Physical modeling I : reflections off a low-Q material

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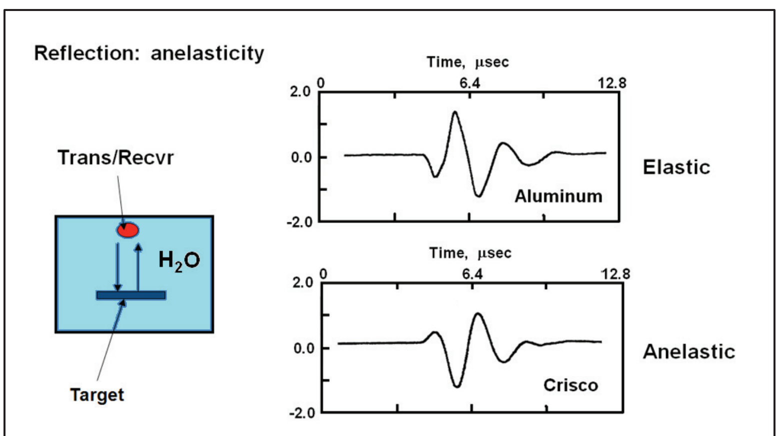
ABSTRACT

This report gives experimental verification of the theoretical prediction that seismic reflections can be created due to Q contrasts. We have acquired near-zero offset ultrasonic seismograms over aluminum and Crisco blocks immersed in water. Aluminum is a high-Q material whose acoustic impedance is large compared to that of water. Unaltered Crisco (lard) is a low-Q material whose impedance is very similar to that of water. In our data, reflections off the aluminum and unaltered Crisco have large and almost equal amplitudes, even though one would expect the water-unaltered Crisco reflection to be weak because of the small impedance contrast. This observation is consistent with previous physical modeling results and with theoretical predictions. After melting and re-solidification, Crisco changed from a low-Q material to a higher-Q material, but its density and P-wave velocity remained practically the same. Reflections from the altered Crisco in water were weaker than those for the unaltered Crisco, but were still much stronger than predicted by the almost negligible impedance contrast with water. Numerical seismograms produced from a reflectivity code that is able to simulate the effects of Q in stratified layers also show strong reflections caused only by large contrasts in Q on the reflecting interface.

INTRODUCTION

Theoretical considerations predict that reflections with significant amplitude should occur on boundaries between media with different attenuation characteristics even if the velocity-density contrasts are small (Lines et al., 2007; Morozov, 2011; Innanen, 2011). Bourbie and Nur (1984) presented physical modeling evidence that attenuation (or Q) affects the amplitudes of reflections.



material	density	Vp	Zp	Rp
water	1	1.47	1.47	0
aluminum	2.65	6.39	16.93	-0.84022
crisco	0.98	1.49	1.46	0.003413

FIG. 1. Reflections off water-aluminum and water-Crisco interfaces (courtesy Carl Sondergeld).

Figure 1 is from Carl Sondergeld (personal communication), and it shows ultrasonic reflections arising from water-aluminum and water-Crisco boundaries (Crisco is the brand name of a lard product commonly used in baking). As indicated on the figure, the P-wave velocity and density of lard are almost identical to those of water. Therefore, one expects that the amplitude of normal incident reflections from the water-Crisco boundary would be very weak. However, the traces displayed on Figure 1 show that both the water-aluminum and water-Crisco interfaces produce reflections with almost equally strong amplitudes. Crisco, unaltered and straight out of its store-shelf packaging, is a highly attenuating material, that is, its acoustic Q is very low. Water, however, has very low attenuation at all acoustic frequencies (in oceanographic tomography, sound waves are transmitted and received over distances of thousands of kilometers). According to Toksöz and Johnston (1981; page 124), the Q of fresh water for signals at 100 kHz is 210,000. The Q at similar frequencies for aluminum is also very high, with a value on the order of 200,000. Since the only strongly-contrasted acoustic property between water and Crisco is the attenuation, we conclude that the large reflection amplitude from the water/Crisco boundary must be due to the attenuation contrast.

DATA ACQUISTION

We conducted measurements to replicate Sondergeld's results using the University of Calgary Seismic Physical Modeling Facility. Figure 2 shows the experimental setup for these measurements. An aluminum block and a block of unaltered Crisco lard were immersed in water. Common offset gathers (offsets = 10 mm) were acquired in a line over the centres of the blocks using piezopin transducers whose active tips are located on the surface of the water.

