic programs. If they match, this comparison provides a means of cross-validation for both. For the match to occur, we need to pose a comparable problem to both programs. We computed and matched synthetic seismic traces from the five-layer model (see next chapter) with both the Kennett code and Osiris synthetics program.

Both Osiris and Kennett code provide full elastic wave solution for their respective models, and should produce similar synthetic traces (zero-offset trace for Osiris). However, they employ different propagation and source models. In the Kennett code the propagation mode is 1-D, which is the same as exciting plane waves only. In Osiris, the seismic wave is excited by a point source (there are other options, but no plane wave source) and the propagation model is true 3-D (2-D optionally).

These differences bring about a significant difference in the zero-offset traces.

- Spherical diversion. The 3-D propagation mode in Osiris causes the amplitude decrease with time as *1/t*. To match the Osiris zero-offset synthetic trace with the Kennett synthetic trace the former needs to be multiplied by *t*.
- Inhomogeneous waves. The point source, modeled in Osiris, in addition to the conventional spherical P-wave, generates inhomogeneous waves, exponentially decaying with depth. One of them has P-wave particle motion, but travels with the S-wave velocity. It is reflected at the first boundary as conventional P-wave and is subsequently recorded at zero offset with PS-wave arrival time, thoroughly confusing the picture. To achieve a clean match between the two synthetics we had to make the top layer so thick, that this wave arrived after the last reflection of interest.

Since we had no control over the velocity dispersion implementation in Osiris, we turned the dispersion off in both programs. We provided identical wavelets to both programs, and considered the z-component of the particle velocity output in Osiris. The reflection arrival time in Kennett code is fully defined by the thickness of the top level. In Osiris it is defined by both this thickness and also source and receiver depths which can not be zero. To achieve a complete match, we had to effectively reduce the thickness of the top layer for Kennett code by the sum of the source and receiver depths in Osiris.

Though we were only interested in the zero-offset trace, we had to compute at least one more non-zero offset trace in Osiris, or else computational instabilities completely distorted the seismic fields. After taking all of the above measures we reduced the difference between the synthetic seismic traces obtained from each program to the level of 0.1% of each reflection.

Conclusion

Achieving virtually identical synthetic seismic traces from these different programs serves as cross-validation for both. The subsequent experiments have been performed with the Kennett normal incidence code because: We have access to the source code, which allowed us to easily control computational parameters and integrate the synthetics computations with our graphical and I/O systems. This code allows to perform computations and displays on a PC in MatLab or Octave environment, which is faster and more convenient. The normal incidence model allows us to exclude from the synthetic traces some of the physical effects that take place in 3-D models (like inhomogeneous waves) but have no relevance to the topic of our investigation, which is attenuation effects on seismic reflection and transmission.

Five-layer Model

We started investigating the effects of attenuation on synthetic seismic with a simple model with five thick layers, presented in Figure 1.

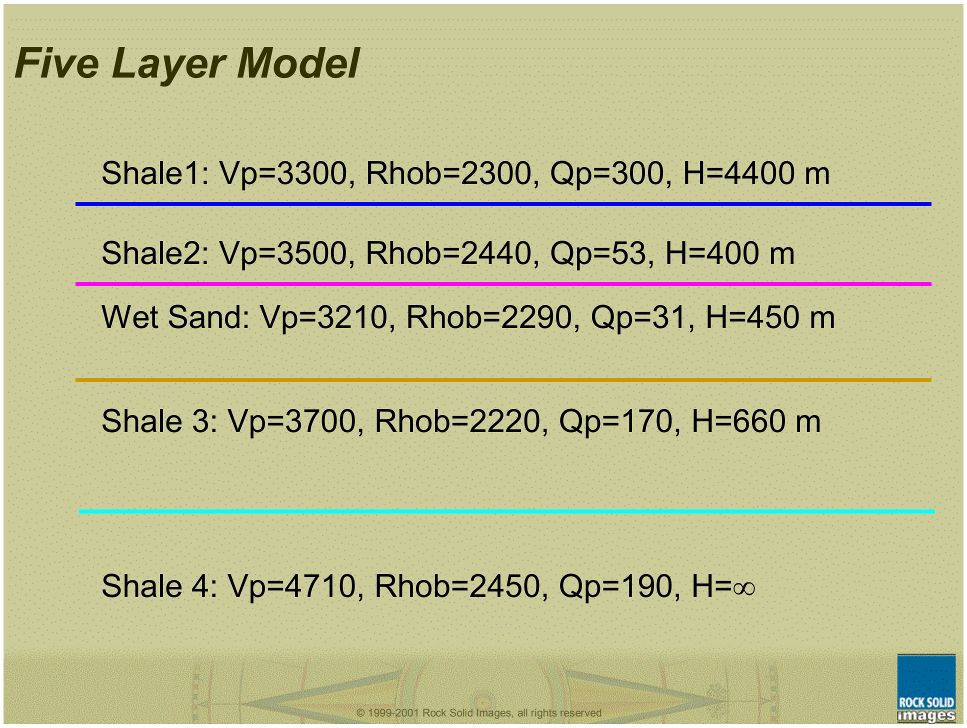

Figure 1. Model with five thick layers.

The thickness of the layers was adjusted so as to avoid any interference between primary reflections and intrabed multiples. The synthetic was computed twice with the same elastic parameters but with different Q values. The first synthetic was computed with Q values shown in Figure 1 (model Q). For the second computation we set the Q values in all layers to 300 (high Q). The synthetic traces obtained in this case are equivalent to the results of conventional zero-offset synthetic seismic modeling with multiples. Comparing these synthetic traces allows us to separate the acoustic contrast effects from the attenuation effects. The wavelet used in these computations and its spectrum is presented in figure two.

