Four-D seismic monitoring feasibility

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ABSTRACT

Time-lapse seismic monitoring of reservoirs is based on changes in fluid saturation and pressure due to production causing observable changes in seismic response. The Gassmann equation can be used to estimate changes in the bulk modulus of the reservoir for given changes in bulk moduli of dry rock and fluids. Gas, oil and water bulk moduli are approximated using published results and commonly available petroleum reservoir data. The lower and upper limits of the fluid mixture bulk modulus are calculated from the saturation-weighted harmonic and arithmetic averages, respectively. The change in the dry bulk and shear moduli due to changes in effective pressure is approximated for sandstones using published data. Estimated changes in the bulk modulus, shear modulus and fluid-saturated density are used to calculate new compressional and shear wave velocities. Percentage changes in velocities and acoustic impedance can be inspected for significance. Finally, synthetic shot gathers are generated which can be compared for changes in seismic attributes such as reflection coefficient, AVO effects or frequency changes.

INTRODUCTION

The fluid and pressure distribution within reservoirs evolves as the reservoir is produced. Fluids and pressure can only be monitored at widely spaced well locations. In between the wells, the fluid distributions can only be approximated. However, many production decisions would benefit from detailed knowledge of the geometry of fluid and pressure distributions.

Seismic data sets offer a spatially dense sample of the subsurface. Direct interpretation of pore fluid saturation and pressure is presently unattainable. However, as production proceeds, changes in pressure, temperature and fluid saturation will cause changes in the seismic response. It is the goal of time-lapse seismic monitoring (4-D surveys) to use changes in seismic response to infer changes in reservoir conditions. The objective is to improve the understanding of fluid flow within the reservoir so petroleum engineers can optimize production decisions.

Changes in seismic response due to changes in the reservoir state can be dramatic or subtle depending on the reservoir rock, depth of burial, and changes in fluid saturation, pressure and temperature. The more competent the rock and the deeper the reservoir, the less the anticipated change in seismic response. Before investing in 4-D surveys, it is useful to estimate the change in seismic response and, then, use that estimate to evaluate the feasibility of observing the changes in the reservoir that will be useful in production decisions.

In the following, we present a procedure for estimating the physical parameters that control the seismic response. Then, a procedure for updating those parameters is developed. Before and after synthetic seismograms can be generated and compared to assess the feasibility of using 4-D surveys to observe the anticipated changes in the reservoir. The method is applied to the Blackfoot reservoir in a companion paper (Bentley, et al. 1999B).

THEORY

Gassmann Equation

The Gassmann equation is used to calculate the undrained bulk modulus of a fluid filled rock (K_U) from the porosity (ϕ), the bulk modulus of the solid grains (K_S), the bulk modulus of the fluid mixture occupying the pore space (K_F) and the dry bulk modulus of the rock frame (K_D) (Wang and Nur, 1992):

$$K_U = K_D + \frac{\left(1 - \frac{K_D}{K_S}\right)^2}{\frac{\phi}{K_F} + \frac{1-\phi}{K_S} - \frac{K_D}{K_S^2}} \tag{1}$$

The Gassmann equation is a low frequency approximation. It is generally valid at seismic frequencies, although the specification of the fluid mixture bulk modulus can be problematic as described below. The Gassmann equation will be used to predict changes in the undrained bulk modulus due to production induced changes in K_D and K_F. The Gassmann equation is also used to compute the dry bulk modulus given K_U, K_S, K_F and ϕ.

Fluids

The modulus and density of each fluid type at reservoir conditions are required to calculate the undrained bulk and shear moduli as well as the fluid-saturated density of the reservoir. The parameters can be determined experimentally in the laboratory, but often they must be approximated given common fluid information, reservoir pressure and reservoir temperature.