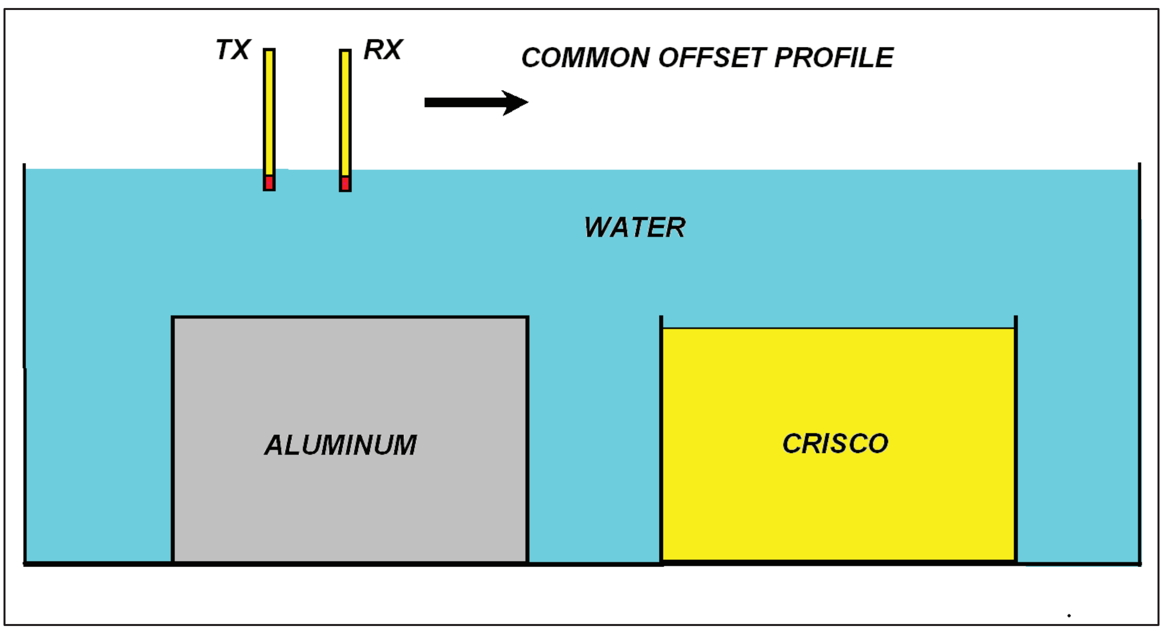


FIG. 2. Acquisition of ultrasonic seismograms over aluminum and Crisco blocks immersed in water. The transmitting and receiving transducers (labeled TX and RX) produce signals with dominant frequencies of about 500 kHz.

We repeated the measurements using melted and re-solidified Crisco in place of the original unaltered Crisco. The velocities and densities of the unaltered and altered Crisco were quite similar, but based on reflection amplitudes (reported below), the Q for altered Crisco must be much higher.

The dimensions of the aluminum block were 101.6 mm by 101.6 mm by 50.8 mm in the depth dimension. For the block of unaltered Crisco, the dimensions were approximately 130 mm by 60 mm by 60 mm in the depth dimension. The block of altered Crisco was 135 mm by 135 mm by 40 mm in the depth dimension. For Figure 3, the depth to the top of the aluminum was about 91 mm, while the depth to the top of the unaltered Crisco was about 93 mm. For Figure 4, the depth to the top of the aluminum was about 81 mm, while the depth to the top of the altered Crisco was about 86 mm.

Velocity and density values for aluminum and Crisco

We have measured the P-wave velocities and densities of the blocks of aluminum and Crisco. The measured velocity and density values and the calculated acoustic impedances of the samples are shown on Table I; they differ slightly from Sondergeld's values shown on Figure 1 (such small differences are not unexpected for different samples measured using slightly different techniques).

TABLE I. Measured velocity and density values.

Material	V_p ,m/s	ρ, kg/m3	Impedance, ρV_p	R_{pp}
Aluminum	6300	2650	16.7×10^6	.837
Unaltered Crisco	1630	970	1.581×10^6	0.031
Altered Crisco	1540	970	1.494×10^6	.003
Water	1485	1000	1.485×10^6	0

We also attempted to estimate the Q's for unaltered and altered Crisco (see Appendix A). Altering the lard by melting it and allowing it to re-solidify changed its seismic properties. For example, the velocity through the re-solidified Crisco has a P-wave velocity slightly below that of the unaltered Crisco. The density remained largely unchanged. We will see that the estimated seismic attenuation or Q also changed.

Reflection seismograms

To record reflections from the water-aluminum and water-Crisco interfaces, we acquired a common offset gather as shown on Figure 2, with the source-receiver offset fixed at 10 mm. The piezopin transducers in water produce acoustic signals with dominant frequencies near 500 kHz. Figure 3 is a constant-gain gray-scale display of the gather with unaltered Crisco. It shows that the reflections off the aluminum (event A on the Figure) and the Crisco (event B) have similar amplitudes.

