CALIBRATION OF SEISMIC ATTRIBUTES FOR RESERVOIR
CHARACTERIZATION

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Abstract

This project is intended to enhance our ability to use seismic data for the determination of rock and fluid properties through an improved understanding of the physics underlying the relationships between seismic attributes and formation. We have expanded our study to include four data sets, covering a variety of rock types and depositional environments; all of which are host to significant reserves in the domestic United States. Previous reports have described the results from each independent study area; this report describes the cross-cutting relationships and some new work on the changes in seismic velocities of the rock frame (rather than the pore fluids) due to changes in pore pressure.

- The use of “phantom” horizons
 - Pitfalls
 - Preferred practices
- Specially-derived attributes
 - Based on seismic petrophysics
 - Specific to each area uniquely
 - Unusual indicators of fracturing, pressure, and lithologies
 - Upscaling
- Pressure-dependence of velocities
 - Changes in velocity
 - Various models

Our current work is concentrating on providing complete examples for use in tech transfer, perhaps using novel means, such as tutorials on CD and/or in short courses.

A significant paper was published in the October 2001 issue of *The Leading Edge*, describing the loss of oil from reservoirs that are not under production, resulting from a decreased pore pressure caused by production from a nearby oil field.

A review of “Reservoir Geophysics” has been written as a chapter for an upcoming new edition of the *Petroleum Engineering Handbook* from the Society of Petroleum Engineers; a copy will be provided under separate cover.

Executive Summary

The project, “Calibration of Seismic Attributes for Reservoir Calibration,” has completed its stated goals in investigation of seismic attributes, has analyzed more data sets than originally committed, and added a time-lapse component to its work, now completed. The remaining work to be done on the project includes some integration of the work done on different data sets, investigation of a few specific details as came to our attention during internal reviews and external presentations, and the final stages of tech transfer. We are using an additional year of the project, through a no-cost extension, to expand our tech transfer component of the work.

There are a few, specific, unanticipated items that stand out in our study, and we emphasize those here. One is the development of a set of preferred practices (and pitfalls) in the use of ‘phantom’ horizons for seismic-attribute analysis. Another is the development of specialized, unusual, attributes, driven by the interpreter’s understanding of the rock physics involved in any given case. Finally, the recognition that oil is being lost from unproduced reservoirs through the decrease in fluid pressure that results from production in a nearby reservoir, observed in attribute analysis from time-lapse seismic observations, is perhaps the most-surprising, unplanned, and yet – significant – result of our work.

Data from Wyoming, North Texas, South Texas, and the Gulf of Mexico offshore of Louisiana have been used extensively in this study. These environments provide a diverse array of physical conditions and rock types, and a variety of interpretation methods to be applied to them. The results of the work in each separate field have been previously reported, in our annual and semi-annual reports. This report summarizes the cross-cutting features of those studies, and includes a detailed description of some new work on the changes in seismic velocities of the rock frame (rather than the fluid) due to changes in pore pressure during production.

We have found that the data sets we have used (particularly the public-domain ones), and the observations we have made and the results we have obtained lend themselves very well to a set of tutorials and interactive guides to the use of seismic attributes, and are planning to culminate this project in the development of such material, probably to be distributed on CD and/or in short courses.

Two major recent publications have resulted from this contract; one has been published, and the other is in press. More publications are being prepared.

Introduction

The objectives of this project are three-fold: To determine the physical relationships between seismic attributes and reservoir properties in specific field studies; to improve the usefulness of seismic data by strengthening the physical basis of the use of attributes; and, in the third year of the project, to test the approaches suggested or developed during the first two years on at least one new data set. These objectives have been met. In association with these studies, collaboration with corporate partners and technology transfer as ideas are developed and tested are ongoing integral components. The tech transfer has begun, and is ongoing.

This project is divided into four main tasks, and these are further subdivided into subtasks. The following sections refer to those tasks; when appropriate, the application of each task to each data set is described. The breakdown in the 'Results and Discussion' section of this report will be based not on tasks, but on the cross-cutting results from those data sets, and on one new (previously unreported in detail) result concerning the changes in seismic velocity of the rock frame due to changes in pressure.

Task 1: Project Management

Project management encompasses reporting and project support. Both are fully on schedule. We continue to use a large number of high-end software suites in our studies and in the preparation of tech transfer material. System administration is running very smoothly; we have had to add new hardware to handle the massive volumes of data and these large software suites, but the cost of hardware has declined such that we remain in budget. We have recently assigned a new systems administrator with primary responsibility for these software suites and data sets. Due to some earlier database problems, we were tardy in some reporting obligations; those have now been remedied.

Task 2: Borehole Data

Borehole data for this project consists of three types: existing data (of all sorts), new core and outcrop data (to determine fine-scale heterogeneities), and new log data acquired for this project. We have made use of data provided by our corporate partners, including production data, have sought out additional data relating to the data sets, and have obtained new data in some instances. This task is complete.

Task 3: Processing

Processing of the seismic data has been completed on schedule, even after expanding the scope of the project to include some pre-stack processing of one data set. Essentially all processing is now complete, although we anticipate performing additional processing in order to obtain appropriate examples for tech transfer.

Task 4: Visualization

Our visualization of reservoir properties has become extremely efficient. We use visualization for improved reservoir characterization, for enhancing communication with our corporate partners, and for technology transfer. Again, some additional visualization will be performed in association with the preparation of tech transfer materials.