Gas

It is assumed that the specific gravity of gas at standard conditions is known. The specific gravity of gas needs to be corrected for separator pressure and temperature. Typical separator pressures and temperatures are 689.5 KPa and 15.6°C, respectively. Equation (1), Vasquez and Beggs (1980) is used to obtain a corrected specific gravity. The bulk modulus (K_G) and density (ρ_G) of the gas at the reservoir pressure and temperature are estimated using the corrected specific gravity and equation (10), Batzle and Wang (1992).

Oil

The oil density at standard conditions, the gas density at standard conditions, the gas oil ratio (R_S) and the oil formation volume factor (B_O) are used to estimate the oil bulk modulus and density at reservoir conditions. In seismic experiments, gas will not exsolve or dissolve during increases and decreases in pressure, because of the short time scale of the applied stresses. Consequently, equation (5), Vasquez and Beggs (1980) for an undersaturated oil is used to compute the bulk modulus (K_O) of oil. The density of the oil at reservoir conditions (ρ_O) is derived from mass balance:

$$\rho_O = \frac{\rho_O^{std} + R_S \rho_G^{std}}{B_O} \tag{2}$$

where $\rho_G{}^{std}$ and $\rho_O{}^{std}$ are the densities of gas and oil at standard conditions, respectively.

Water

It is assumed that the salinity of the water is known as well as the temperature and pressure of the reservoir. Water density (ρ_W) is approximated using equation (27) Batzle and Wang (1992). The water bulk modulus (K_W) is approximated using equations (28) and (29) Batzle and Wang (1992).

Fluid Mixture Properties

In general, gas, oil and water will exist in the pore spaces with saturations S_G, S_O and S_W, respectively. The fluid mixture density is a volume average:

$$\rho_F = S_G \rho_G + S_O \rho_O + S_W \rho_W \tag{3}$$

In order to use the Gassmann equation, we must approximate the bulk modulus (K_F) of the fluid mixture. The bulk modulus of the fluid mixture depends on the details of the small-scale fluid distribution (Mavko and Mukerji, 1998). If the fluids are mixed uniformly at a very fine scale, the saturation weighted harmonic average is appropriate (Reuss' model or isostress average):

$$\frac{1}{K_F} = \frac{S_G}{K_G} + \frac{S_O}{K_O} + \frac{S_W}{K_W} \tag{4}$$

If the fluids are "patchy" at a scale that is smaller than the seismic wave length, but larger than the scale at which the pore scale fluids can equilibrate pressures through local flow, then the effective fluid bulk modulus is larger. The upper bound on the fluid mixture bulk modulus is the saturation weighted arithmetic average (Voigt's model or isostrain average):

$$K_F = S_G K_G + S_O K_O + S_W K_W \tag{5}$$

The averaging method makes a significant difference in the application of the Gassmann equation. If the harmonic average is used, the smaller bulk modulus values are more heavily emphasized. In this case, any small amount of gas will cause the estimate of the fluid mixture bulk modulus to be very low. On the other hand, the arithmetic average tends to emphasize the larger bulk modulus values, and increases in water saturation will cause the fluid bulk modulus estimates to increase significantly.

The choice of averaging method depends on the fluid distribution and the frequency of the seismic waves under consideration. For surface seismic experiments over undisturbed reservoirs, the uniform fluid distribution assumption will often be valid and the harmonic average will be appropriate. However, for surface seismic data over areas where fluid displacement has taken place through water flooding or exsolution of gas, we might expect some patchiness of fluid distributions. In such a case the appropriate bulk modulus of the fluid mixture will be between the isostress and isostrain limits.

PROCEDURE

Reservoir Properties

Reservoir properties can be estimated using core and well log data. In this procedure, we assume that we have access to a full waveform sonic log and a density log. Average porosity and solid grain density can be computed from the core analysis. Density logs are corrected so that log densities are consistent with core porosity and density measurements within the zone of interest. Porosity is then calculated from the density log by:

$$\Phi = \frac{\rho_S - \rho_U^C}{\rho_S - \rho_F} \tag{6}$$

where ρ_S is the solid grain density derived from core measurements, ρ_F is the average fluid density and $\rho_U{}^C$ is the corrected density from the well log.