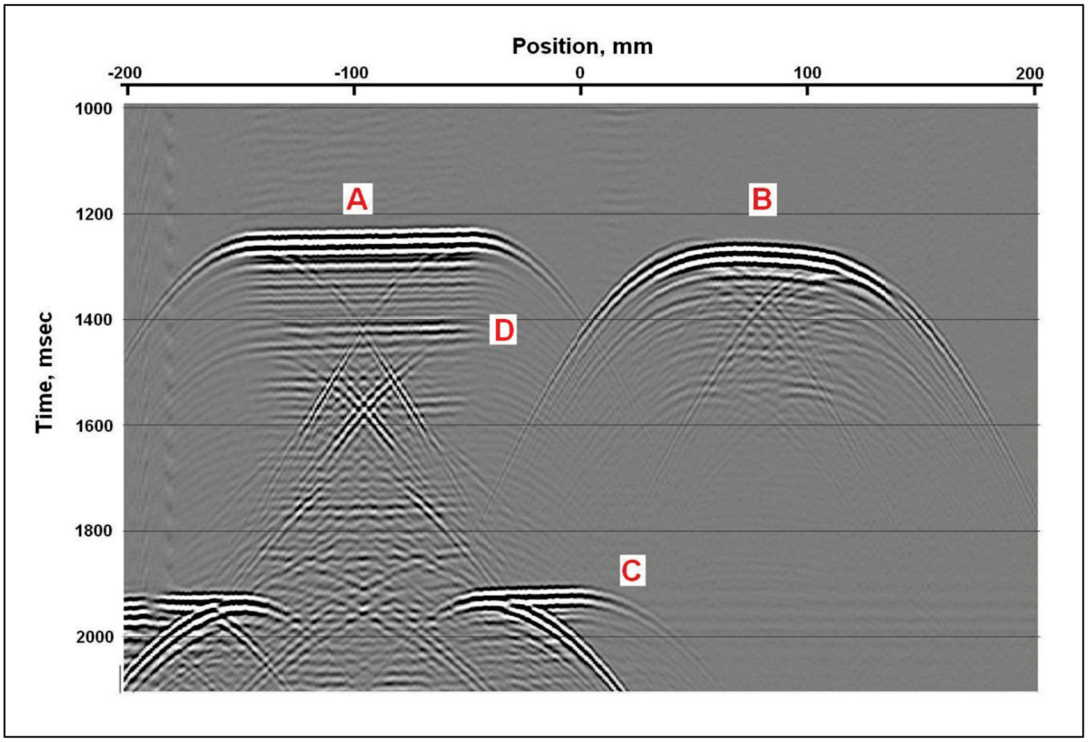


FIG. 3. Common offset gather over aluminum and unaltered Crisco Immersed in water.

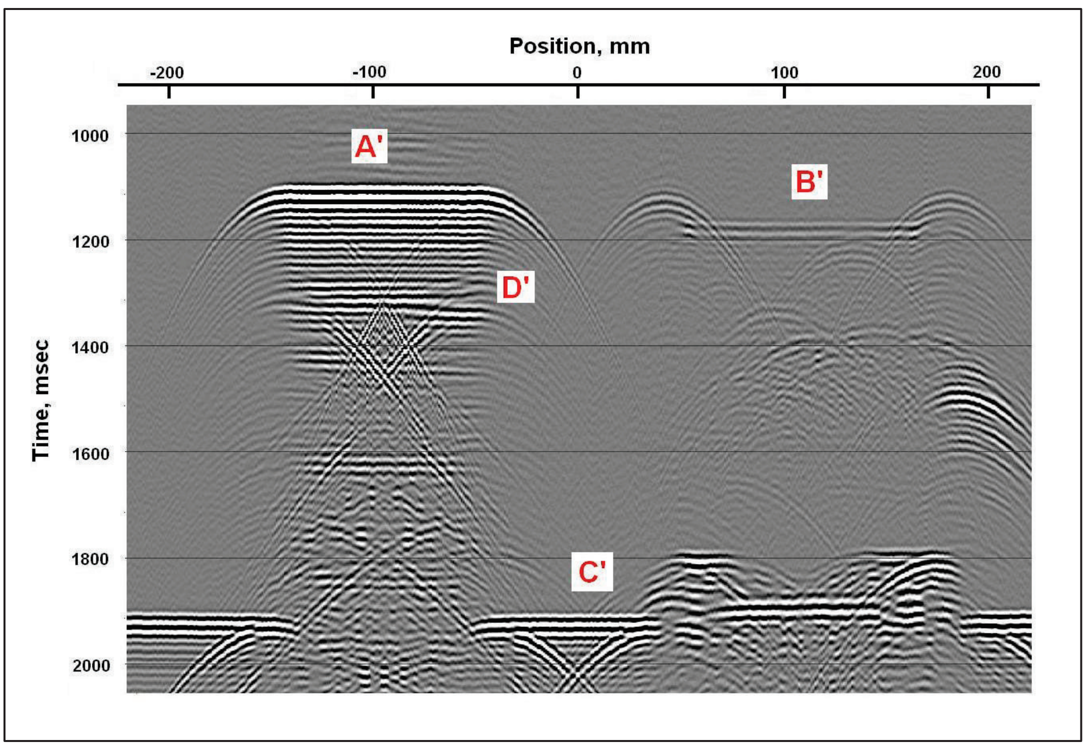


FIG. 4. Common offset gather over aluminum and altered Crisco Immersed in water.

Event C is the reflection from the surface on which both blocks rest. Event D is the reflection off the bottom of the aluminum block, and though it is very weak (because most of the down-going energy has been reflected by the top surface), it is nevertheless present. No similar reflection Event E from the bottom of the Crisco block can be seen; it seems that any acoustic energy that has entered the lard has been highly attenuated.

Figure 4 is a similar fixed-gain gray-scale display, but the common offset gather in this case is over aluminum and altered Crisco immersed in water. The depths in water to the tops of the blocks are different from those for Figure 3, and the lateral dimension of the altered Crisco is larger. Reflections off the water-aluminum (event A') and the water-Crisco (event B') interfaces are readily discernible, but the reflection amplitudes off the water-Crisco interface are significantly weaker. In contrast to the case for unaltered Crisco, there is now a strong reflection (Event C') due from the bottom of the Crisco block. The interpretation is that acoustic attenuation through altered lard is much less than that for unaltered lard, where there is no observable reflection off the bottom of the lard block (see Figure 3).

To the left of the bottom of the lard, at positions near C' corresponding to the gap between the aluminum and lard blocks, we see a reflection with a small pull-down. This reflection is due to the surface on which the aluminum and lard blocks rested. The pull-down is due to the difference in velocities of water and lard. We can measure the difference in times between the top of the lard arrivals and the two arrivals near C'. The time through water in the gap t_w is about 74.9 μs, while the time t_c through altered Crisco is about 70.5 μs. The ratio t_w/t_c is about 1.06, and is very close the velocity ratio v_c/v_w = (1540 m/s)/ (1.485 m/s) = 1.04.

ANALYSIS AND RESULTS

From Figures 3 and 4, several traces over the centres of the aluminum (events A and A') and Crisco (events B and B') blocks were aligned according to the reflection times, windowed, and summed to produce average reflection traces. On Figure 5, these average traces (plotted in red) are compared with Sondergeld's traces (plotted in black).