Technology Transfer

Our web site is complete, and being updated regularly (<http://www.geo.mtu.edu/spot>). A significant invited review paper on “Time Lapse Seismic Surprise at Teal South: That Little Neighbor Reservoir is Leaking” was published in THE LEADING EDGE (October 2001 issue). An invited manuscript of a chapter on “Reservoir Geophysics” has been approved for publication in the upcoming new edition of the Petroleum Engineering Handbook from the Society of Petroleum Engineers; an advance copy is being provided to DOE under separate cover. Informal presentations have recently been made to other academic groups and to operating branches and research centers of a number of oil producing and service companies; their feedback is being used in designing the tech transfer materials as well as other research publications.

Results and Discussion

Phantom Horizons:

A “phantom” horizon is a time-slice taken from a volume that has been flattened on a horizon tracked through the data set. Modern seismic interpretation software packages do not require the actual flattening process, so a phantom horizon can simply be any horizon made parallel to one that has been tracked along a real horizon. Interpreters often create phantom horizons in order to track the seismic response of a layer that may not be easy to track on the seismic data, but which is known (or suspected) to exist, conformable with the tracked horizon. It is often used to track events that the interpreter feels do not lie along peaks or troughs of the seismic data.

Pitfalls:

The amplitude of an event that does not lie along a peak or trough of the seismic data is likely to be strongly influenced by subtle and minor changes in phase. These changes in phase may be meaningful in their own right, and are often interpreted as if they are. But we suspect, and demonstrate through dramatic examples (see earlier reports on the Stratton data set, in particular) that they are more often simply artifacts that arise from very small changes in stratigraphic thickness (in seismic travel time) between a ‘real’ horizon that is approximated by the phantom horizon, and the horizon that was used to create the phantom (that is, the one on which the volume was flattened).

Preferred Practices:

The use of phantom horizons can be an extremely powerful tool if the attributes studied are windowed attributes, and not point-based. (We demonstrated this in the Wamsutter data set in previous reports, although we did not identify this as an application of phantom horizons.) Phantom horizons can also be used as ‘proxies’ for isopach thickening and thinning in cases where one of the horizons is not easy to track, but such application must be undertaken with great care to avoid over-interpretation.

Specially-derived Attributes:

If one understand the nature of the exploration or development target, one can design purpose-built attributes intended to extract uniquely that data which is most appropriate.

Based on Seismic Petrophysics:

In one dramatic example, using the Wamsutter data set, we showed how to create a phantom-horizon-based windowed attribute of average “variance” within a stratigraphic interval, in order to identify a beach or sandbar facies that was associated with the ‘sweetspot’ of production from the Almond formation. In another example from the same data set, we showed that a painstaking approach to determination of lower-than-average impedance values along stratigraphic intervals could be used to identify what seem to be fractured and overpressured areas in the overlying and productive shales.

Specific to Each Area Uniquely:

We showed that a simple key to identifying stratigraphically similar regions could be developed through the use of a modified cross-correlation algorithm, using specific seismic traces (usually at wellbores, although not necessarily) as guides to the areal classification of seismic ‘facies’ in the Boonsville data set. This technology must be calibrated uniquely for each new data set, and probably for small areas within each data set.

Unusual indicators of fracturing, pressure, and lithologies:

It may be that the specific attributes we developed in our test data sets can be applied directly to other data sets, but we feel instead that local calibration is important. On the other hand, the approaches that we have demonstrated for the development of each unusual indicator can be directly applied to developing new indicators, with a sound physical basis, in new data sets.

Upscaling:

We have tested a variety of methods intended to provide an easy-to-use upscaling for correctly establishing a time-depth relationship, which is required for accurate synthetic seismogram construction. We think that after running a few more models, we can issue what we think are appropriate guidelines and rules-of-thumb for routine upscaling of sonic-log data.

Pressure-Dependence of Velocities

It has long been known that seismic velocities of rocks are strongly dependent on the confining pressure. It has only recently been recognized that this dependence is extremely important over the pressure ranges in which many modern reservoirs are operated, and that we must take this dependence into account in the interpretation of any time-lapse seismic studies.

Changes in Velocity:

If one tries to model rock velocities as functions of pressure, one often finds that there are simply too many independent variables to easily construct a reliable model (although such models are becoming increasingly realistic). Instead, we felt that a more-reasonable approach is to find a relationship between the changes in velocity with changes in pressure, given that a velocity has already been measured (logged or through interval velocities from stacking) at one known pressure.

Various Models

A model that accomplishes this has been previously published by other workers, and some theoretical models (Hertz-Mindlin in particular) can also be applied. We attempted to find a new relationship from De-Hua Han's data set of dry-rock samples. Our new relationship was intended to predict the changes in velocity with pressure (dV/dP) given known velocity (V_{Po}) and confining pressure ($P_{confining}$). That is, $dV/dP = fcn(V_{Po}, P_{confining})$. Although the principal is sound, it is not yet clear that our new method has in fact provided any advantage over the existing methods. Our next efforts in this area will concentrate on establishing the use of changes in velocity as routine technologies in the industry. The details of this methodology are provided in the following section, since they are new, and have not previously been reported to DOE.

