Evaluation of an Inelastic (Q) Synthetic Seismic Generator

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Summary

A large number of Q algorithms exist for both Q prediction and Q compensation which require analysis using both real and synthetic seismic data. A methodology was devised to check the accuracy and validity of these algorithms, and is dependent on the creation of a reasonably accurate Q log and an accurate synthetic which shows the effects of various wave propagation phenomenon.

This paper shows results of testing the synthetic algorithm, which is a necessary prelude to evaluating the effectiveness and robustness of Q prediction algorithms.

Using a rigorous process for log correction and the appropriate rock physics models, a suitable log suite was prepared for usage in this experiment. Dvorkin's Heterogeneous Q model was then applied to create a Q log. This input data was used to create several full waveform, normal incident Kennett synthetics, each showing a different wave effect or fluid case. These were then quantitatively analyzed.

Introduction

Research and development of algorithms to measure and compensate for the effects of attenuation in seismic data have been ongoing for several decades. Taner and Treitel (2005) have tabulated approximately 14 Q estimation methods and 2 Q compensation methods. This list will most likely grow further as symposiums and workshops discuss attenuation.

The requirement is therefore apparent to have a methodology in place to objectively test and evaluate these different methods, but a more necessary requirement is to evaluate the synthetic generator prior to testing the algorithms.

Method

Although the process contains many steps, there are two fundamental concepts involved:

- The creation of a Q log.
- The creation of a seismic synthetic that accurately reflects seismic effects, including attenuation.

An appropriate Q log was created using Dvorkin's Heterogeneous Q Model (Dvorkin & Uden, 2004). Accurate synthetics were created using Kennett's full elastic wave solution for the normal incident case (Kennett, 1974; Kennett & Kerry, 1979).

The process includes the following steps:

1. Identify a suitable well log suite and seismic data set.
2. Properly condition the logs so that they are self-consistent and conform to a rock physics model appropriate for the depositional environment.
3. Calculate a Q log for the in-situ case and various fluid substitution cases.
4. Calculate synthetics for each fluid case. Each case should contain a suite of synthetics with various combinations of possible wave propagation effects.
5. Analyze and quantify the changes in seismic reflectors in each of the above cases.

This will provide a baseline from which Q compensation and Q estimation algorithms may be tested.

Results

The data set chosen for the development of this methodology is in the deep Gulf of Mexico and contains distinct, well-separated sands (Figure 1). Wet sands and pay sands are present, as well as a fining-upward, shaly sand that contains residual (fizz) gas. The seismic data are clean and well imaged, and tie the synthetics and VSP very well.

Well Log Data: The well data were conditioned using a process called Geophysical Well Log Analysis (GWLA®). This process is performed to ensure all curves are passed through a consistent and rigorous conditioning prior to synthetic seismic modeling. Standard processes include corrections for environmental conditions, borehole rugosity, mud filtrate invasion, tool malfunctions such as cycle skips or stick & pull, and the computation of missing curve data.

Rock Physics Diagnostics (RPD) is an integral part of this process. It establishes rock physics models that relate the elastic properties to lithology, thickness, porosity, and fluid properties. This is particularly important for the geophysically-important log curves (Vp, Vs, and density). In this well, the following summarizes the rock physics model most appropriate for this depositional environment:

Pore Fluid Properties: The density and bulk moduli of water, oil, and gas were chosen to be constant in the entire interval under examination. The density of water, oil, and gas were 1.0157 g/cc, 0.7071 g/cc, and 0.2679 g/cc, respectively. The bulk modulus of water, oil, and gas were 2.8795 GPa, 0.8283 GPa, and 0.1472 GPa, respectively.