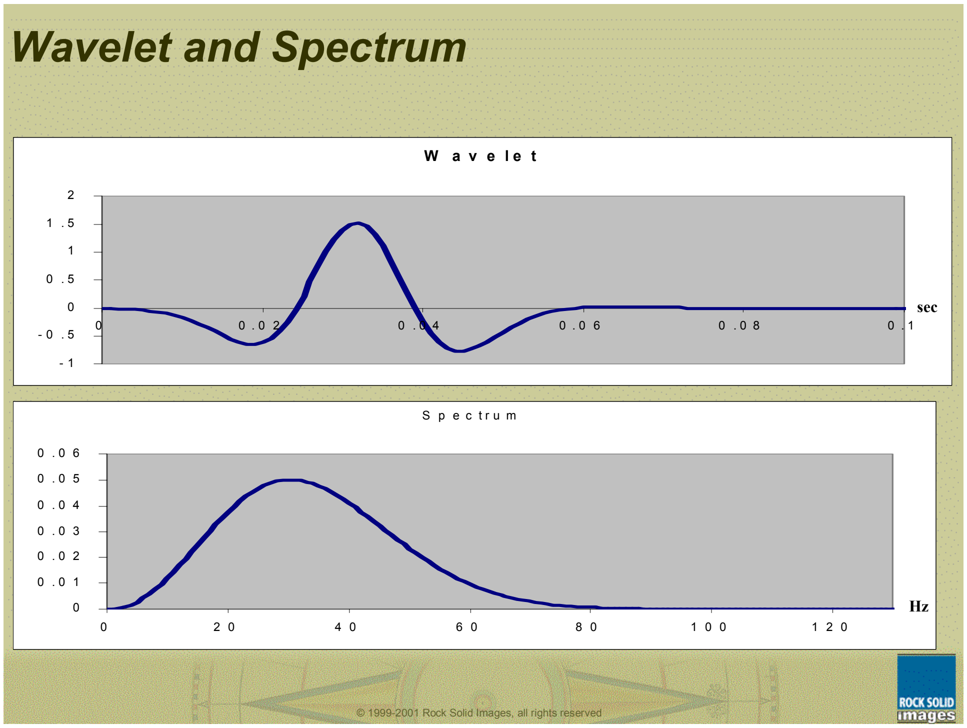

Figure 2. Wavelet and its spectrum. The central frequency is 30 Hz.

The synthetic seismic traces computed with high Q and model Q are presented in figure 3. The amplitude effect of attenuation can be seen by comparing the reflection amplitude of model Q synthetics (black curve) with the high Q synthetics (pink curve). Attenuation obviously reduces the amplitudes of seismic reflections.

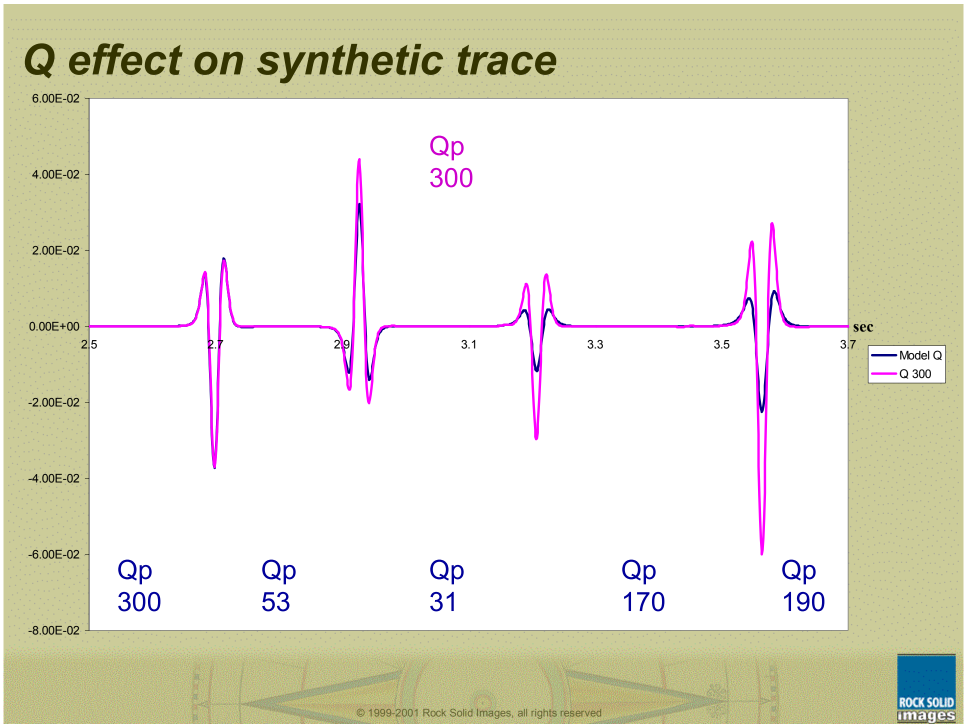

Figure 3. Synthetic seismic traces computed with model Q and high Q.

However most of the methods designed to estimate seismic attenuation from seismic traces are based on the way attenuation affects seismic spectra. Namely, higher frequencies in the seismic wave experience higher attenuation than the lower ones, thus shifting the dominant frequency of seismic reflections.

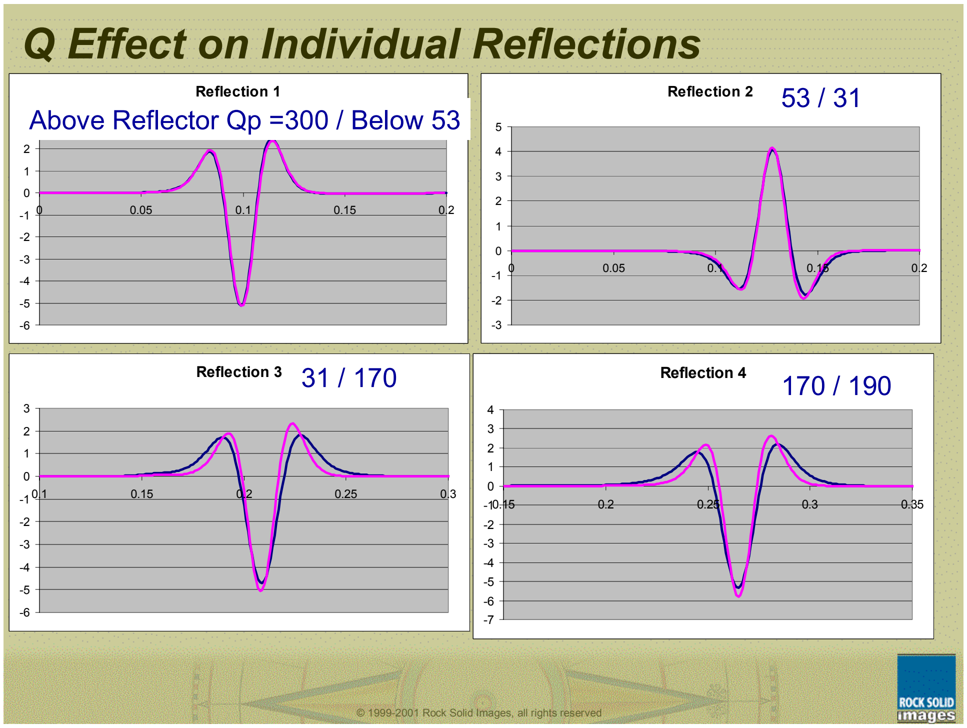

Figure 4. Effect of attenuation on individual reflections.