Changes in Velocity:

The following section is a summary taken directly from the Master's thesis of Aaron Green, at Michigan Technological University, completed in Fall, 2001. All appendices and tabular data have been removed in the interest of brevity, but are available from the original work.

THE EFFECTS OF THE VARIATION OF EFFECTIVE PRESSURE IN RESERVOIRS ON MEASURED COMPRESSIONAL WAVE AND SHEAR WAVE SEISMIC VELOCITIES

Background

As any reservoir is produced, changes in subsurface rock and fluid properties will occur. This can be important, because seismic reflections result from certain rock properties, and if these properties change, then the seismic data can change. This is of particular interest in today's petroleum industry, where many times seismic data that is years old (and therefore may no longer represent the current in situ conditions) is interpreted to find new reservoirs. The push towards 4-D or time lapse seismic data itself is evidence that it is important to consider these changes in rock and fluid properties. This study focuses particularly on how seismic velocities of the rock matrix can change due to pressure changes that often accompany production.

Three types of pressure are of interest in this study: Overburden pressure (confining pressure), pore pressure (reservoir pressure), and effective pressure (here assumed to be identical to differential pressure). Effective pressure (P_e) is defined as this difference between confining pressure (P_c) and pore pressure (P_p), such that, $P_e = P_c - P_p$ (Wyllie 1962). This expression is not as useful at high pore pressures and confining pressures, where P_c and P_p do not cancel each other out (Prasad and Manghnani 1997), and a distinction between differential pressure and effective pressure should be made.

As a reservoir is produced, effective pressure increases, due to a decrease in pore pressure (Craft et al., 1991). This makes sense, since pore pressure is caused by the incompressibility of fluids that saturate the pores, such as water, oil or gas (Mavko et al., 1998).

a)

b)

FIG. 1. Acoustic microscopy micrograph of Michigan and Berea sandstones at 1 GHz showing quartz grains, cementation, and pore structure. The scanned image of Berea sandstone (a) is $312\ \mu\text{m} \times 312\ \mu\text{m}$, that of Michigan sandstone (b) is $1000\ \mu\text{m} \times 1000\ \mu\text{m}$. Impedance contrasts in the micrograph are color coded: cyan through blue to white denote progressively higher impedance. Pore spaces and interfaces appear as cyan and blue areas. Grains are green to white colored. Michigan sandstone (b) has well cemented, rounded grains with few visible microcracks. Impedance (brightness) contrast within the grains is low. The grains in Berea sandstone (a) are angular ($150\text{--}200\ \mu\text{m}$) and show microcracks. The grain contacts are somewhat jagged and are weakly cemented. The grain contacts are wider than in Michigan sandstone.

very gradual, as the remaining ellipsoids slowly close with pressure.

Velocity-Pressure Data

The aim of this paper is to develop an empirical relation to predict velocity changes (and therefore bulk modulus changes, also) as effective pressure changes in the microcrack closure region. In order to develop these relations, one data set was used, based on 67 samples studied

Micro-crack closure

The most important pressure effect on velocity is due to closing of pores as effective pressure increases. Figure 1 shows an example of pore space in two different rocks.

The upper image shows a rock with pores that are very thin and narrow – basically shaped like cracks. The lower image shows a rock with pores that exhibit a much higher aspect ratio (aspect ratio is defined here as the ratio of the width of a pore to its length). The thin crack-like pores close up at much lower effective pressures than the more round, ellipsoidal pores. Numerous authors (Prasad 1997, Khaksar, et al., 1999; Mavko et al., 1995) have remarked that the closing of these microcracks will cause a marked increase in velocity (both P-wave and S-wave).

Velocity-pressure curves are characterized by an increase in velocity that is much sharper at lower effective pressures (Figure 2). The steeper slope in this region is due to the closure of the microcracks. The velocity increase at higher effective pressures is much lower, and nearly linear, since all the thin cracks have closed.

Figure 1: taken from Prasad, (1997)

Figure 2: Sharp velocity increases are shown on the left of the graph, due to cracks closing. The velocity increase to the right is very gradual, as the remaining ellipsoids slowly close with pressure.

by De-Hua Han (Han, personal communication). A second data set of 88 samples studied by Freund (1992) was used to test the general applicability of the relations.

The velocities had been measured on dry samples at ultrasonic frequencies using the pulse transmission technique. For a discussion of the pulse transmission technique see King, 1966. For the Han data set, the dry samples were also saturated and velocity measurements were taken on these wet samples; these saturated velocities were published in Han et al., 1986, but the dry-sample velocities have not been previously published. The error in P-wave velocities was about 2 percent and the error in S-wave velocities was about 3 percent. Further details concerning these data sets can be found in Freund, 1992 and Han et al., 1986.