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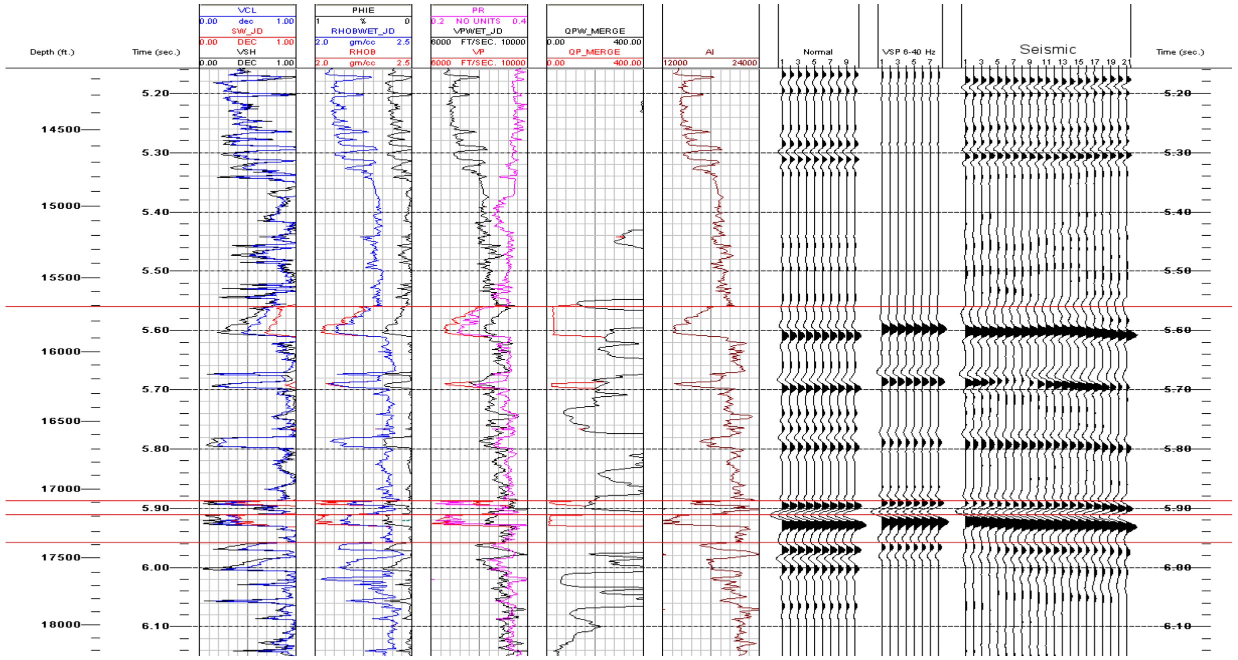


Figure 1: Lower portion of subject well showing zone of interest. Calculated Q logs are in panel 4 (black = wet case, red = insitu case). Normal incident, ray-trace synthetic is in panel 6, and VSP (6-40 Hz) in panel 7. No alterations to the log interval velocity (i.e., "tying") have been performed so that phase relationships are not inadvertently altered.

The original system in the well was water/gas. The bulk modulus of the pore fluid (K_f) was calculated as the harmonic average of those of water (K_w) and gas (K_g), weighted by water saturation S_w:

$$\frac{1}{K_f} = \frac{S_w}{K_w} + \frac{1-S_w}{K_g}. \qquad (1)$$

The density of the pore fluid (ρ_f) was the arithmetic average of those of water (ρ_w) and gas (ρ_g), weighted by S_w:

$$\rho_f = S_w \rho_w + (1-S_w)\rho_g. \qquad (2)$$

Porosity: The total porosity (ϕ) was calculated from the bulk density (ρ_b) by assuming that the bulk density is that of the virgin formation with water saturation given by S_w.

It was also assumed that the density of the mineral phase (ρ_s) was 2.65 g/cc and constant throughout the entire interval. Then, from mass balance, the total porosity was:

$$\phi = \frac{\rho_s - \rho_b}{\rho_s - \rho_f}. \qquad (3)$$

Elastic Model: The elastic model used in the entire interval was the uncemented (soft) sand model. It was assumed that the mineralogy was quartz and clay, and that other minerals were nonexistent. The differential pressure was fixed at 50 MPa, the critical porosity at 0.36, and the coordination number at 8. The fudge-factor (the reduction factor for the tangent ional contact stiffness between the grains) was 1; that is, the Hertz-Mindlin contact model (Mavko, et. al., 1998) was not corrected.

Fluid Substitution: Fluid substitution was conducted using the P-wave-only Mavko-Gassmann method (Mavko, et. al., 1998). The compressional modulus of the solid phase was calculated from those of quartz and clay according to Hill's average (Mavko, et. al., 1998).