In order to calculate the change in bulk modulus due to changes in fluid pressure and fluid saturations, the dry bulk modulus (K_D) must be estimated. The Gassmann equation will be used to estimate the dry bulk modulus. To use the Gassmann equation, the undrained bulk modulus, the solid bulk modulus, the fluid-mixture bulk modulus and the porosity are required. The porosity was calculated above. The fluid bulk modulus will be estimated from the assumed fluid saturations using the harmonic average, equation (4), the arithmetic average equation (5) or an intermediate value depending on the frequency of sonic logs and the assumed fluid distribution. Using equation (4) will lead to higher K_D, and therefore conservative estimates. Compressional (V_P) and shear (V_S) velocities were derived from the full wave form sonic log. The undrained bulk modulus can be calculated:

$$K_U = \rho_U^C \left(V_P^2 - \frac{4}{3} V_S^2 \right) \tag{7}$$

and the undrained shear modulus:

$$\mu_U = \rho_U^C V_S^2 \tag{8}$$

where $\rho_U{}^C$ is the corrected log density. It is assumed the saturating fluid does not affect the shear modulus and that the undrained shear modulus equals the dry shear modulus ($\mu_U = \mu_D$).

The solid bulk modulus (K_S) can be assumed. For example, 40 GPa is a typical value for quartz. In summary, the dry bulk modulus is calculated for each location along the logged interval within the producing zones with the following procedure (Figure 1):

1. Use the density log and core data to calculate the corrected log density (ρ_U^C) at each location.

2. Use the corrected density, assumed fluid saturation, calculated fluid density at reservoir conditions and assumed solid rock density to calculate porosity (ϕ) at each location.

3. Use the corrected density, compressional sonic log and shear sonic log to calculate the undrained bulk modulus (K_U) at each location.

4. Calculate the fluid bulk modulus (K_F) assuming a fluid saturation and the bulk moduli of the fluids at reservoir conditions.

5. Assume the solid grain bulk modulus (K_S).

6. Use K_S, K_U, ϕ, K_F and the Gassmann equation (1) to calculate the dry bulk modulus (K_D) at each location.

The values of V_P, V_S and ρ_U^C are used to generate the synthetic seismograms for the original conditions.

Updating Physical Parameters

Synthetic seismograms will be calculated from the previously measured or estimated values of V_P, V_S and ρ_U^C. Estimates of new reservoir pressure temperature and saturation distributions are made. We wish to calculate new synthetic seismograms that incorporate the change in reservoir conditions into the seismic response. The procedure is summarized in Figure 2.

From the logs and the previously described procedure, estimates of K_D, ϕ, K_S and μ_U are available. Both K_D and μ_D change with changing effective pressure. Using data from Han, et al. (1986) we found that the average change for dry bulk modulus of sandstones with effective pressure could be modeled by:

$$\frac{dK_D}{dP_{eff}} = 0.2437 \exp\left(-0.0582 P_{eff}\right) \tag{9}$$

and the dry shear modulus by:

$$\frac{d\mu_D}{dP_{eff}} = 0.2794 \exp(-0.0549 P_{eff}) \tag{10}$$

these expressions do not account for velocity dispersion associated with high frequency lab measurements and will under predict the changes with respect to effective pressure. A procedure for accounting for velocity dispersion is currently being developed (Zhang and Bentley, 1999).