Dry Rock vs. Wet Rock

Most velocity-pressure data is obtained from tests in the laboratory on wet (or saturated) rocks. At first, this may seem to make sense, since any rock in the ground is going to be more saturated than dry. However, rocks under the ground are measured by low frequency seismic pulses, while rocks in the laboratory are measured with a high frequency sonic pulse. The difference turns out to be quite important. Low frequency sonic pulses allow time for the fluids to ‘squirt’ out of the thin cracks into the ellipsoidal cracks as the pulse compresses the more-compliant cracks of the rock. With low frequency pulses there is enough time in between each pulse for the fluid to flow and equilibrate. High frequency sonic pulses are much more rapid, so the fluid within the thin cracks never has the chance to squirt all the way out into the stiffer equant pore spaces. The fluid thus remains in the thin cracks, and this provides an additional incompressibility, or stiffness, giving an overestimate of bulk modulus (which also causes an overestimate in velocity). Laboratory measurements done on saturated rocks will therefore give overestimates of velocity at seismic frequencies. It can be more accurate to perform laboratory measurements on dry rock, and then convert the dry modulus (or velocity) into wet modulus (or velocity) using Gassmann’s equation (Murphy et al, 1986).

Equation Description

In order to develop an empirical equation that relates effective pressures to compressional and shear wave velocities (or to changes in velocities), previous works in this area were studied. Of particular interest were empirical equations published by Eberhart-Phillips et al, 1989 and Bentley et al, 2000.

Eberhart-Phillips attempted to predict velocity from effective pressure using an exponential relationship:

$$V = A + KP_e - Be^{(-DP_e)} \quad (\text{eq.1})$$

The physical meaning behind these coefficients is as follows: A is the crack-free velocity, effected by porosity and clay content, K is the linear section slope on the velocity-stress curve, D relates to the closure of microcracks, and A-B indicates velocity at zero effective stress (Khaksar et al., 1999).

Using saturated rock samples that included P-wave and S-wave velocities at pressure ranges from .05 kbar to .50 kbar (Han 1986), Eberhart-Phillips found best fit values for coefficients A, B, D, and K for every rock sample in the Han data set. They attempted to correlate the best-fit

values of these coefficients to measured values of clay content or porosity. They found that the pressure dependence based on these coefficients did not have a statistically significant relationship with clay content or porosity.

Bentley developed equations to predict changes in dry bulk modulus, K_D , and dry shear modulus, μ_D (from which changes in P-wave and S-wave velocities are easily derived):

$$\frac{dK_D}{dP_{eff}} = .2437 \exp(-.0582P_{eff})$$

(eq. 2)

$$\frac{d\mu_D}{dP_{eff}} = .2794 \exp(-.0549P_{eff})$$

(eq. 3)

(These expressions assume pressure is measured in MPa, and changes in bulk modulus are also given in MPa. The key to using Bentley's equations is the assumption that bulk modulus and shear modulus (and therefore seismic velocities) are known at one pressure.

This assumption can be utilized in other equations, too, such as the Duffy-Mindlin relationship (White, 1983; Merkel et al., 2001). The assumption is realistic, since in most fields where time lapse seismic is of interest, well logs contain velocities known at the original, pre-production pressure. This assumption, then, adds another "known" to equations that originally were developed to predict velocities using pressure, clay content and porosity alone. **Figure 3** shows how much more accurate velocity predictions can be if a seismic velocity is known at just one pressure.

Figure 3: Velocity predictions tied at a point are more accurate than general velocity curves

This is a significant difference, since in other work on this relationship, best fit values for coefficients A, B, K, and D were estimated assuming these coefficients were a function of pressure alone. In this study, since we assume we know a velocity at a certain pressure, we can solve for the best fit coefficients as a function of pressure and velocity.

It was recognized that if we know a velocity at one pressure, then that adds one more parameter (besides clay content and porosity) to which the coefficients A, B, D, and K could be related. This assumption that we have a known velocity is one of the mainpoints that distinguish the empirical equation formed in this study or Bentley's from others. The further distinguishing factor is our use of dry (unsaturated) rock data instead of wet (saturated) rock data; Bentley's equations were developed using the data published by Han et al., 1986, which were provided for saturated rock samples only.

Development of equation

Eberhart-Phillips' original equation was:

$$V = A + KP_e - Be^{(-DP_e)} \quad (\text{eq. 1})$$

We simplified this equation by combining coefficients B and K, so that

$$V = A + BP_e - Be^{(-DP_e)} \quad (\text{eq. 4a})$$

- or -

$$V = A + B(P_e - e^{(-DP_e)}) \quad (\text{eq. 4b})$$

(As a side note, many others have simplified Eberhart-Phillips' to $V = A - Be^{(-DP_e)}$ similar to our equation, except without the $B \times P_e$ term). This equation is of the form $y=mx+b$, where $y=V$, $m=B$, $b=A$, and $x=[P_e - e^{(-DP_e)}]$ (also termed P'). For every rock sample, we plotted dry P-wave velocity vs. $[P_e - e^{(-DP_e)}]$ (**Figure 4**). (Actually, we plotted velocity vs. $[P_e - e^{(-DP_e)}] + 1$, since it was recognized that at certain values of D and P_e , the P' term would equal zero, and therefore could cause divide-by-zero problems). In this analysis, the velocities measured at the lowest pressure (.05 kbar) were excluded for reasons that will become evident later. Coefficient D was varied until the best linear correlation between velocity and $P' + 1$ was found. The slope for this best fit value would be coefficient B, and the intercept at the best fit value would be coefficient A.

Figure 4: Fitting $P_e - e^{(-DP_e)} + 1$ to velocities to solve for coefficient A and B. Coefficient D was varied until the least R^2 value was found.

In this way, best fit values for coefficients A, B, and D were found for every rock in the data set of dry P-wave velocity. This method was repeated for dry S-wave velocity data.