Figure 4 represents individual reflections from each of the four reflectors in the model, computed with model Q and high Q. All reflections have been equalized by their RMS value. This graph shows how the apparent frequency decreased after the seismic wave passed through the wet sand layer. To make this frequency shift more apparent, we computed the spectra of all reflections, which are represented in figure 5. The spectrum shifts to lower frequencies when the seismic wave passes through layers with model Q values, and stays unchanged when the Q values are high. The dominant frequency of the latest reflection is around 20 Hz, while the top reflection has the dominant frequency of the original wavelet equal to 30 Hz.

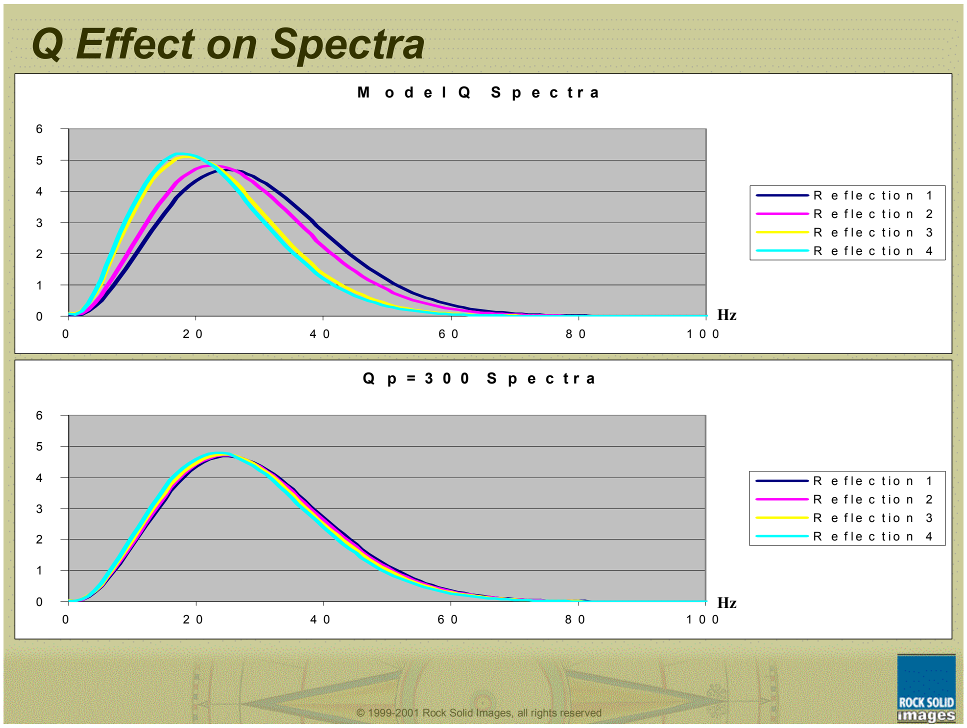

Figure 5. Reflection spectra.

Wedge Model

Experiments with the five-layer model demonstrated that the synthetic seismic exhibits the expected effects of attenuation on the seismic waves. In the next series of experiments we wanted to investigate the synthetic seismic sensitivity to the sand thickness. For this purpose we computed the synthetic seismic traces in a series of five-layer models with the sand thickness decreasing from 450 m to zero. At the same time the thickness of the Shale 3 layer increased from 660 m to 1110 m to keep the arrival time of reflection 4 constant. We investigated the amplitude and frequency effects of varying sand thickness with model Q and high Q values in the model.

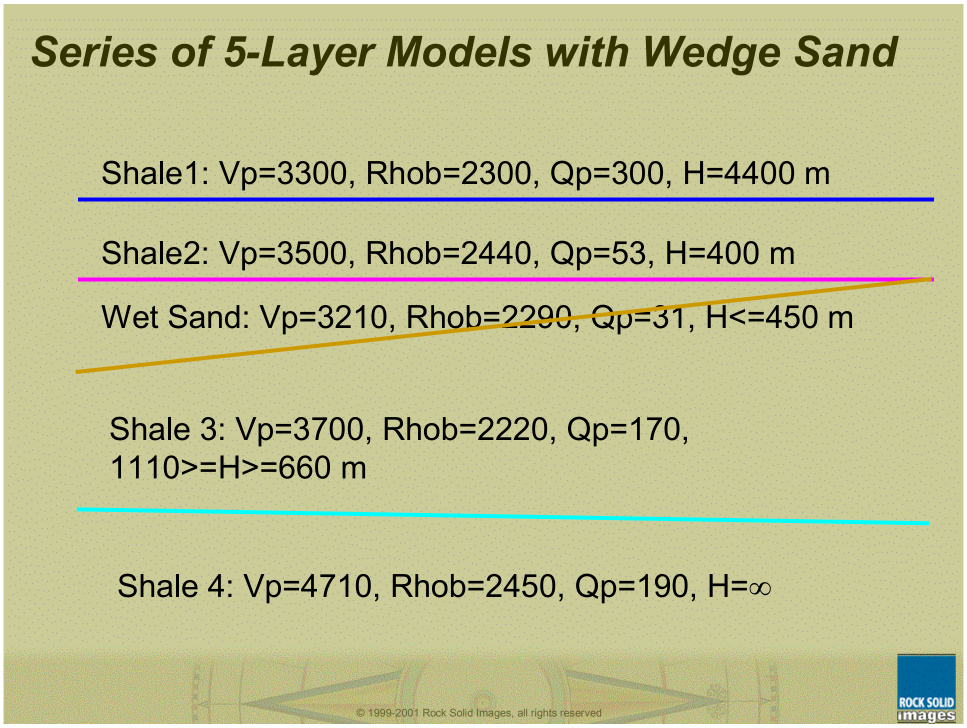

Figure 6. Schematic representation of the series of 1-D models with decreasing sand thickness.

The plots in Figure 7 represent synthetic seismic traces displayed on the background of color-coded instantaneous amplitude. The amplitude of the bottom reflection is of greatest interest here. The amplitude of the bottom reflection in synthetic computed with high Q remains constant regardless of sand thickness and is practically unaffected by the tuning effects in the sand layer. On the other hand, the decrease in the sand thickness when synthetic is computed with model Q causes significant increase in the amplitude of the bottom reflection. Even when the sand thickness falls below tuning, and reflections 2 and r merge, the amplitude of the bottom reflection continues to increase with the sand thickness decrease, demonstrating high sensitivity of the synthetic seismic to the changes in the attenuation along the ray path.