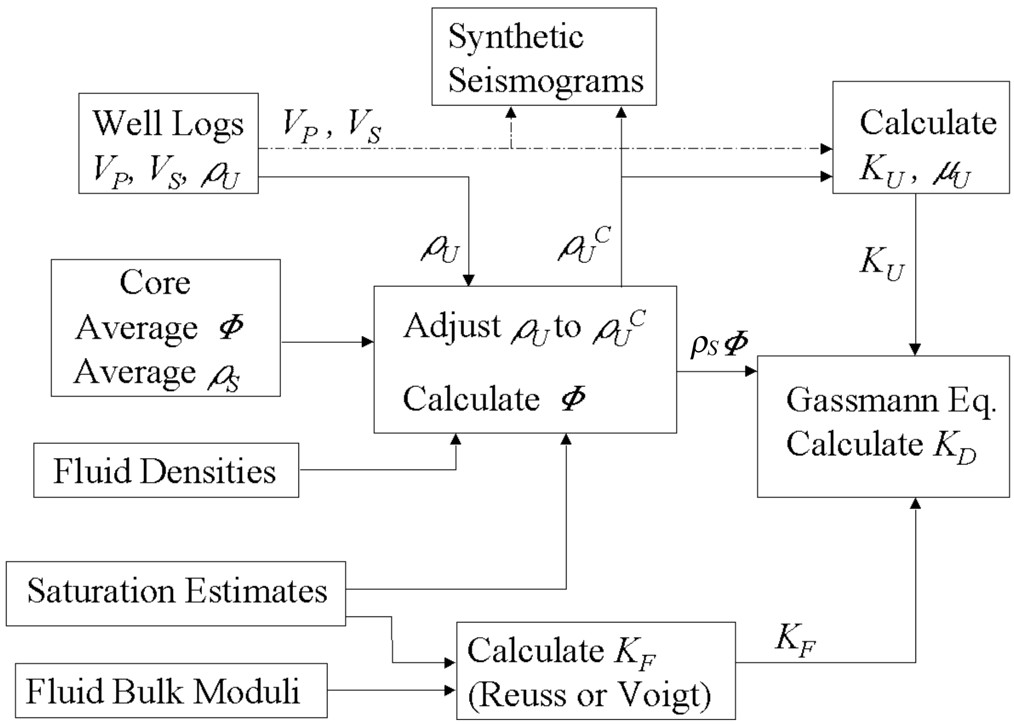

Figure 1. Procedure for calculating K_D and beginning state synthetic seismograms.

The procedure for estimating velocities and densities at a given set of reservoir conditions is summarized:

1. Specify new pressure within the reservoir.

2. Using equations (9) and (10), calculate new dry bulk (K_D^N) and shear moduli (μ_D^N) at each point in the zone.

3. Specify new saturations within the production zone.

4. Calculate new gas, oil and water bulk moduli and densities at the specified reservoir temperature and pressure (K_G^N, K_O^N, K_W^N, ρ_G^N, ρ_O^N, ρ_W^N) using the procedures described in the fluids section.

5. Calculate new fluid density (ρ_F^N) using equation (3) at each point.

6. Use solid density, porosity and the new fluid density to calculate new density at each point (ρ_U^N).

7. Approximate the new fluid bulk modulus (K_F^N) using either equation (4), (5) or an intermediate value.

8. Use the new dry bulk modulus, new fluid bulk modulus, previous porosity and Gassmann equation (1) to calculate the new undrained bulk modulus (K_U^N) at each point.

9. Use the new undrained bulk modulus, new shear modulus and new density to calculate a new compressional wave velocity (V_P^N) at each point.