Just as Eberhart-Phillips tried to correlate clay content and porosity with their coefficients found using Han's wet rock data, we tried to correlate clay content, porosity, and velocity with our coefficients

found using Han's dry rock data. In accordance with Eberhart-Phillips' conclusion, we found that there was no significant pressure dependent relationship between any of the coefficients and clay content or porosity (**Figure 5**). This was true for both P-wave and S-wave velocities.

We continued the comparison, to observe if velocity and any of the coefficients have a relation. There was no correlation between velocity and coefficient D (**Figure 6**). This figure shows no correlation between coefficient D and P-wave velocity at .20 kbar, but the lack of correlation is true for both P-wave and S-wave velocities at any pressure. This means that in any empirical

Figure 5: These plots show that there is no correlation between clay or porosity and coefficient A, B or D. These are the same results that were found by Eberhart-Phillips.

equations, an average D value could be used for the entire data set. Although this is not entirely desirable, coefficient D does not affect our equation enough to cause significant errors in predictions.

Next, having fixed the value of D at 10.66, the relation between coefficient A and velocity was examined (Figure 7). Not only are coefficient A and velocity related at .20 kbar as shown in this figure, but coefficient A and velocity (either P-wave or S-wave) show a strong correlation at any pressure. Coefficient B and velocity relations were also examined (Figure 8). This is not a statistically significant correlation. However, coefficient B vs. *change* in velocity was plotted, and this does show a strong correlation (Figure 9). The correlation coefficient for velocity changes between pressures of .10 and .20 kbar is nearly 98 percent for this figure. This correlation coefficient drops as velocity changes between higher pressures are considered, down to about 56 percent for velocity changes between .40 and .50 kbar. However, this shows that there is still some sort of correlation between coefficient B and change in velocity, even at higher pressures.

Figure 6: Best fit coefficient D values show no relation to velocity measurements in Han's data set

Figure 7: Best-fit coefficient A values show a strong correlation with measured velocity. This means if we start with a known velocity, we can predict coefficient A.

Figure 8: Best-fit coefficient B values show a weak correlation with measured velocity. Though there may be a trend of decreasing velocity with increasing coefficient B, velocity alone is not useful in predicting coefficient B values.

Figure 9: Best-fit coefficient B values show a strong correlation with change in measured velocity. This means if we can solve for coefficient B , we can predict what the change in velocity is.

Figure 7 shows that coefficient A can be predicted with a known velocity. This is true at every pressure. But the equation of the line used to make this prediction is different at every pressure, since there are different slopes and intercepts for each of the measured pressures. If we plot these slopes and intercepts against the varying pressure, we obtain a smooth line (Figure 10).

Figure 10: Plot giving the equations that predict the slope and intercept in the coefficient A vs. velocity best fit line. The reason for retaining the equation up to eight decimal places is to increase accuracy in the final equation.

Finding the equation of this line allows us to predict, at any pressure, the slope or intercept that should be used to find coefficient A from a known velocity. For example, if we know the P-wave velocity at a certain pressure – say 3.5 km/s at .23 kbar – we can solve for coefficient A using Figure 10. Just plug in .23 kbar to find the slope and intercept values – a slope of .7119 and an intercept of 1.592 in this case. Then, we have $V = .7119 * \text{Coef. } A + 1.592$, and since $V=3.5$, we can solve the equation for coefficient A : 2.68.

Using the same method to plot the different slopes for the relationship between coefficient B and the change in velocity, a similar plot can be generated (Figure 11).

This equation only gives what coefficient B would be if .10 kbar pressure increments are desired (as is the case in Han's data set). In order to be able to apply this equation between any two pressures, the plot in **Figure 11** is integrated, resulting in **Figure 12**.

Figure 11: Plot of Table 2, giving the equation that will predict the slope in the best fit line that relates coefficient B and pressure change. Note that the data points for changes between two pressures are plotted at the midpoint of these two pressures.

Figure 12: This is simply an example of integrating the equation in figure 11 above, and applying it at different pressures.

The equation of this curve is:

$$y = -.14457050 \times e^{(-5.70756542x)} \quad (\text{eq. 5})$$

Using this, coefficient B can be found between any two pressures, by finding y at a certain pressure, x, and subtracting from the y value at another pressure, x. Dividing this by .1 will give the slope, or, in other words, the rate of change of the velocity (in km/s) between two pressures (in kbar). These plots can similarly be generated for S-wave velocities.

The end result of all these correlations, along with the assumption that the equation 1c is correct, is that an empirical relationship between change in velocity and change in pressure can be developed. A brief summary follows describing the use of these relationships:

Start with your known velocity and pressure. Use **Figure 10** to find the slope and intercept at the pressure of interest. Using these slopes and intercepts, and the known velocity, you solve for coefficient A.

Our original equation was $V = A + B(P_e - e^{(-DP_e)})$. We have our known velocity at an effective pressure, and we now have A, and D is 10.66, the average for the Han data set for P-wave velocities. We now solve for the remaining unknown coefficient B.

Once we have coefficient B, we can use the equation that comes from integrating **Figure 11** (shown in **Figure 12**) to find the slope of our equation between the original pressure and whatever new pressure we want. Our new velocity will simply be our original velocity plus or minus coefficient B times the slope we found in this step.