Attenuation Modeling: The maximum possible inverse quality factor was calculated according to Dvorkin's Heterogeneous Q model (Dvorkin & Uden, 2004). One important input used in this calculation was the irreducible water saturation (S_{wirr}). S_{wirr} was assumed to be a constant 0.05 where the interval contained commercial gas saturation (i.e., 17,000-17,300 ft). However, where residual gas intervals were located (15,500-16,500 ft), S_{wirr} was set at 90% of the actual water saturation: $S_{wirr} = 0.9 S_w$.

The above selection of the irreducible water saturation is somewhat arbitrary and serves the purpose of qualitatively matching the presumably recorded fact that the attenuation in the residual-gas interval was smaller than in the commercial gas interval. (Theory calls for low gas saturations [“fizz gas”] to have a larger attenuation than high gas saturations if S_{wirr} is fixed; Cadoret, 1993; Murphy, 1982).

The physical rationale for this is the shaley character of the residual-gas sand and the resulting abundance of small shale particles, large capillary forces, and small permeability (Dvorkin, 2005).

Kennett Seismic Synthetics: The synthetic generation algorithm chosen to model the seismic response was the Kennett algorithm (Kennett, 1974; Kennett & Kerry, 1979; Mavko, et. al., 1998). This algorithm is a 1-D (i.e., plane wave) full elastic wave solution to a propagating wave front. We chose to implement only the normal incidence case in this initial study (full offset synthetics will be introduced at a later date). Nevertheless, the elastic solution contains all effects occurring at normal incidence, such as multiples, transmission losses, and attenuation. The algorithm assumes homogeneity and thus does not model anisotropy. Since it is a vertically propagating plane wave, it also does not contain energy loss due to spherical divergence.

The algorithm computes a number of cases (Figure 2). The user may choose multiples or no multiples, Q or no Q, and for the cases with Q, dispersion or no dispersion. By dispersion we mean velocity-frequency dispersion, which has to accompany attenuation according to the causality principle. Therefore, strictly speaking, dispersion has to always be included if Q is modeled. However, algorithmically we have an option of testing the code with Q but without dispersion.

In the in-situ case (Figure 2), multiples do not cause a large amount of interference, primarily being confined to the zone below the main pay zone (5.9 sec). There is also a large amplitude reduction with Q, particularly in the pay zone (panel 1 vs. 2). This is the result of absorption. Dispersion is present, but is a secondary factor that needs to be measured more precisely to discern its effects.

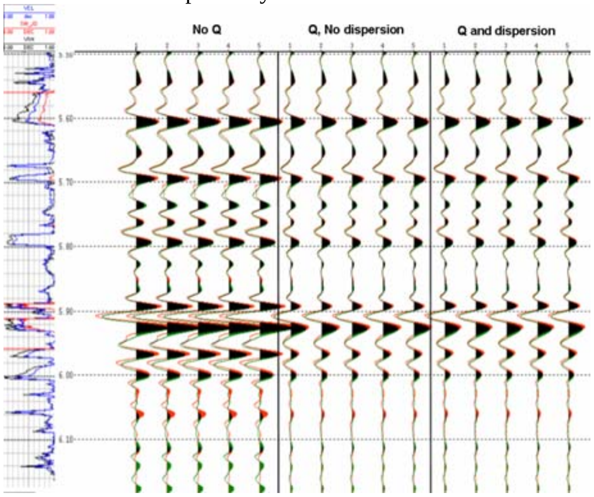


Figure 2: Kennett synthetics for “in-situ” case. Various “Q” states are shown in the panels (no Q: left, Q without dispersion: center, Q + dispersion: right), while the “multiple” state is shown in overlay (red = no multiples, green = multiples, black = both). Vsh log panel shown on left column for reference.