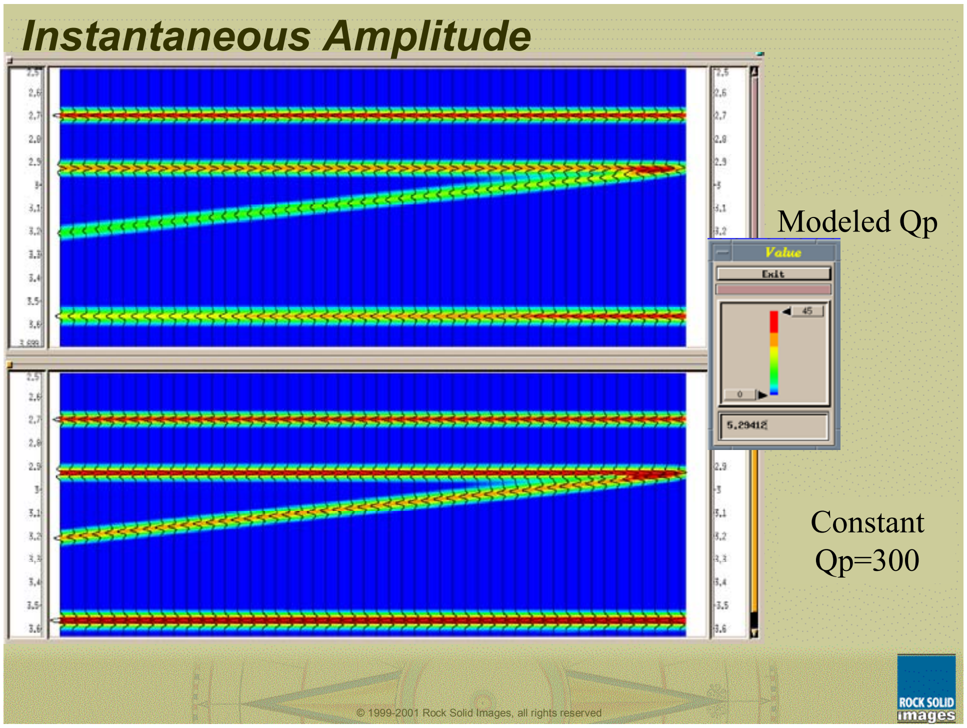

Figure 7. Synthetic traces and the Instantaneous Amplitude.

The frequency effects of changing sand thickness can be observed in the plots presented in figure 8. Here the same synthetic traces are plotted on the background of color-coded dominant frequency. The tuning effects can be clearly seen on the dominant frequency of reflections 2 and 3. These effects seem to be the same when synthetic is computed with model Q and high Q values. The dominant frequency of the bottom reflection, however, is unaffected by tuning, and only responds to changes in the sand thickness when synthetic seismic is computed with model Q values.

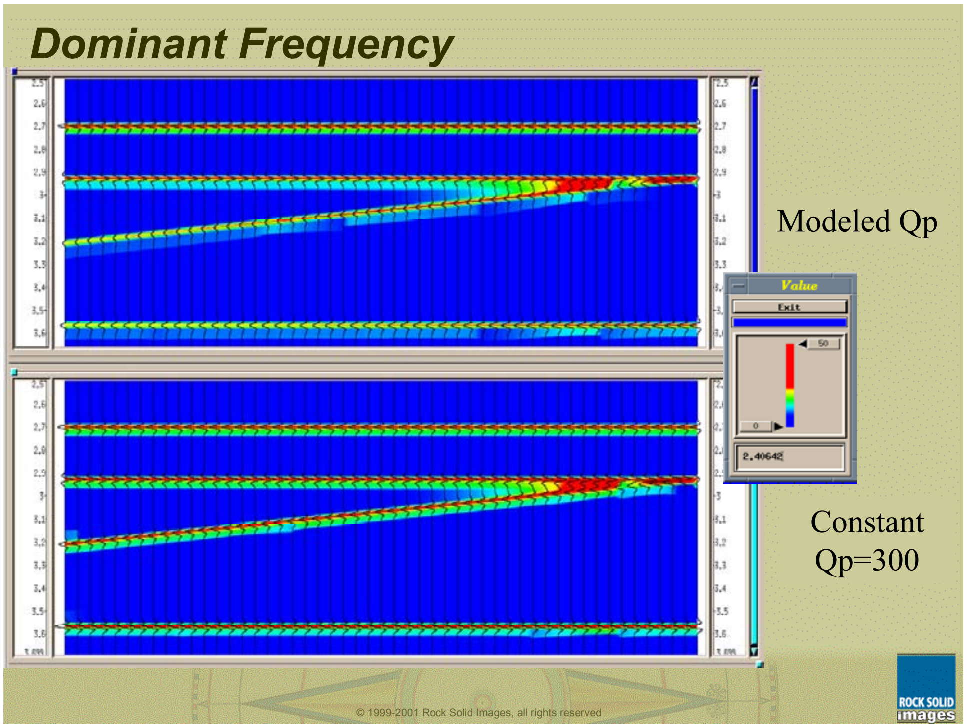

Figure 8. Synthetic traces and the Dominant Frequency.

Well 1 in-situ case

Subsequent synthetic seismic computations were performed on an earth models built from well log measurements obtained in a deep water well in the western GOM (well 1). The well log measurements had been subjected to the standard MOSS™ procedures in order to obtain the most accurate set of elastic parameters. The Q values have been predicted through a combination of theoretical and empirical methods. The synthetic traces were subsequently compared with the seismic values extracted from the migrated seismic stack along the well bore path.

Figure 9 represents the wavelet and its spectrum used in the synthetic seismic experiments with earth models based on well 1. This wavelet was selected after the spectral analysis of the migrated stack, with which the synthetic seismic traces were to be compared.