All these steps put together result in the following empirical equations:

P-wave velocities (eq. 6):

$$\Delta V_{1-2} = \left[V_1 - \frac{V_1 - (.64 \ln P_{e1} + 2.53)}{-.12 \ln P_{e1} + .54} \right] \left[\frac{-1.45(e^{-5.71P_{e2}} - e^{-5.71P_{e1}})}{P_{e1} - e^{-10.66P_{e1}} + 1} \right]$$

S-wave velocities (eq. 7):

$$\Delta V_{1-2} = \left[V_1 - \frac{V_1 - (.35 \ln P_{e1} + 1.39)}{-.09 \ln P_{e1} + .63} \right] \left[\frac{-1.44(e^{-5.39P_{e2}} - e^{-5.39P_{e1}})}{P_{e1} - e^{-10.54P_{e1}} + 1} \right]$$

These equations become more accurate as the step size between the two pressures decreases.

Results

This method was developed entirely from the Han dry data set by the procedures described above. All correlations between velocity and coefficients A, B, and D were made using all of Han's velocity values at effective pressures ranging from .10 kbar to .50 kbar (we originally included the .05 kbar point to build our method, but we found that our empirical equation was not accurate for pressures below .10 kbar. After redoing the method based only on the data between .10 and .50 kbar, we found our equation could more accurately predict velocities in this range.) For this section, we will only discuss our results relating to P-wave velocity predictions, since the S-wave, bulk modulus and shear modulus results were done in a similar fashion to the P-wave velocity. At the conclusion of this section, we will give results for these remaining three parameters, and discuss any difference in these results and the P-wave results.

The first test to see if this method works is to see how accurately it can predict the entire data set when only given the initial information of one velocity at a certain pressure for each rock in the data set. This means that if we were given the P-wave (or S-wave) velocity at .20 kbar for each sample in the data set, we should be able to accurately predict the P-wave velocity at all other

Figure 13: Plot of data for sample 49.

The average error values at each pressure for the entire data set, along with the average overall error (just the sum of the average errors) is shown in **Figure 14**.

Figure 14: Actual values in Han's dry P-wave data set vs. values predicted by my method, assuming a known velocity at .20 kbar. This is for every sample in the entire data set.

This figure shows that we can accurately predict the P-wave velocities of this data set with this new method if we assume a known velocity at a certain pressure. However, how accurate is this method if we choose a pressure that is near the limits of our data set, instead of a pressure like .20 kbar, which is in the middle? We can generate a set of predicted velocity values starting with a known velocity of .50 kbar instead of .20 kbar. **Figure 15** shows how accurate this prediction is for a characteristic sample, sample 45. Finally, just as we did for our predictions starting at known velocities at .20 kbar, at known velocities at .50 kbar we can analyze the error for the entire data set (**Figure 16**).

Figure 15: Plot of data for sample 45..

Figure 16: Actual values in Han's dry P-wave data set vs. values predicted by my method, assuming a known velocity at .50 kbar. This is for every sample in the entire data set.

From **Figures 13 and 16**, it can be seen that, generally, the error increases as the predictions are made with increasing differences in pressure. Comparing the residual values at .05 kbar in these tables to the residual values at other pressures in the tables, and to the total residual values, it can be seen that the error at the .05 kbar point is significantly higher than the error at any other pressure. By removing the .05 kbar point, the error

in the .20 kbar original pressure drops from .0749 to .0333, a decrease in error of 56 percent. For the .50 kbar original pressure, this decrease in error is from .1862 to .0748, or 60 percent. From these results, the conclusion is made that this method does not accurately predict velocities down to .05 kbar. This conclusion is very similar to that of Bentley et al, 2000, who also concluded that his method is valid only at effective pressures greater than .10 kbar.

This method seems to accurately predict velocities using the data set that it was developed for. This was a good internal check on the method, but to truly prove useful, we need to see how accurately this method can predict velocities given a new data set. The data set used to do this is from Freund, 1992. Freund's data set contained dry velocity measurements at pressures ranging from .08 kbar up to 3.0 kbar. Effective pressures in a reservoir generally range from near 0 kbar up to about .50 kbar, and our method was based on data to .50 kbar. For these reasons, we will only test our method on the .08, .24, .40, and .60 kbar pressures in Freund's data.

To test our method on Freund's data, we first assumed that we only knew the velocities at the .24 kbar pressure. From this central pressure, we predicted velocities up to .60 kbar and down to .08 kbar, and compared them to the actual values. After this, we started with the velocities at .60 kbar as known, and predicted velocities down to .08 kbar, to check how accurate our method would be when starting at the edge of the data we're interested in. A plot of the predicted values vs. the actual values for both cases are shown in **Figure 17** and **Figure 18**.

Our conclusion from Han's data about predictions below a pressure of .10 kbar being inaccurate holds for Freund's data as well. The total error reduces from .2809 per sample to .1243 per sample (a decrease of 56 percent) for the .24 kbar starting point, and for the .60 kbar starting

point, it decreases from .7255 per sample to .1430 per sample (a decrease of 80 percent). This reinforces our conclusion that this method is not accurate below .10 kbar.

Figure 17: Actual values in Freund's dry P-wave data set vs. predicted values, assuming a known velocity at .24 kbar. This is for pressures .08, .40 and .60 for every rock sample in the entire data set.

