Application of the new Gassmann theory in seismic modeling of selected gas reservoirs, offshore Netherlands. Aaron E. Auduson*, Delft University of Technology

Summary

In the Southern North Sea, Buntsandstein reservoirs which, can be gas- or water-bearing, frequently contain solid (salt) in the pores spaces. Recent literatures on extension of the Gassmann equation investigate the substitution of fluids and solids in the pore space of reservoir rock. Conventional substitution (fluids only) is described by the Gassmann equation, whereas extension of this theory is needed to account for solid material (such as salt) in the pore-space. First, the impact of solids in the pore-space was assessed and modelled. With this model, gas- and water-bearing wells were substituted into salt, and vice versa, to verify interpretation. With this modified rock physics framework, predictions were made for Amplitude Versus Offset (AVO) behaviour. The substitution between gas, water and salt correctly predicted the elastic moduli and therefore the AVO behaviour of salt-plugged intervals. It is demonstrated that salt-plugged wells show clearly different elastic parameters with respect to gas- and water- bearing wells. This led to an improved understanding of the rock physical behaviour of gas- bearing and salt-plugged reservoirs in the Lower Volpriehausen formation. With this understanding in mind, interpretation risk is reduced when interpreting the top of the Volpriehausen reservoir in particular. The results of this research should lead to an improved characterization of the Buntsandstein reservoirs and as a result, to a higher success rate in drillings (i.e. less “dry wells”).

Introduction

Predicting the quality of Buntsandstein reservoirs of the Southern North Sea gas fields based on seismic data only has proven a major exploration challenge in the area due to salt-plugging. The seismic response resulting from the presence of salt in the reservoir pore spaces at a glance, look similar on post-stack data as it would for gas-filled reservoirs. Many wells failed for this reason; hence, solution is to be found by modelling and characterizing the salt-plugging scenarios.

Conventional substitution has been described by the Gassmann equation (Gassmann, 1951), as:

$$K_{dry} = \frac{K_{sat} \left(\frac{\phi K_0}{K_{fl}} + 1 - \phi \right) - K_0}{\frac{\phi K_0}{K_{fl}} + \frac{K_{sat}}{K_0} - 1 - \phi} \quad (1)$$

$$K_{dry} = K_{dry} + \frac{(1 - \frac{K_{dry}}{K_0})^2}{\frac{\phi}{K_{fl}} + \frac{1 - \phi}{K_0} - \frac{K_{dry}}{K_0^2}} \quad (2)$$

$$\mu_{dry} = \mu_{sat} \quad (3)$$

Where;

K_0 = bulk modulus of mineral material making up the rock.

K_{dry} = effective bulk modulus of dry rock.

K_{sat} = effective bulk modulus of the rock with pore fluid

K_{fl} = effective bulk modulus of the pore fluid

ϕ = Porosity of the reservoir rock

The extended version of this theory (Ciz and Shapiro, 2007; Ciz et al. 2008) accounts for solid materials (such as salt) in the reservoir pore spaces (equations 4 and 5).

$$K_{sat}^{*-1} = K_{dry}^{-1} - \frac{(K_{dry}^{-1} - K_{gr}^{-1})^2}{\phi(K_{if}^{-1} - K_{\phi}^{-1}) + (K_{dry}^{-1} - K_{gr}^{-1})} \quad (4)$$

and

$$\mu_{sat}^{*-1} = \mu_{dry}^{-1} - \frac{(\mu_{dry}^{-1} - \mu_{gr}^{-1})^2}{\phi(\mu_{if}^{-1} - \mu_{\phi}^{-1}) + (\mu_{dry}^{-1} - \mu_{gr}^{-1})} \quad (5)$$

Where:

K_{sat}^{*-1} and μ_{sat}^{*-1} are solid saturated bulk and shear moduli;

K_{dry} and μ_{dry} denote drained bulk and shear moduli of the porous frame;

K_{gr} and μ_{gr} represent bulk and shear moduli of the grain material of the frame;

K_{if} and μ_{if} are bulk and shear moduli related to the solid body of the pore infill;

K_{ϕ} and μ_{ϕ} are the bulk and shear moduli related to the pore space of the frame.