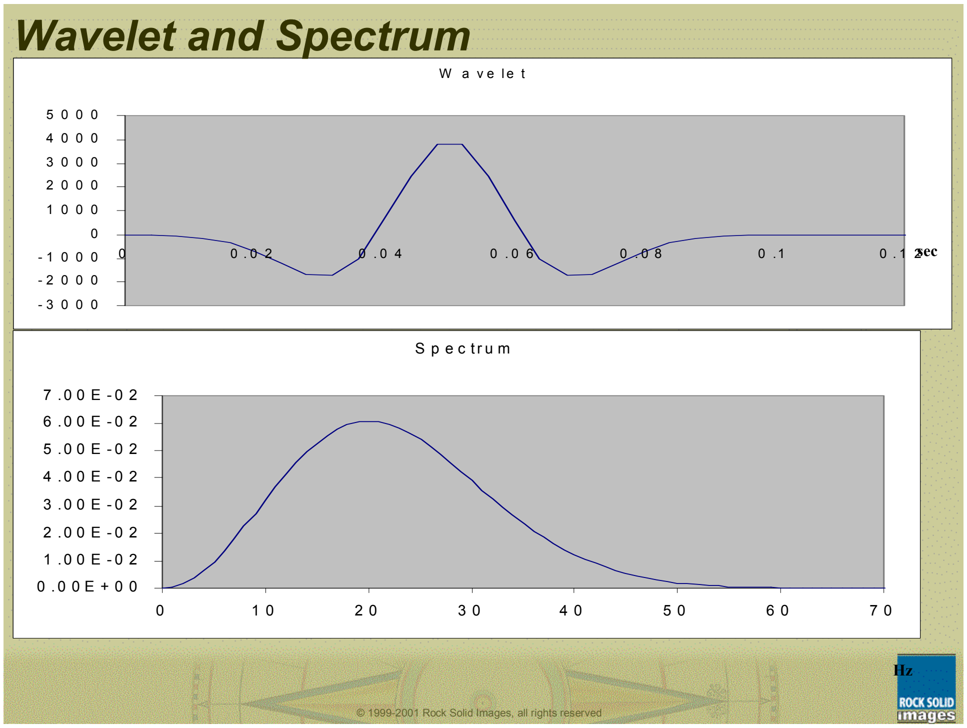

Figure 9. Wavelet used to compute synthetics in well based earth models. The dominant frequency is equal to 20 Hz.

Building an earth model for synthetic seismic computations from the well measurements is a non-trivial task. First of all, there is uncertainty in the shallow part of the model. To correctly match synthetic and seismic we have to know the velocity and Q distribution from the seismic datum surface all the way to the bottom of the well. The velocity can be estimated from the check shot information, but there is no reliable way to estimate the attenuation in the shallow part of the well, which had not been logged.

This problem had been resolved in the following way:

1. The seismic wavelet had been estimated at the time location of the beginning of the logged interval.
2. We assumed the earth model above this depth to consist of one homogenous non-absorptive (Q=300) layer.
3. The synthetic trace had been shifted and scaled in order to match the time and amplitude of reflection from the top of the logged interval with the corresponding reflection on the seismic trace (check shot information had been used to identify that reflection and time shift).

In this way, we could study the effect of only the known part of the well on the synthetic trace and compare it with the effect of real subsurface properties in the same depth range on the real seismic data. This solution is adequate for zero-offset synthetic studies, but additional efforts will be needed for offset synthetics. The well log contained 8600 samples at 0.5 ft increments. The synthetic seismic program considers each well log sample as a measurement at the top (or bottom) of a separate geologic layer. The computation time and memory requirements are proportional to the number of layers, and can become quite large when the number of layers exceeds 1000. On the other hand, the seismic wave, having apparent frequency of 20 Hz, provides depth resolution of 15 ft at best. In other words, the seismic wave effectively averages the models' characteristics in a sliding window of the above size. Therefore, there is no need to retain in the earth model built for synthetic computations the sampling interval of the original well measurements.

Instead we built a smoothed model with larger sampling intervals *d* equal to 5 ft, which reduced the number of samples in the model to 800. The elastic parameters at each depth *h* of the smoothed model were computed as Backus average of the elastic parameters from the original well log computed in the depth range between *h-d/2* and *h+d/2*. Most of the other parameters in the smoothed model (porosity, Sw, etc.) were computed as algebraic average of those parameters in the original well in the same depth range. The Q values were computed as harmonic average.

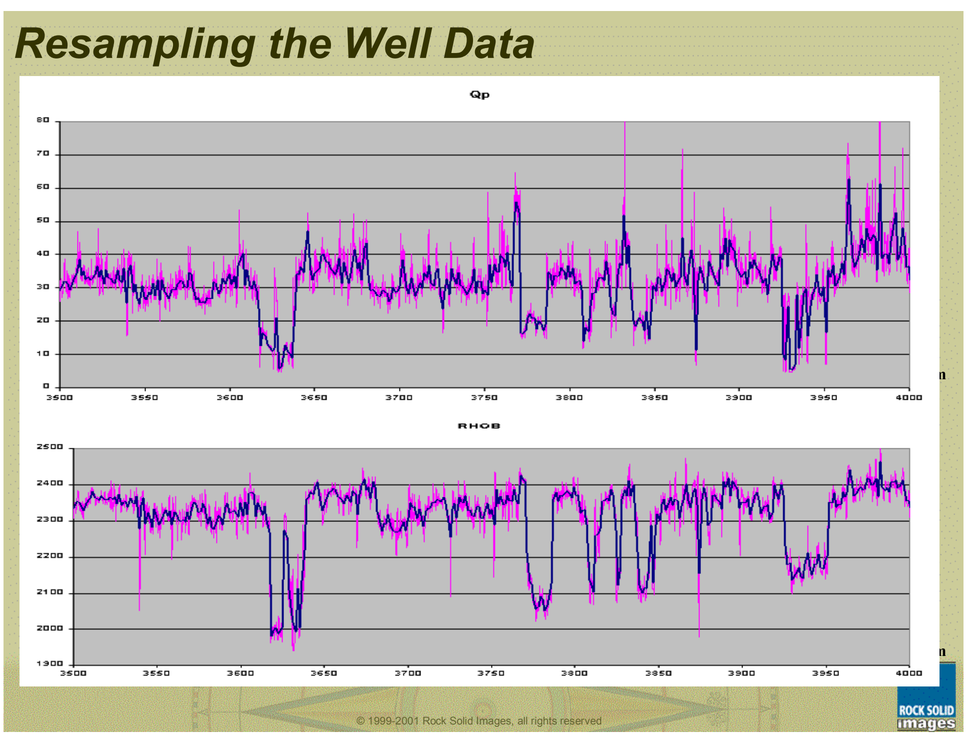

Figure 10. Comparing the original well log with the smoothed model.