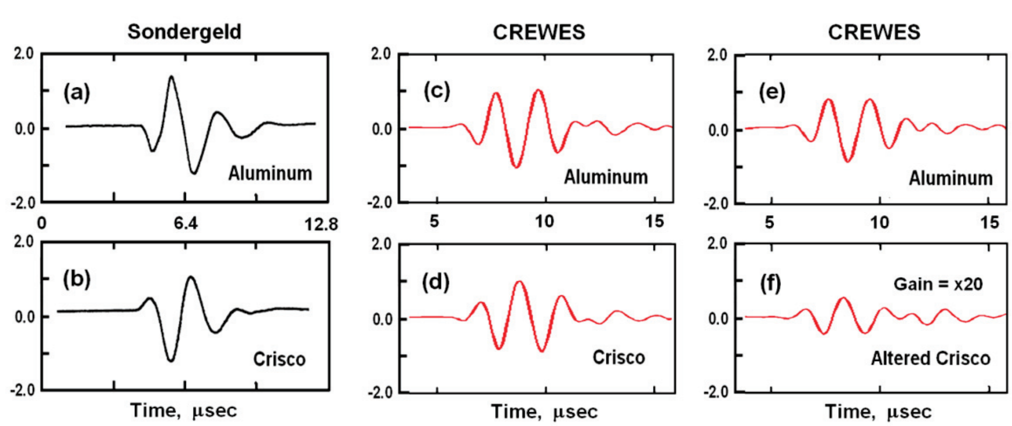


FIG. 5. Comparison of reflected wavelets off aluminum and Crisco immersed in water. CREWES results are shown in red. Sondergeld's results are shown in black.

The Sondergeld traces are displayed on Figure 5a and 5b. Figures 5c and 5d show the average traces over aluminum and unaltered Crisco, and they have very similar relative amplitudes in agreement with Sondergeld measurements. The average traces for aluminum and for altered Crisco are plotted on Figures 5e and 5f, and they show that the reflected amplitude off altered Crisco is only a small fraction of the reflected amplitude off aluminum. For both the Sondergeld and the CREWES reflected wavelets, there is a clear phase shift between the aluminum and Crisco reflections.

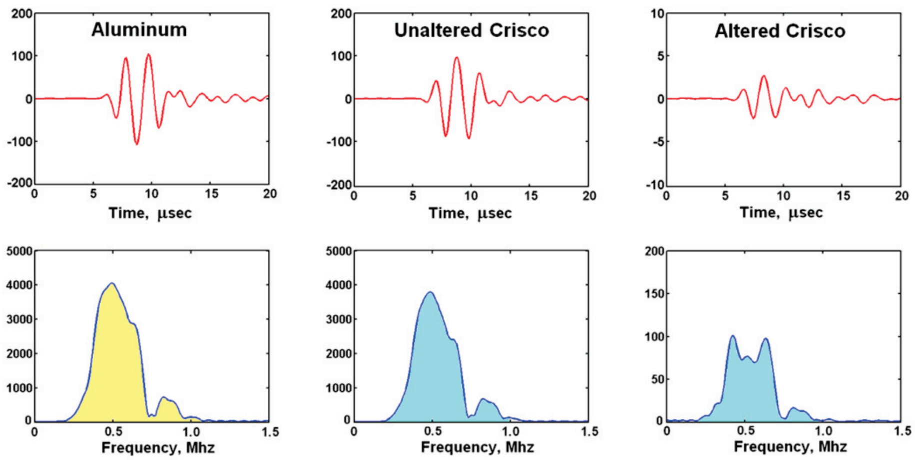


FIG. 6. CREWES-measured reflected wavelets and their amplitude spectra.

Figure 6 displays the reflected wavelets off the water-aluminum and water-Crisco interfaces and their amplitude spectra from the CREWES experiment. The vertical scales give an accurate measure of the relative amplitudes for aluminum reflections and for the Q-induced reflections for Crisco. Comparing the maximum peak-to-trough excursions, we find that the ratio of amplitudes of unaltered Crisco reflections (event B on Figure 3) to aluminum reflections (event A on Figure 3) is about 0.83. For altered Crisco, this ratio is about 0.047, almost 18 times less than the corresponding ratio for unaltered Crisco and aluminum. Since the velocity and density of Crisco did not change materially because of melting and re-solidification, we conclude that the dramatic decrease in reflection amplitude between unaltered and altered Crisco must be caused by a large increase in Q.

SYNTHETIC SEISMOGRAMS FROM A REFLECTIVITY CODE

Using reflectivity code originally published by Redman et al. (1992) and subsequently updated by Ma (2003), we have produced synthetic seismograms to simulate reflections over the water-aluminum and water-Crisco interfaces. The algorithm implemented by the code models the seismic responses of horizontally-stratified earth structures with many layers, each having its own thickness, density, Q value, and elastic wave velocities. In their code, Rudman et al. (1992) used the Q formulation presented by Strick (1970).

Synthetic near-offset traces showing reflected wavelets from a "water-water" boundary are plotted (with fixed gain) on Figure 7. The interface is located at a depth of 500 m, and the two water layers have identical P-wave velocities and densities. The top water layer has Q = 5000, and the figure shows how the reflection amplitudes increase as the Q of the bottom layer decreases to 100, 10, 3, and 1, respectively. The reflectivity code predicts that large-amplitude reflections occur off boundaries with large contrasts in Q even if the velocity and density contrasts are zero.