Figure 18: Actual values in Freund's dry P-wave data set vs. predicted values, assuming a known velocity at .60 kbar. This is for pressures .08, .24, and .40 for every sample in the entire data set.

But, looking at **figures 17 and 18**, we can see that predictions for Freund's data are much less accurate than the predictions for Han's data. This is to be expected for a few reasons. First, the method was developed empirically for

Han's data, so it should fit this data set better than an outside data set like Freund's. Second, we're looking at a greater range in Freund's data – all the way up to .60 kbar – and as we said before, the accuracy of the predictions decrease the further from a known velocity you go. This being said, the best way we can determine how accurate our method is would be to compare it to other methods. Many have worked on this problem

to develop an empirical equation that would predict velocity, so a comparison to these equations can show how useful this new method is.

Landro's Method

Another equation that predicts velocity changes due to pressure changes is described by Landro, 2001. Landro's technique utilized the equation

$$\frac{\Delta\alpha}{\alpha} \approx k_{\alpha} \Delta S + l_{\alpha} \Delta P + m_{\alpha} \Delta P^2 \text{ (eq. 8)}$$

where α is P-wave velocity, ΔS is change in oil saturation, ΔP is change in net pressure, and k_{α} , l_{α} , and m_{α} are empirical parameters estimated from saturation and pressure curves from laboratory studies of core samples (Landro, 2001). Note that the change in net pressure for Landro's equation must be entered with the units of MPa (1 kbar = 100 MPa). A similar equation exists for S-wave velocities also, with slightly different empirical parameters. If we want to look at pressure effects alone (instead of pressure and fluid effects), we can simplify the equation to:

$$\frac{\Delta\alpha}{\alpha} \approx l_{\alpha} \Delta P + m_{\alpha} \Delta P^2 \text{ (eq. 9)}$$

Empirical parameters l_{α} and m_{α} are solved for by plotting change in P-wave velocity vs. effective pressure, giving a curved line (**Figure 19**). A second order polynomial can be fit to this curved line

line – the coefficient in front of the x^2 term is m_{α} , and the coefficient in front of the x term is l_{α} . While l_{α} is positive, m_{α} is usually negative.

Figure 19: Changes between two pressures for the average velocities of the entire Han data set. Coefficient l_{α} is .0366 and m_{α} is -.0004.

Although Landro intended his method to be used for specific rock samples, we have applied it to an aggregate set of velocities from all the samples in the Han data set, assuming a known velocity at a pressure of .20 kbar. The accuracy of this method can be compared with the accuracy of our new method. Landro's method is accurate, but our method is a significant improvement. These results can be explained because our implementation of Landro's method uses a best fit polynomial from the entire data set to predict all velocity changes. This means that the magnitude of the velocity change is not dependent upon the original velocity. This point will be illustrated in the next section.

Also, it's important to note that Landro developed this equation based on the assumption that several core measurements already exist. In order to find coefficients l_α and m_α and solve for new rock velocities, velocity measurements at various pressures must be available for rocks in the area of interest. Our method only requires one known velocity at one known pressure to predict its velocities at other pressures.

Bentley's Method

As stated earlier, the equations developed by Bentley et. al. are:

$$\frac{dK_D}{dP_{eff}} = .2437 \exp(-.0582P_{eff})$$

(eq. 2)

$$\frac{d\mu_D}{dP_{eff}} = .2794 \exp(-.0549P_{eff})$$

(eq. 3)

Both Bentley's method and our method are empirically derived equations based on Han's data. However, Bentley et. al. used Han's wet rock data, and did not include any data above pressures of .40 kbar. Our method used Han's dry rock data, and also included pressures up to .50 kbar (Han, personal communication).

There is another significant difference between Bentley's method and our method. This difference is most evident at the highest velocities on **Figure 16**. Looking closely at the upper right velocities in this figure, it can be observed that the predicted velocity is actually *increasing* as the pressure decreases. This is because, according to the empirical method we developed, velocity changes decrease linearly as original velocity increases. At about 5.6 km/s (depending on the original pressure), the velocity changes predicted by our method hit zero. At velocities higher than this, the predicted velocity changes will be negative, suggesting that velocity would actually *decrease* with a pressure increase. This is a limitation in our method, and allows our method to be applied to rocks only with velocities under about 5.6 km/s.

Figure 20 shows how our method and Bentley's method predict velocity changes for different original velocities (this figure assumes a starting pressure of .20 kbar), and compares them with the measured velocity changes in Han's data. The method developed in this paper shows a linear relationship, while Bentley's method shows a relationship roughly in the shape of a hyperbola. Interestingly, the relationship for Bentley's method does not produce a well defined function. This is caused because in Bentley's method, predicted velocity changes are not dependent on P-wave velocities alone, but also on S-wave velocities. Bentley's original equations were

developed for bulk modulus and shear modulus, each of which is dependent on both P-wave and S-wave velocities.

Figure 20: Comparing velocity change predictions between our new method and Bentley's method. The original pressure of .20 kbar and pressure change between .20 and .30 kbar are arbitrarily chosen to use in the respective empirical equations. Other pressure values would alter the placement of the data slightly, but the same trends would still be observed. This figure uses P-wave velocities only.