In figure 10 we can see graphs of original and resampled/smoothed values of Qp (top plot) and RHOB (bottom plot). The original well log values are plotted in pink color. Vp plots look similar to RHOB. These plots illustrate the smoothing effect. The resampled model still contains more details than the normal incidence seismic wave is sensitive too. To illustrate this fact figure 11 display the resampled model compared with the well log upscaled to seismic resolution.

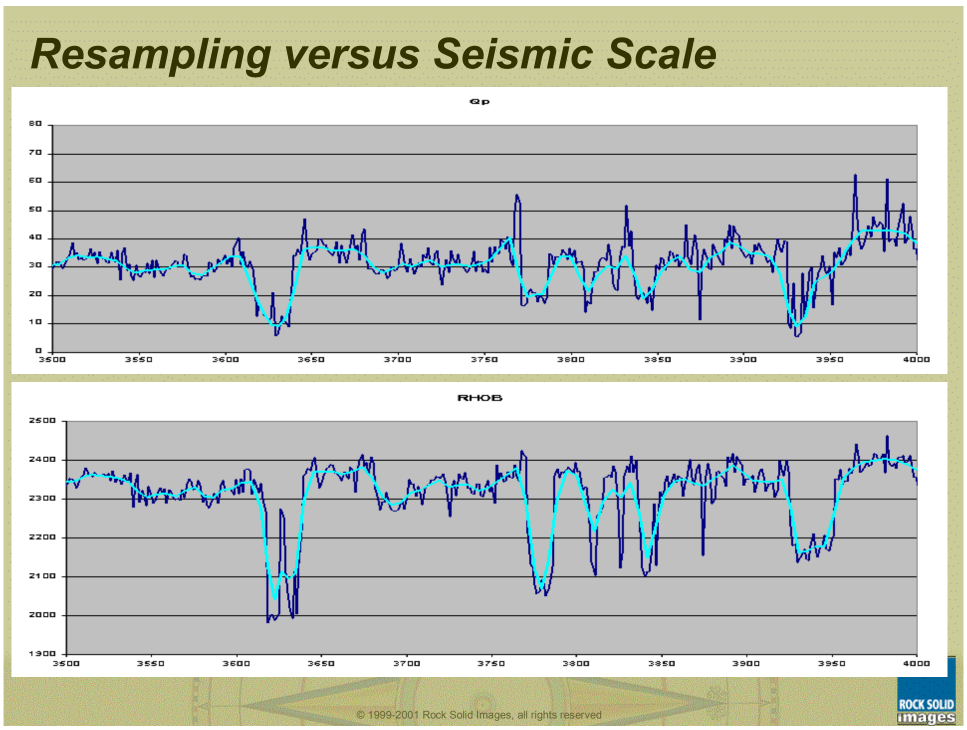

Figure 11. Comparing the original resampled model with the upscaled well.

The upscaling had been performed by adaptive Backus averaging within constant time intervals of 4 ms. The light-blue curve represents the upscaled well log and confirms the fact that the seismic wave effectively senses a much smoother medium, and therefore the resampled model retains more than enough detail.

As with the five-layer model, we computed synthetic seismic with the same acoustin parameters of the resampled earth model twice: with model Q (predicted Q values) and with high Q (a Qp=300 in all layers). Comparing these synthetic traces allows us to separate the effects of the acoustic impedance contrasts, including the "extrinsic", or scattering attenuation from the effects of intrinsic attenuation of the seismic waves in the model. The plots in figure 12 provide instantaneous amplitude comparison between synthetic traces with model Q (top plot) and high Q (bottom plot). Of interest to us is the comparison between the amplitude levels of the first reflection in the model (*R1*) (topmost wet sand) and the second reflection (*R2*) (gas sand). When the smplitudes are only defined by the acoustic impedance contrast (high Q case) the ratio between *R2* and *R1* is $R2/R1 \approx 2$, whereas with model Q $R2/R1 \approx 1.3$. The decrease of the relative amplitude of the gas sand reflection with model Q is caused by attenuation in the shale layer between those two sands, and has very little to do with the attenuation in the gas sand whatever its value is.

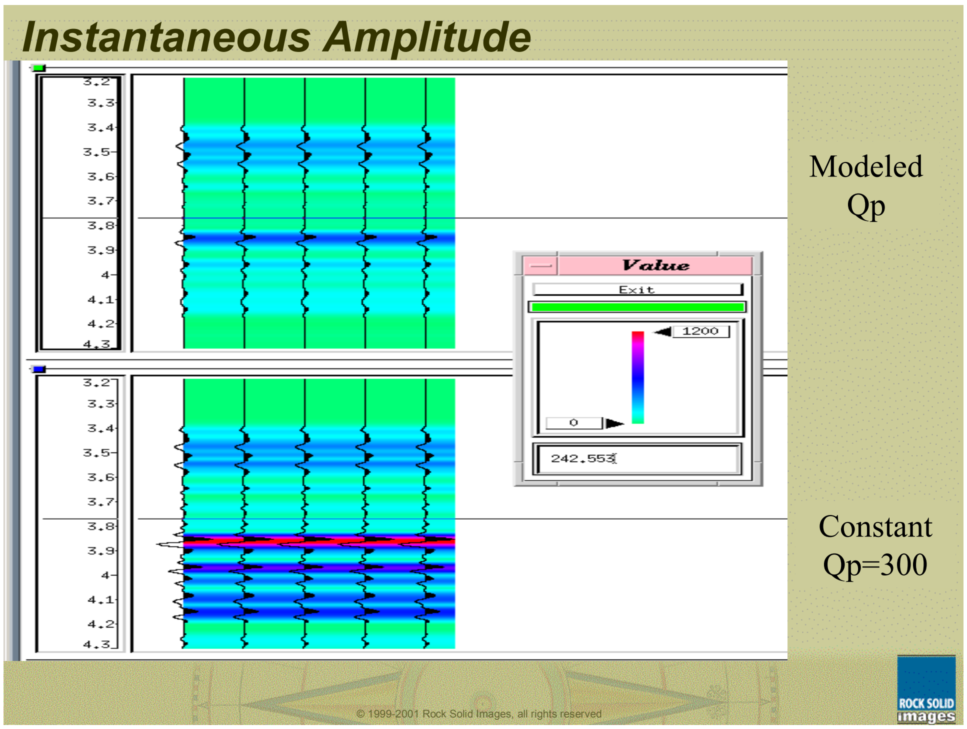

Figure 12. Instantaneous amplitude plots.