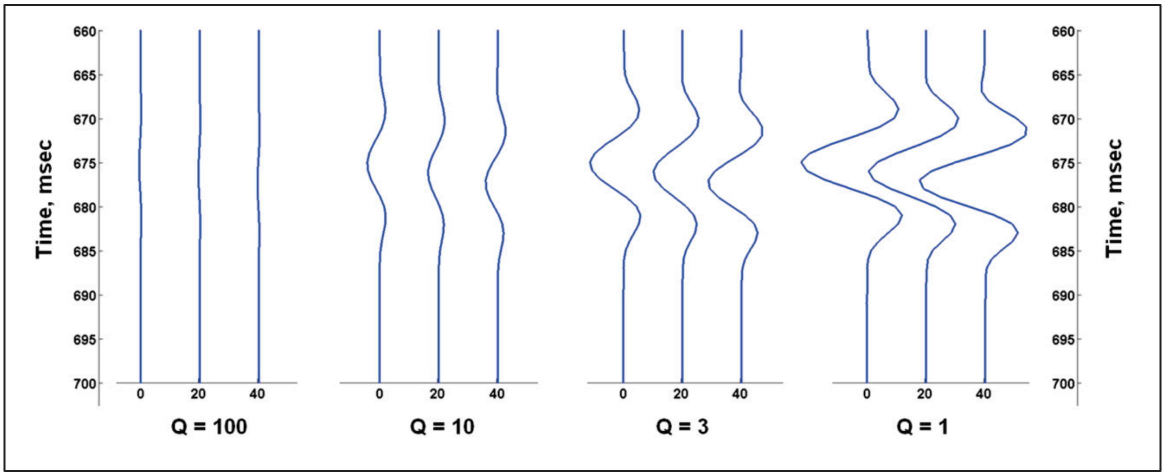


FIG. 7. Vertical-incidence reflection wavelets calculated using the reflectivity code for an interface between two media. Both media have V_p = 1510 m/s and ρ = 1000 kg/m^3. The top medium has Q = 5000; the bottom medium has Q varying from 100 to 1.

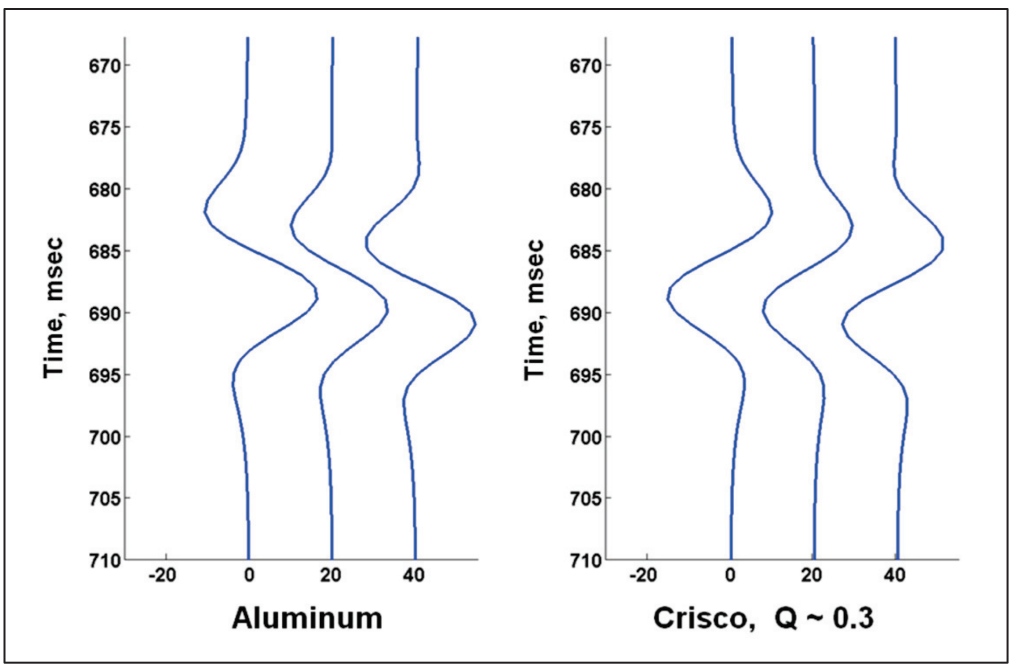


FIG. 8. Synthetic reflected wavelets for water-aluminum and water-Crisco interfaces at 500 m depth. For water, V_p = 1485 m/s, ρ = 1000 kg/m^3, Q = 5000. For aluminum, V_p = 6300 m/s, ρ = 2650 kg/m^3, Q = 5000. For Crisco, V_p = 1630 m/s, ρ = 970 kg/m^3, Q = 0.3.

Figure 8 compares the synthetic wavelets reflected off a water-aluminum interface and a water-Crisco interface. With Q = 0.3 for Crisco, the peak-to-trough amplitude of the wavelet off the water-Crisco interface is virtually identical to that of the wavelet off the water-aluminum interface, even though the density and velocity contrasts of Crisco with water are very small. The phase change between the aluminum and Crisco reflected wavelets observed for the measured data on Figure 5 is also present for the numerically modeled data on Figure 8.