The current objective of the study is to use this new Gassmann model in performing solid-fluid substitution in order to distinguish between salt-plugged and potential gas-bearing reservoirs in the lower Volpriehausen formation , thereby studying the seismic response at various existing

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wells covering different reservoir depths with the appropriate logs. Previously, synthetic-to-seismic calibration at the well locations (Auduson, 2010, 2013) has been carried out earlier. The analyses were carried out on six wells labeled as WTR, WTR3, GAS, SALT, SALT2 and SALT3 that penetrated the Buntsandstein reservoirs within the Lower Volpriehausen formation (the target location of this investigation).

Methodology

This involves conceptual modeling and fluid substitution, in which parameter (elastic and acoustic) codes were generated using scientific programming and software for the respective substituent: gas, water and salt on the bases of which predictions were made for the elastic moduli and the AVO behaviors. AVO (Amplitude Variation with Offset) responses, elastic and acoustic parameters were used to indicate the differences of the fluid- and solid-filled reservoir scenarios. For the AVO analysis, the solution of Shuey's (1985) approximated Zoepppriz (1919) equation which assumes small layer contrasts was used.

Input parameters (V_p and V_s), as the average sets of each type of well (table 1) were modeled with empirical relations based on the locally derived Greenberg-Castagna parameters (Castagna et al., 1998). Then, with programming, the bulk (K) and shear moduli (μ) were calculated for all types of pore fillings the using following relations respectively (equations 6 and 7):

$$\mu = V_s^2 \rho \quad (6)$$

and

$$K = V_p^2 - \frac{4}{3} \mu \quad (7)$$

Based on these elastic properties and characteristic velocities, the reflectivity between an average shale and the sandstone with different pore-filling was calculated, again with code generation. This was performed to check the sensitivity of parameter input in the Shuey's equation and to understand the steps behind the program's blocky AVO analysis. With these modeling exercises, the rock physics model was fully constrained and calibrated.

Table 1: Three well examples of average Shale and a Sandstone Rock Physics parameter values - Column A, B and C respectively are the real gas-bearing well, the real water bearing well and the average of the salt-plugged zone.

Parameters	A(Gas)	B(Water)	C(Salt)	Average Shale	Sand-stone
V_p (m/s)	3952	40001	4757	4164	6000
V_s (m/s)	2426	2228	2868	2279	4000
ρ (g/cm ³)	2.292	2.355	2.556	2.62	2.65
Φ (g/cm ³)	15	15	3-6	<1	10
GRC(API)	50-65	40-60	44-55	>80	Nil
K (GPa)	17.7	22.1	28.6	27.2	38.8
μ (GPa)	13.4	11.7	18.6	13.5	42.4

Further, parameters such as the Young's modulus E , Poisson's ratio $\Delta\sigma$, acoustic impedance AI , elastic impedance EI were calculated with average initial velocities. Using the program's modeler, codes were generated based on the new Gassmann model for solid substitution which were used to calculate the bulk and shear moduli. To this end:

- Gas-bearing reservoir was substituted into salt- and water-bearing reservoir intervals;
- Salt-plugged well was substituted into water and gas well;
- Water-bearing well was substituted into gas and salt pore fillings.

Next, for seismic modeling, 'Wavelet estimation through matching' method as described in White and Simm (2003) was followed. Reflectivity series was generated from log data in two-way traveltime (TWT) and convolved (Funck et al, 1998) with Ricker wavelet. This was done for original wells within the 3D seismic survey area and the two pseudo-wells created. The compressional velocity, shear wave velocity and density set (V_p - V_s - ρ) prepared was selected for the respective well and Ricker wavelet was created using sample interval 2ms at frequency 25Hz. Iterative stretch/squeeze and extraction of statistical wavelets was routinely performed. The result of this procedure displayed in Figures 1.

In each well tie, the input seismic time window was defined by the "cross correlation range" and for maximum output, 500msec was the cross-correlation time interval. In the data used for this study, neural network technique was adopted where the time-converted log data was covering too little interval; hence, to make the estimation work reliably, a minimum of 300ms time window was used in the simulation.

Accuracy is measured by the phase error within the seismic bandwidth which can be found roughly from:

$$S.E[Phase] \approx \sqrt{\left(\frac{1}{bT} * \frac{1-P}{P}\right)} / 2rads \quad (8)$$

Where ;

$\frac{1}{bT} * \frac{1-P}{P}$ is the NMSE (normalized mean squared

error); b represents seismic analysis bandwidth; T is the time window; P is the Predictability and S.E is the squared error.