The frequency effects of attenuation are illustrated in figure 13, where the same synthetic traces are plotted on the background of color-coded dominant frequency.

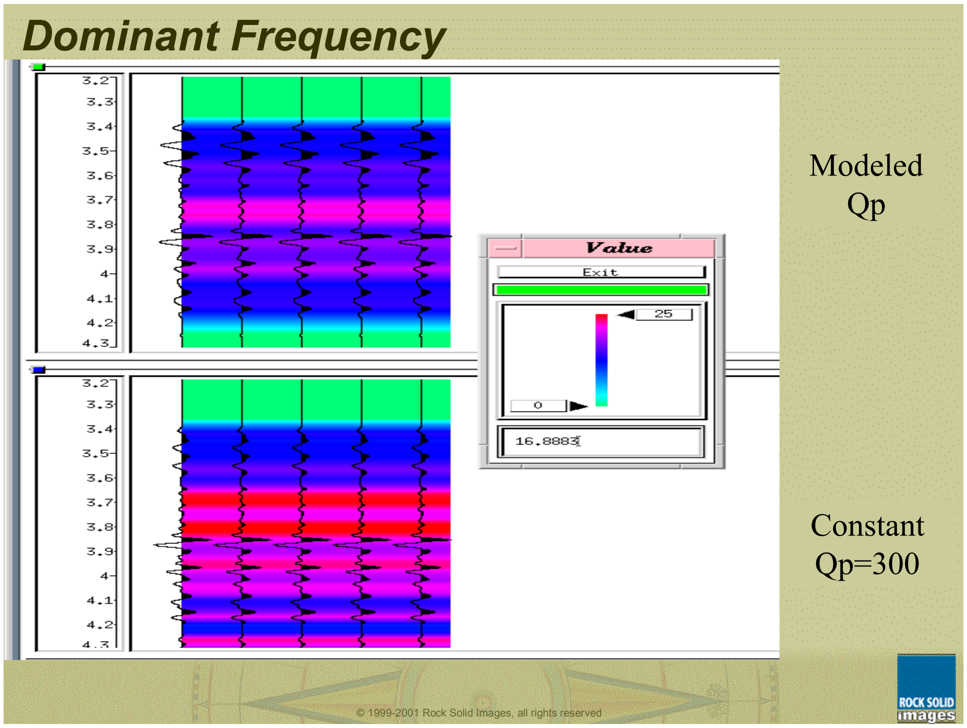

Figure 13. Dominant frequency plots.

The dominant frequency content of the seismic trace is affected by both extrinsic attenuation (e.g., interfering reflections within a pack of thin layers) and intrinsic attenuation. With high Q values only the extrinsic effects take place, and cause an increase in the dominant frequency. With model Q values the intrinsic attenuation causes the decrease of the dominant frequency with time, which is the effect usually observed in real seismic.

Considering the difference that model Q values make on synthetic we can expect that the synthetic with model Q values will come considerably closer to the real seismic than the synthetic with high Q values (conventional synthetic).

Figure 14 allows us to compare the two synthetics (model Q and high Q) with the real seismic trace. To ease the identification of various reflections on the synthetic and real seismic traces, the Vp curve is displayed at the top of the plot.

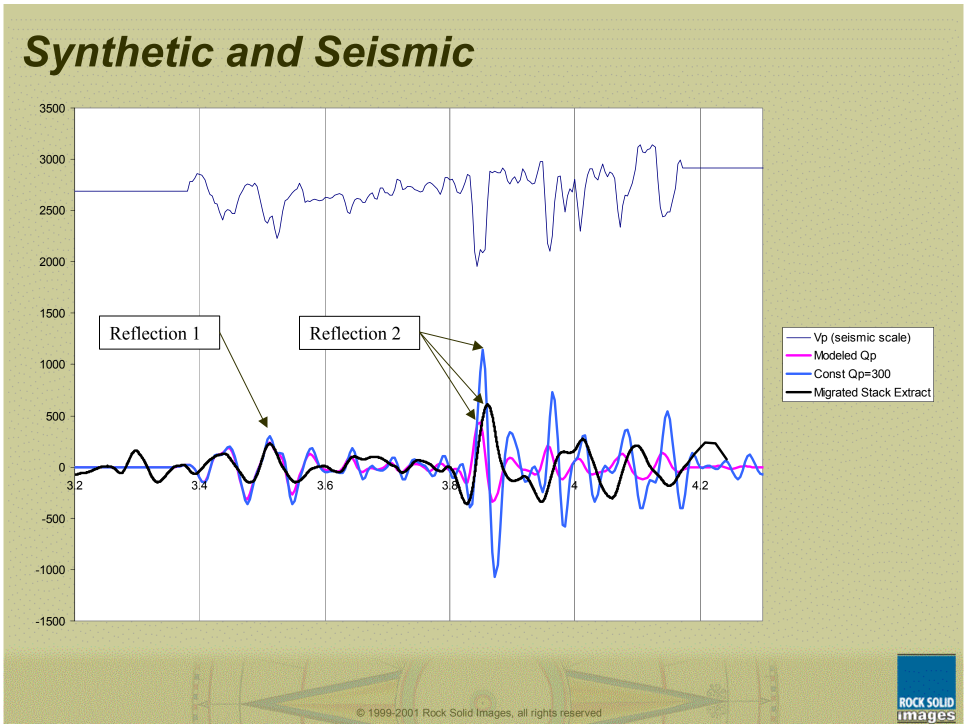

Figure 14. Comparison between synthetic and real seismic reflection amplitudes.

We can see, that though the amplitude of reflection 1 is the same for all three traces, reflection 2 on the synthetic trace with high Q (light blue curve) is much higher than the reflection amplitude on the real seismic trace (black curve), while the amplitude of reflection 2 on synthetic trace with model Q (pink) is much closer to it. This comparison confirms that including model Q values in the synthetic computations provides a better synthetic-to-seismic match. It also confirms that the predicted Q values are reasonably close to the Q values in the real rocks.

Well 1 fluid substitution

To study how the synthetic traces change with changing fluids, a pseudo-well was constructed from well 1 by replacing gas with brine in the gas sand. The elastic properties and Q values had been predicted in the pseudo-well via rock physics modeling. Then the synthetic traces were computed with the high Q and model Q values.