10. Use the new shear modulus and new density to calculate new shear velocity (V_P^N) at each point.

11. Calculate synthetic seismograms using V_P^N, V_S^N and ρ_U^N.

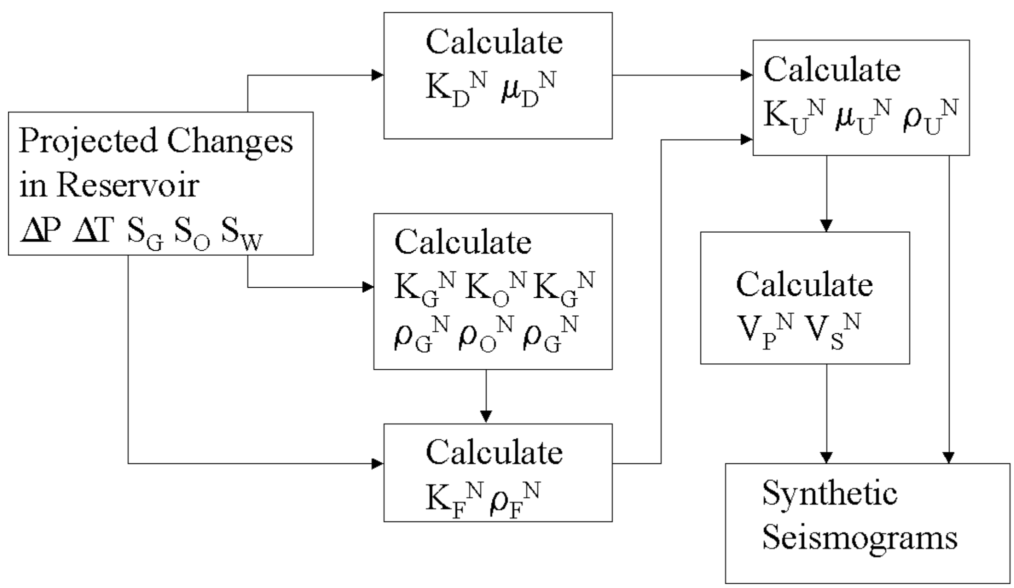

Figure 2. Update Procedure

FEASIBILITY ANALYSIS

The updated V_P, V_s and ρ_U can be used to predict an updated seismic response. The updated seismic response can then be compared to the original response. Figure 3 shows a projected percentage change in the compressional and shear wave velocities over a portion of reservoir which has reached the bubble point. In this case, the compressional velocity has decreased about one percent because the bulk modulus of the pore fluids decreased with the addition of a gas phase. The shear velocity increased slightly over one percent because the bulk density decreased with the replacement of some of the oil phase with gas phase. The compressional velocity changes are small because the dry bulk modulus is large and changes in the bulk modulus of the pore fluids have little effect on the undrained bulk modulus.

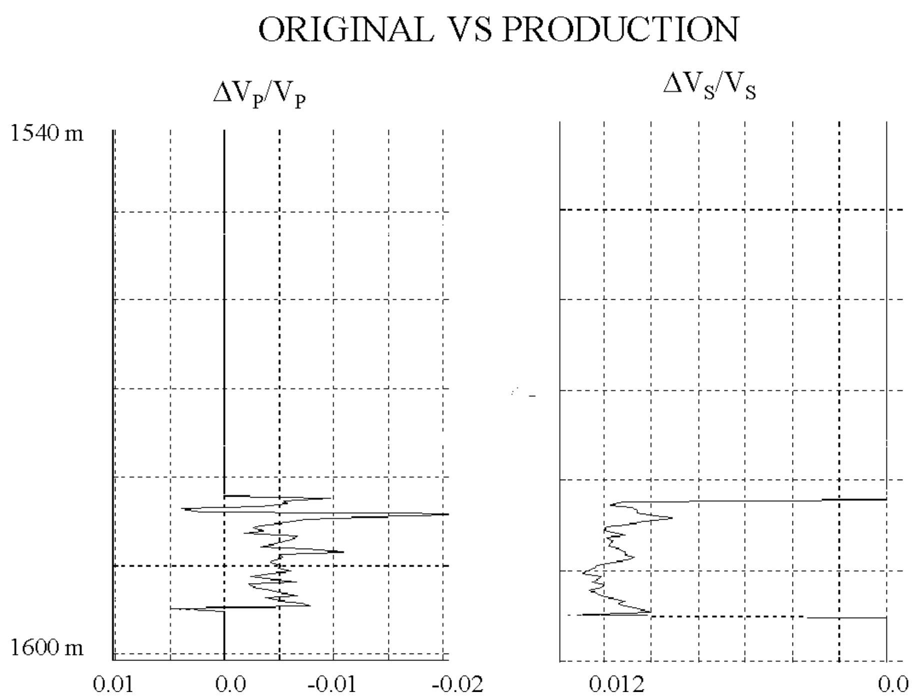

Figure 3. Percentage change in compressional wave velocity and shear wave velocity.