SUMMARY AND DISCUSSION

Our measurements have confirmed Sondergeld's original experimental data showing that strong reflections occur at a water-Crisco interface, even though the density and velocity contrasts are negligible. For unaltered Crisco, the reflection amplitudes are almost equal to those observed for a water-aluminum, interface, even though the traditional acoustic impedance of Crisco is almost identical to that of water, while the impedance of aluminum is about 16 times that of water. For melted and re-solidified Crisco, the reflection amplitudes are about 18 times less than those for aluminum, suggesting that the Q of altered Crisco has increased from that of unaltered Crisco, even though the density and P-wave velocity remained essentially unchanged. Synthetic seismograms created using a reflectivity algorithm verify the experimental observation that a material with extremely low Q immersed in water can result in strong reflections, even if the P-wave impedances are virtually identical.

The analysis leading to an expression predicting Q-induced reflection amplitudes may be found in Lines et al. (2008) and also in a companion CREWES report in this volume (Lines et al., 2011). Exceptionally low Q values (on the order of 3 to 0.3 or less) are required for the reflectivity code to produce synthetic seismograms with reflected amplitudes that match observed reflection amplitudes for the water-aluminum and water-Crisco interfaces. These perhaps unrealistically low Q values, predicted also by Lines et al. (2008; 2011), suggest that we may need to consider in more detail the physics and mathematics regarding energy dissipation, wave propagation, acoustic impedances, and Q (see, for example, the discussion, Grant and West, 1965, section 2-11).

ACKNOWLEDGEMENTS

This research has been supported by NSERC and the industrial sponsors of CREWES.

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APPENDIX A: MEASURED VELOCITY AND ATTENUATION

We acquired data that allowed us to estimate the velocity and attenuation of Crisco lard. The first set of measurements were made on unaltered Crisco, i.e., on lard "straight out of the package". The second set of measurements were made on altered Crisco, i.e., on lard that was melted and re-solidified. Figure A1 is a schematic depiction of the measurement procedure. The active tips of a transmitting and receiving piezopin transducers were inserted a few millimeters into the lard samples. Ultrasonic traces were recorded at many offsets between the transmitter (TX) and the receiver (RX). Different offset distances were obtained with TX fixed in position and RX moving along a straight line in 1 mm increments. The time moveout of first arrivals on fixed source gathers gives us estimates of velocity v, while the change in amplitude as a function TX-RX offset distance, corrected for spherical divergence, gives us estimates of attenuation α.

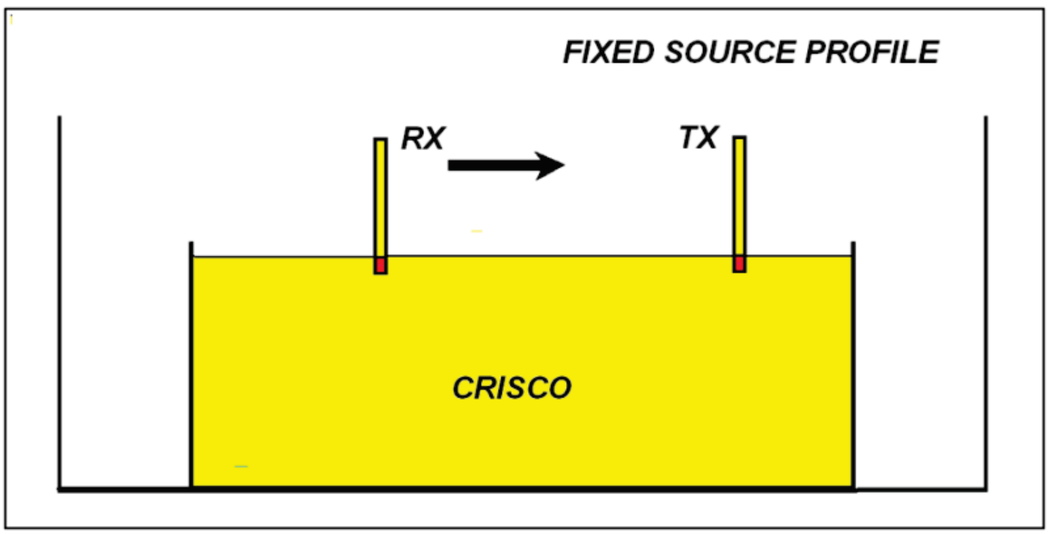

Figure A1. Acquisition procedure to acquire data for estimating velocity and attenuation for lard.

Unaltered Crisco

Figure A2 is fixed-gain display of a fixed-source gather of traces with the piezopin transducers inserted into the unaltered lard block. The red line plots the first arrival times, and its slope indicates that P-wave velocity for our particular block of Crisco is 1630 m/s, about 8% higher than Sondergeld's value. The first arrivals are very weak,, much weaker than similar arrivals through water; we take this observation as evidence for the strong attenuating property of Crisco. We have roughly measured the density of our unaltered Crisco sample to be about 970 kg/m^3 (values found on the internet for lard are in the range 948 to 960 kg/m^3).

We applied a 6.4 ms tapered window on the traces after the first arrival times and aligned the windowed traces according to the arrival times. These are plotted on Figure

A3 with fixed gain. The decrease in amplitude of the first arrivals as source-receiver distance increases is evident. The red trace on Figure A3 is the normalized average trace of the aligned traces. Its frequency spectrum, plotted in blue, indicates that the dominant frequency is about 270 kHz. Since the velocity is 1630 m/s, the dominant wavelength λ is about 6 mm.