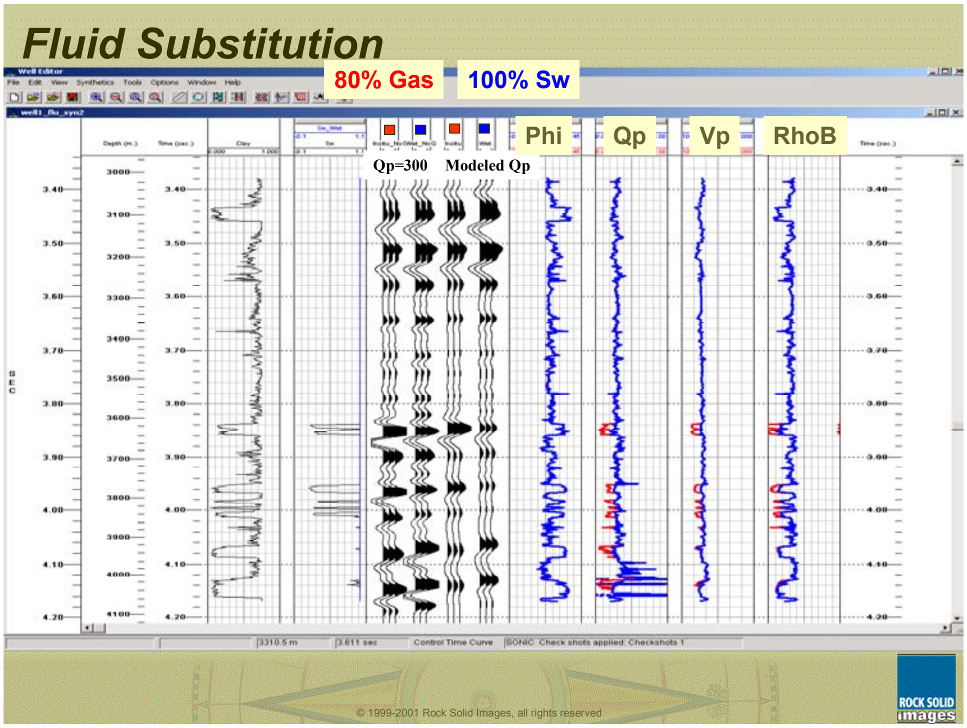

Figure 15. Synthetic computations with fluid substitution

Figure 15 presents the pseudo-well curves and synthetic traces. The in-situ curves and traces are color-coded red, the fluid-substituted ones are color-coded blue. Substituting gas with brine eliminates the attenuation and Vp anomaly associated with the gas sand, but still leaves an anomaly in bulk rock density, which produces a reflection from the sand, though weaker than the reflection from the in-situ case. This effect is visible on both high Q and model Q synthetic traces. However, the correlation coefficient between the two high Q synthetic traces (for in-situ and brine filled wells) is 0.58, while for the model Q it is 0.7. In other words, fluid substitution causes greater changes in the synthetic traces when attenuation is not included in the synthetic computations. It means that at least in this case, the seismic is less sensitive to the fluid change than it could be expected from the analysis of conventional synthetics.

Well 1 porosity modeling

We constructed two additional pseudo-wells from well 1 by replacing the in-situ porosity values in sands with values 5% high (Hi) and 5% lower (Lo). The acoustic parameters and Q values were computed for each pseudo-well via rock physics modeling, and synthetic traces computed with the model Q and high Q values for each pseudo-well. The results are presented in Figure 16. Increasing porosity in this case did not seem to produce a noticeable effect on attenuation and elastic parameters, which resulted in little changes between in-situ and high porosity pseudo-well synthetic.

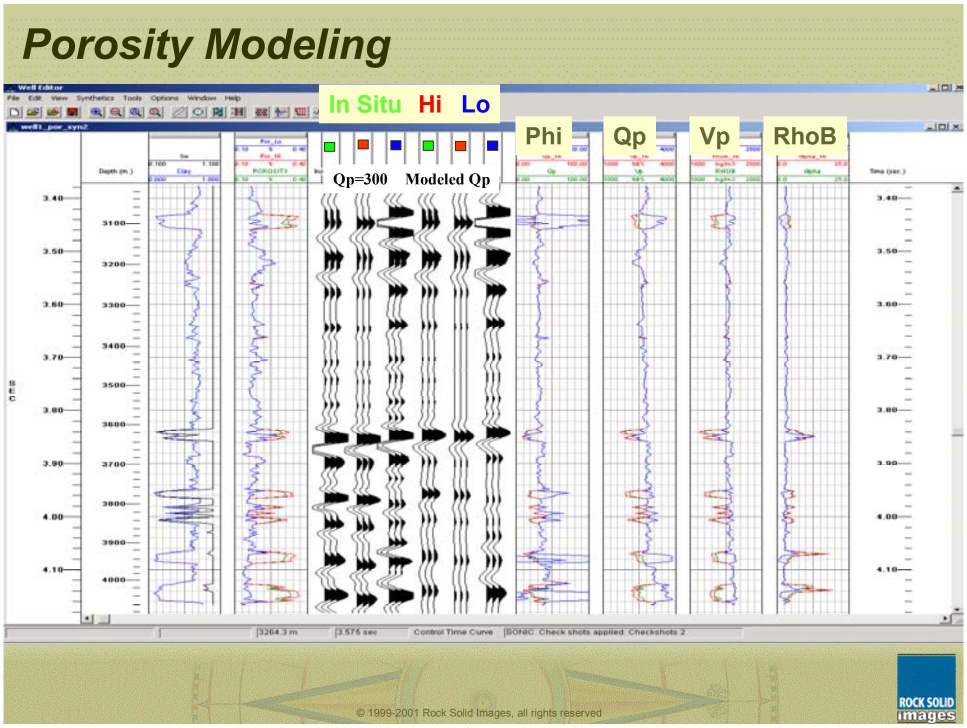

Figure 16. Synthetic computations with porosity modeling

Lowering the porosity, on the other hand, drastically increased the acoustic impedance and Q in wet sands, while having pretty small effect on the gas sand. The resulting synthetic trace differs considerably from the in-situ synthetics, especially in the wet sands.

WORK PLANNED FOR NEXT PERIOD

We will continue to test our, rock physics, synthetic seismic, and seismic absorption attributes on the Burlington-Seitel data set we have obtained. We will also show some results, on absorption computed from full waveform sonic log data.

PROBLEMS ENCOUNTERED THIS PERIOD

No significant problems have been encountered in our work so far. The only exception is that we have not had as many contributed data sets from industry as we had anticipated.

One reason may be that the data quality requirements during this testing phase are fairly stringent. Fortunately, we have the Burlington-Seitel data, which seems to be very acceptable.