This leads into another interesting aspect of Bentley's method. Bentley's method predicts changes in bulk modulus and shear modulus, regardless of what the original modulus is. Bentley's method is dependent only of the original pressure – the original modulus has no effect on further modulus predictions, meaning that the change in modulus predicted by Bentley's method is always the same for a given pressure and change in pressure. The method presented in this paper takes into account the original modulus – that is, changes in modulus predicted for a sample with a high known modulus would be different than changes predicted for a sample with a low known modulus at a certain pressure. Our new method predicts more realistic modulus changes compared to Bentley's. However, as we noted earlier, this appendix again shows that our method can predict negative changes in velocity or modulus at high velocity samples. So our method more accurately predicts modulus changes, but just as with high velocities, a high modulus can lead to unrealistic predictions.

Therefore, Bentley's method is preferred over our method at higher velocities, but our method can be used when only P-wave velocities are known, compared to Bentley's method that requires both P-waves and S-waves, and our method predicts modulus changes more realistically. The question that this leads to is: at what velocities is it better to use Bentley's method, and when is it better to use this new method? To examine this, we plotted our velocity predictions and Bentley's velocity predictions versus actual velocities for characteristic samples exhibiting high, medium and low original P-wave velocities (**Figures 21, 22 and 23**). From these figures, we make the conclusion that Bentley's method is more accurate at higher velocities (above about 5 km/s), but our method is more accurate for original velocities that are lower (below about 4 km/s)

Figure 21: For this typical high velocity sample, Bentley's method predicts velocity changes more accurately than our new method. The new method predicts values that are too low for the slope of the curve at high velocities.

Figure 22: The typical medium velocity sample shows that the new method is more accurate than Bentley's method in this situation.

Figure 23: The new method predicts the actual velocity values even more accurately at this typical low velocity value.

Comparison of Results

We will compare tables showing total residual for this new method for P-wave, S-wave, bulk modulus, and shear modulus, for both the Freund data set and the Han data set. These will be compared to Bentley's method. Also, plots of predicted vs. actual values for all four parameters will be shown for both methods. The S-wave values for our method were calculated in the same way that we calculated the P-wave values. Our predictions for shear and bulk modulus were done two ways: 1. Simply by converting our predicted P and S-waves to shear and bulk modulus and 2. Building an entire empirical equation (solving for coefficients A, B, and D) by using bulk modulus and shear modulus values alone. The results showed that it was significantly more accurate to predict bulk and shear modulus by the first method – directly converting our P and S-wave predictions to shear and bulk modulus.

Two other pieces of data that we have for both the Han and Freund data set are porosity and clay content. These are also two parameters that many have often attempted to correlate to observed velocity changes. Both porosity and clay content in the Freund data show no correlation between error and porosity. However, **Figure 24** shows clay content vs. residual error and displays a strong relationship. It's obvious from this figure that as clay content increases, the error in prediction tends to decrease. Particularly, sands with a clay content below 30 percent seem to have a much higher error. This observation is consistent for both this paper's predictions and Bentley's equation's predictions. Residual error vs. clay content was plotted for Han's data (**Figure 25**), but no relationship similar to that in the Freund data was observed.

Figure 24: Clay Content vs. residual error for Freund's P-wave data is shown here. Samples with clay content below about 30 percent show a much higher error.

Figure 25: Clay Content vs. R^2 error (residual) for Han's P-wave data is shown here. Unlike the Freund data set, the magnitude of error does not seem to be affected by clay content.

Summary of Results

1. For both P-wave and S-wave velocities, the method presented in this paper is more accurate than Bentley's method when starting at lower pressures and predicting to higher pressures. However, when starting at higher pressure ranges (.50 or .60 kbar) and predicting to lower pressures, Bentley's method is more accurate.
2. In almost every case, the new method presented here is more accurate than Bentley's method in predicting bulk modulus values. Bentley's method is more accurate in almost every case at predicting shear modulus, though. This seems difficult to explain, since differences in Bentley's method and this method only depend on starting pressure for velocities. One possibility may be that Bentley's velocity predictions are compounded when converting to bulk modulus. Bulk modulus is calculated in part by subtracting S-wave velocity from P-wave velocity. If estimates for P-wave velocity were too high, and estimates for S-wave velocity too low, then the bulk modulus would be significantly overestimated. The error in bulk modulus estimates in this case would be greater than if velocity predictions overestimated (or underestimated) the velocity in both cases.
3. Clay content and error in velocity predictions are strongly related in the Freund data set. The trend shows that both velocity predictions become less reliable in cleaner sands. Han's data set shows that this isn't always the case – the clean sands in this data set show no more error than other samples.
4. Comparing AVO effects observed in an actual producing field (the Teal South study, previously reported) to those predicted with the inclusion of pressure effects successfully demonstrated that velocity changes due to pressure variation must be considered. Pressure changes can have as significant an effect on velocity as fluid changes do, and are important to consider in any reservoir characterization.

Conclusions

The project, "Calibration of Seismic Attributes for Reservoir Characterization," is on schedule as planned. We have reached a number of firm conclusions, and made some unexpected discoveries which have been confirmed by testing. Our work has included investigations of point-based attributes, neural-networks, window-based attributes, phantom horizons, upscaling, special attributes designed by considering seismic-petrophysical aspects of the reservoir under study, and the pressure dependence of velocity on the rock dry frame. Remaining work in the project involves an enhanced technology transfer component.

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