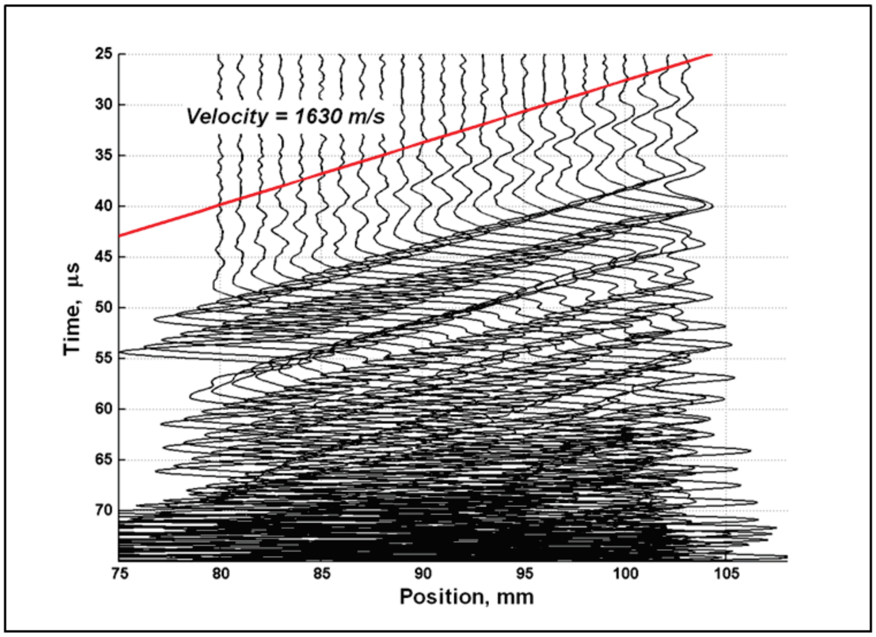

Figure A2. Fixed-source seismograms through unaltered Crisco plotted against receiver position.

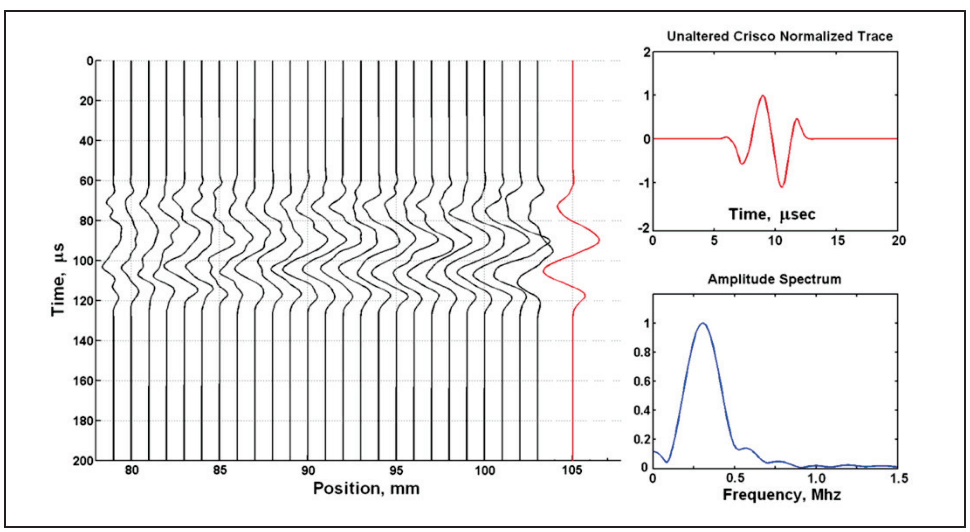

Figure A3. Aligned and windowed reflected wavelets for unaltered Crisco immersed in water, with the average wavelet (red) and its amplitude spectrum (blue).

Altered Crisco

Figure 4 shows the fixed-source traces for altered Crisco with the velocity estimate. Figure A5 displays the windowed and aligned traces. The average trace plotted is in red, and its frequency spectrum indicates that the dominant frequency is about 520 kHz. Since the velocity is 1540 m/s, the dominant wavelength λ is about 3 mm.

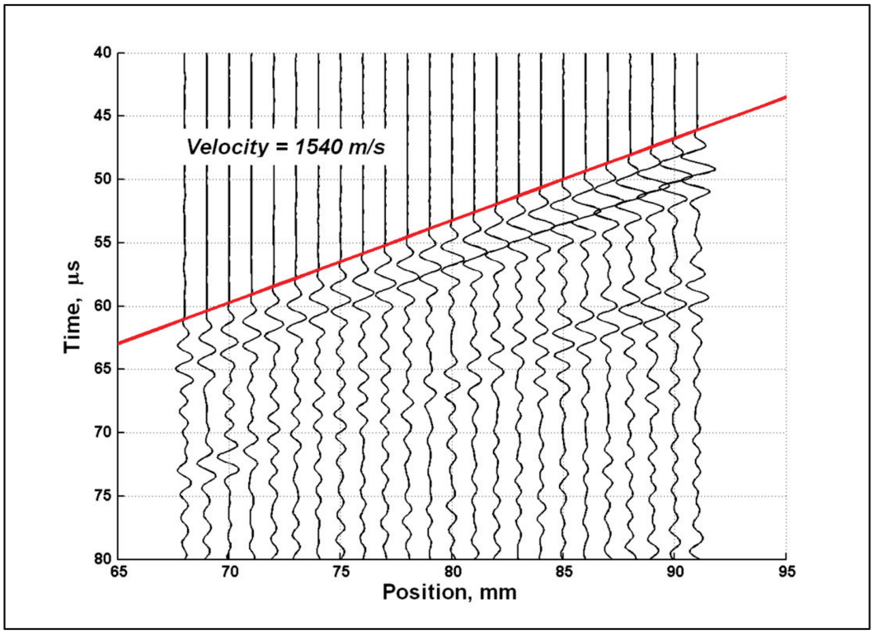

Figure A4. Fixed-source seismograms through altered Crisco plotted against receiver position.