Synthetic shot gathers can also be generated to compare the predicted before and after production responses. Figure 4 shows an example of a comparison of synthetic shot gathers. The figure shows the original synthetic gather, the updated synthetic gather and the difference between the gathers. The difference between the first traces is plotted with the first trace of the original seismic response, giving an indication of the percentage change due to the predicted change in stiffness and density.

CONCLUSIONS

The bulk modulus, shear modulus and density of fluid filled rocks changes with changes in fluid saturation, reservoir pressure and effective pressure. The Gassmann equation is used to predict the change in the undrained bulk modulus of the fluid filled rocks if the changes in dry bulk modulus and fluid bulk modulus can be predicted.

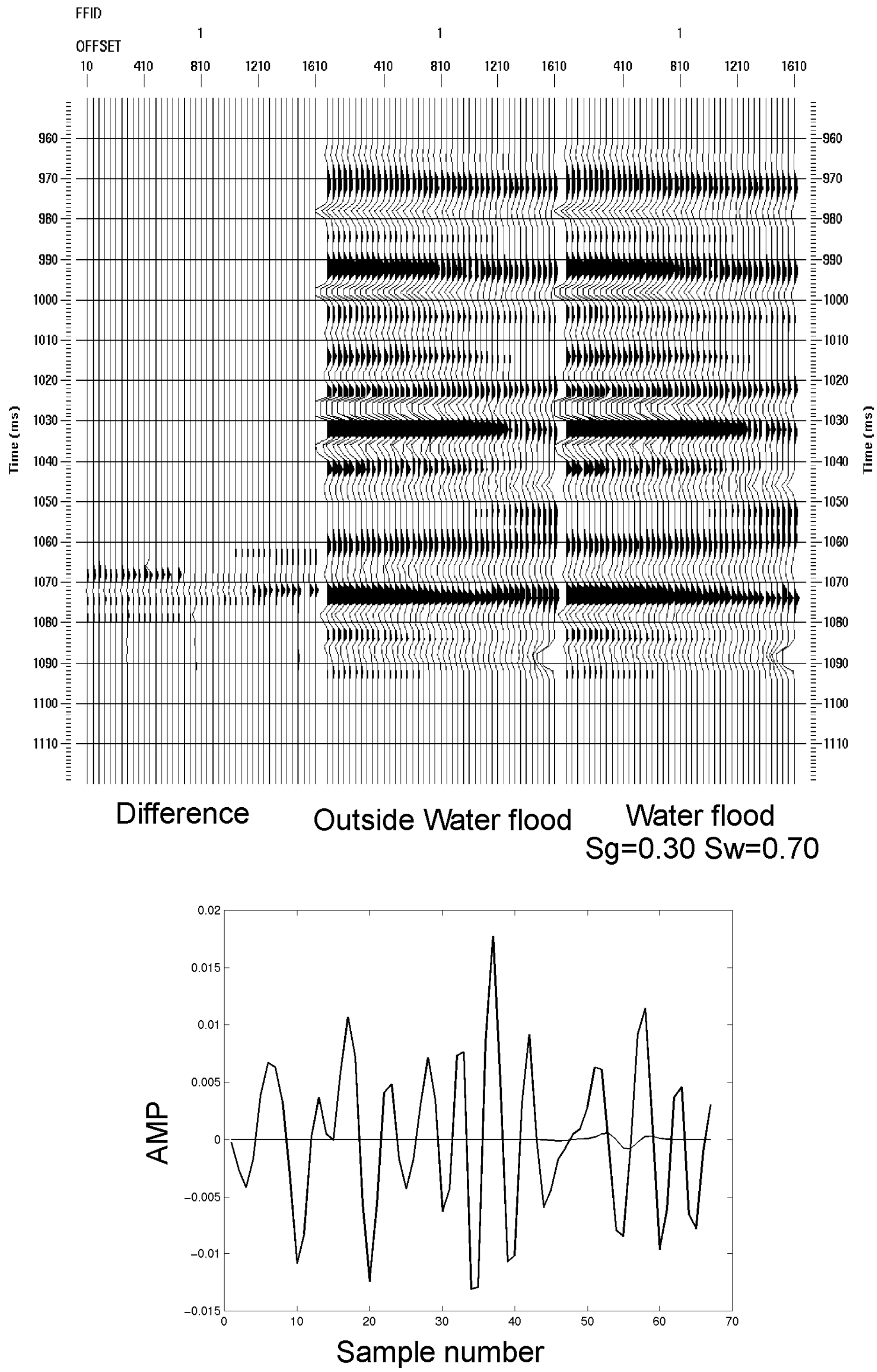

Figure 4. Comparison of Synthetic shot Gathers. Synthetic shot gathers within and outside of a water flood zone and the difference between them. In addition, trace 1 from outside the water flood zone is plotted with the difference of trace 1. In this case the percentage change is small.

Individual fluid properties change with changing reservoir conditions. The change in the bulk modulus and density of gas oil and water due to the change in reservoir pressure and temperature can be predicted from empirical relationships. The bulk modulus of the fluid mixture is an average of the bulk moduli of the individual fluids. The appropriate choice of averaging is dependent on the small-scale fluid distribution and the frequency of the seismic waves. For homogeneously distributed fluids, the appropriate average is the saturation weighted harmonic average. The harmonic average places a stronger importance on the lower values of the bulk moduli. The other end member is the saturation weighted arithmetic average which place stronger importance on the higher values of the bulk moduli. It is appropriate when the fluid distribution is patchy. The actual value of the fluid mixture bulk modulus is between the end member cases.