Solid-fluid Substitution and Predictive Modeling

Forward seismic modeling involved creation of artificial wells from real well tagged WTR well (figure 1). Both the Poststack and Prestack synthetics were generated for two pseudo wells created using fluids and solid substitutions. The pseudo logs were used in the V_s - V_s - ρ sets for

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The columns for the Poststack and prestack seismic models calibrated with the real poststack seismic (figure 1) from left to right show:

- Gamma ray log; used for the stratigraphical interpretation.
- Volume of shale (Vsh) indicated for N/G ratio.
- Calibrated compressional wave velocity (Vp) log from sonic.
- Calibrated shear wave velocity (Vs) log from sonic.
- Calibrated density log.
- Reflectivity (amplitude) series convolved with the wavelet; designated as 'Refl'.
- Real poststack seismic section displaying seismic trace along the well path.
- Seismic trace selected on PEP plot.
- Synthetic trace using selected wavelet.
- Composite seismic trace at well location.
- Real seismic wiggle traces.
- Synthetic seismic wiggle traces stacked from the gather.
- The pre-stack model to evaluate the AVO.

synthetics when 80% of the water-bearing well became filled with gas and salt each. These are now two 'wells' referred to as 'GASintoWTR' and 'SALTintoWTR' respectively. Figure 2 displays gathers of GAS substituted

into water and SALT substituted into water, compared with the originally water-filled pores spaces of the reservoir interval (Lower Volpriehausen particular)

Discussion of Results and Conclusions

Interpreting from the diagram in figure 1 using the green horizontal dashed lines, we can observe that:

The match between the seismic (both Poststack and Prestack) and its correlation with logs shows a good. For the salt substituted into water artificial well, the frequency of the real seismic data is higher compared with the synthetic model and the magnitude of the amplitude as observed in the original salt wells is consistent.

The amplitude behaviour in the initial reservoir pore spaces filled with water (figure 1) and those of the pseudo well logs (figure 2) are different, indicating the influence of fluid change (in the case of GASintoWTR) and solid (in the case of SALTintoWTR) on amplitude responses and seismic signals. The amplitude signal in the initial water-filled scenario is moderate while that of the pseudo gas-filled is high and that of the pseudo salt-filled is lower, conforming to the expectations in the normal reservoirs.

The substitution from initial water-filled into pseudo gas-filled reservoir shows the expected decrease in compressional velocity and density, while shear velocity remains relatively constant (Red rectangle around the

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The columns in figure 2 show from left to right:

- Track one: the gamma log.
- Track two is a representation of the clay and sand volume fractions.
- Track three: the three compressional-wave velocity (V_p) logs (blue for initial water-filled pores, and the set of substituting pseudo logs of gas (red) and salt (dark green)).
- Track four: the three shear-wave velocity (V_s) logs (blue for initial water-filled pores, and the set of substituting pseudo logs of gas (red) and salt (dark green)).
- Track five; shows the initial density log for water (blue) and a set of pseudo density logs for substituting logs of gas (red) and salt (dark green).
- Track six: 3D seismic section around the water well.
- Track seven: gather for initial water-filled reservoir.
- Track eight: gather for Water to gas substituted
- Track nine: gather for water to salt substitute

Lower Volpriehausen reservoir interval (figure 2). Also, the expected increase in compressional velocity and density, and relatively constant shear velocity in the salt substituted into water scenario is observed (figure 2).

We notice in this work that application of the new Gassmann theory (Ciz and Shapiro, 2007; Ciz et al, 2008; Auduson et al, 2010 and Auduson, 2012) from one well to another did not give satisfactory results, for example, predicting the response of a salt well from a water well (cf. Gurevich et al, 2008). This may be due to the variability in the input parameters between the different wells preventing a universal application in the area. However, for a single well, with a water-filled reservoir compartment plugged by salt only partially, a very good prediction of the sonic and density properties in these different zones has been

achieved with the theory (cf. Stuermer et al, 2008). With the interpretations of the various scenarios, the difference between the amplitude signals of the water-, gas- and salt-filled reservoir pore medium is made clearer:

- ❖ Water-filled reservoir medium shows amplitudes of moderate magnitude with normal (North Sea) polarity
- ❖ Gas-filled medium has larger amplitude magnitude with normal (North Sea) polarity;
- ❖ Salt-filled porous medium shows lower amplitude magnitude with reversed polarity; normal-averaged negative amplitudes.

With this understanding in mind, interpretation risk is reduced when interpreting the top of the Volpriehausen reservoirs. This will help in finding good quality reservoirs rather than poor-quality, salt-filled reservoirs.

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EDITED REFERENCES

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