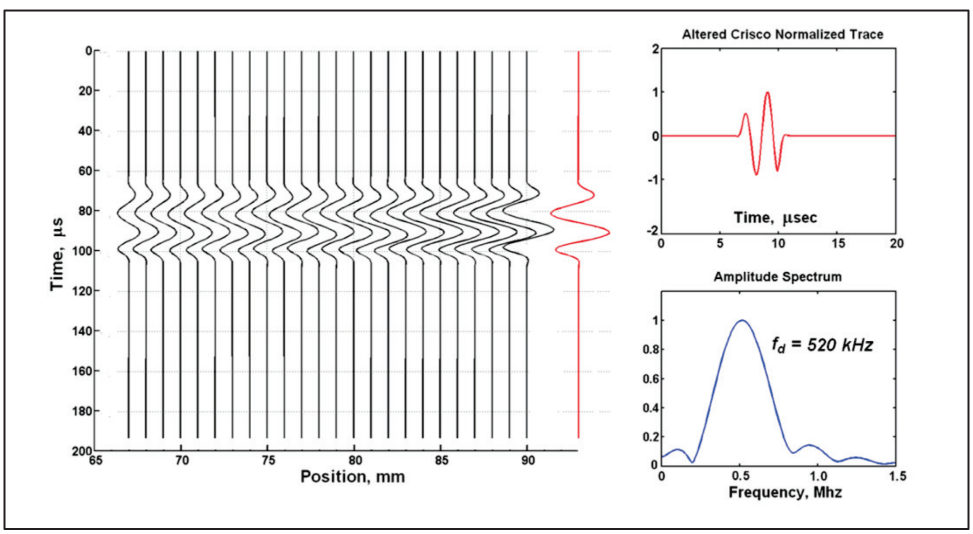

Figure A5. Aligned and windowed reflected wavelets for altered Crisco immersed in water, with the average wavelet (red) and its amplitude spectrum (blue).

Estimating attenuation for Crisco

The peak-to-trough amplitudes of first arrivals were by picked from Figure A3 for unaltered Crisco and from Figure A5 for altered Crisco. The picked amplitudes were corrected for spherical divergence by multiplying by distance between the source and receiver positions. On Figure A6 we have plotted the logarithms of the corrected amplitudes as a function of offset distance. The slopes of fitted straight lines to the plots give estimates for the attenuation constants α. The picked first-arrival amplitudes for unaltered Crisco are quite scattered because they are so weak. For unaltered Crisco, α is about .035/mm = 35 /m. For altered Crisco, α is about .021/mm = 21 /m.

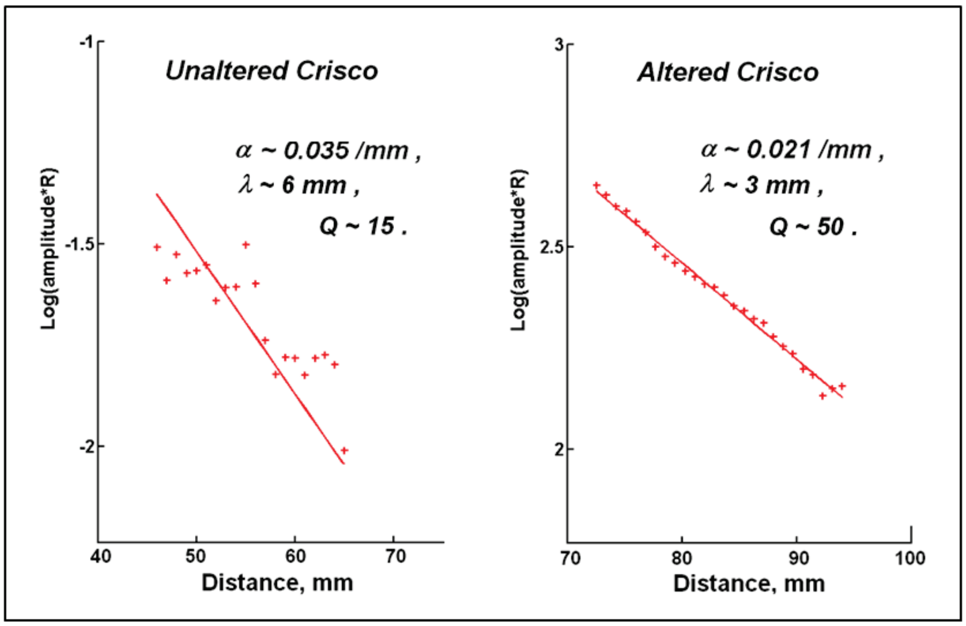

Figure A6. Estimates of attenuation for unaltered and altered Crisco.

The Q of a material can be estimated from the wavelength λ and the measured attenuation α using the equation

$$Q = \pi/(\alpha\lambda) . \tag{A1}$$

For unaltered Crisco, the estimated Q (at the dominant frequency of 270 kHz) is about 15. We believe that this value for unaltered Crisco is unreliable, mainly because the amplitudes of the first arrivals on the relevant seismograms are so low. For altered Crisco, the estimate for Q (at the dominant frequency of 520 kHz) is about 50. The measured amplitudes are large and show very little scatter. In this care, the estimated values for α and Q would seem to be quite reliable. In both cases, the estimated attenuation constants and Q values seem much too high to cause significant reflections. The synthetic seismograms from Figures 6 and 7 suggest that Q values on the order of 3 to 0.3 must exist to explain the observed reflection amplitudes from the water-Crisco interface.