The change in the dry bulk modulus and shear modulus of the reservoir rock due to changes in temperature and pressure can be predicted from relationships empirically derived from published data. For moderate to large effective pressures, the change in dry bulk modulus due to changes in effective pressure will typically be a minor effect.

The Gassmann equation is used with the change in dry bulk modulus and fluid mixture modulus to calculate a new undrained bulk modulus. Combining the undrained bulk modulus, shear modulus and new density, new values for the compressional wave velocity, shear wave velocity and density are derived. Percentage changes in compressional wave velocity, shear wave velocity, acoustic impedance, compressional-shear wave velocity ratios and other attributes can be investigated for significance. In addition, synthetic shot gathers can be generated and differenced. These displays can then be used to assess the potential for observing reservoir production induced changes in the seismic response.

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REFERENCES

Batzle, M. and Wang, Z., 1992, “Seismic properties of pore fluids,” Geophysics, 57, 1396-1408.

Bentley, L.R., Zhang, J. and. Lu, H.-X. 1999B, “Four-D seismic monitoring: Blackfoot Reservoir Feasibility,” this CREWES Research Report.

Mavko, G. and Mukerji, t., 1998, “Bounds on low-frequency seismic velocities in partially saturated rocks,” Geophysics, 63, 918-924.

Vasquez, M. and Beggs, H. D., 1980, “Correlations for fluid physical property predictions,” JPT, 32, 968-970.

Wang, Z. and Nur, A., 1992, “Elastic wave velocities in porous media: a theoretical recipe,” in Seismic and Acoustic Velocities in Reservoir Rocks, Vol. 2 Theoretical and Model Studies, (ed.s Z. Wang and A. Nur), SEG, 1-35.

Zhang, J. and Bentley, L. R., 1999, “Change of bulk and shear moduli of dry sandstone due to change of effective pressure and temperature,” this CREWES Research Report.