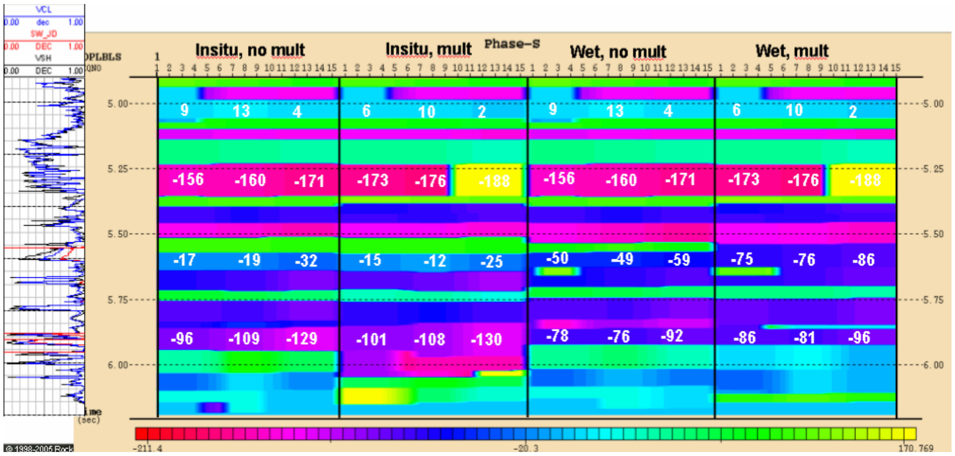
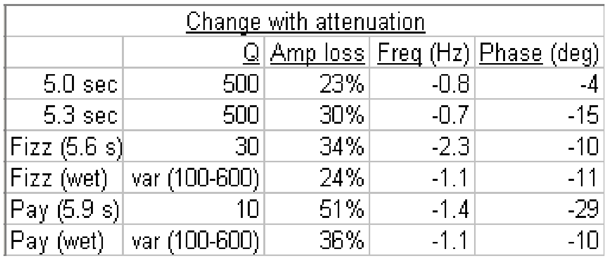


Figure 3: Wavelet phase attribute plot for all synthetics. Main groupings of synthetics are labeled at top of page. Within each group are 3 different sets of 5 traces each. These sets are the same groups as are shown on Figure 2 (i.e., no Q, Q without dispersion, and Q + dispersion).

The wet case shows some amplitude reduction, indicating that a small amount of attenuation is taking place, but both multiples and dispersion are minimal, as we would expect.

Measurement of Changes in Synthetic with addition of Q: To quantify changes in the character of the Kennett synthetic with the addition of various wave propagation effects, we used "wavelet attributes". These are instantaneous attributes measured at the maximum points in the trace envelope (Taner, 1992). This is the point where the majority of the energy from different frequency bands is in phase. These values are displayed over the length of the envelope, defined as the time span between two adjacent envelope minima (Figure 3).

The wavelet attributes showed there was a progressive loss in amplitude and frequency with depth after the application of Q (the quality factor was set at a non-zero, arbitrary value of 500 from the surface to 5 seconds), and that this loss increased if hydrocarbons were present (Table 1), particularly in the reservoir zone (with a Q factor of 10).



Change with attenuation				
	Q	Amp loss	Freq (Hz)	Phase (deg)
5.0 sec	500	23%	-0.8	-4
5.3 sec	500	30%	-0.7	-15
Fizz (5.6 s)	30	34%	-2.3	-10
Fizz (wet)	var (100-600)	24%	-1.1	-11
Pay (5.9 s)	10	51%	-1.4	-29
Pay (wet)	var (100-600)	36%	-1.1	-10

Table 1: Changes in seismic synthetic with addition of attenuation. General progressive loss is evident with increasing depth, with anomalous changes in pay zone. Wet values are generally significantly less than in-situ values.

The wavelet phase attribute increased to about 10 degrees below 5 seconds and remained there for all cases and zones except when very high attenuation was present (Table 1 and Figure 3). In the in-situ reservoir zone, the Q factor was 10 and the resulting phase rotation increased to 30 degrees.

Conclusions

Normal incident synthetic seismograms were generated from an appropriate log suite including a computed Q log. Various propagation effects were modeled for different sand lithologies and saturations.

Analyzing the amplitude, phase and frequency responses of these synthetics and their variations showed that the effects of the Q model and a layered earth were consistent with those expected for these types of lithologies and saturations.

Validating the inelastic synthetic generator provides the background for evaluating the Q prediction algorithms for a number of different cases, using a combination of VSP data, seismic data and computed Q log data.

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