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Summary

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Prediction of porosity and fluid in chalk from acoustic measurements

Ph.D. Thesis
Environment & Resources DTU

by

Lars Gommesen
January 2003

Summary

Objective

Using seismic data for predicting high porosity reservoir zones in chalk has provided promising results within hydrocarbon exploration and production. Research is therefore aimed at a better quantification of the limitation of this method and at an improved understanding of the link between the elastic response of the chalk and the variation in porosity and pore fluid.

The objective for the Ph. D. study is thus to provide reliable predictions of variations of porosity and pore fluid in North Sea chalk from acoustic measurements.

Background and motivation

Recent discovery of significant gas and oil reserves in high porous North Sea chalk of Danian and Maastrichtian age outside the structural traps has increased the interest for the predictability of porosity and pore fluid from seismic measurements (Jacobsen *et al.*, 1999).

In spite of the renaissance in exploration for North Sea chalk targets a relatively limited number of papers directly discuss dynamic elastic porosity models (Borre, 1998; Walls *et al.*, 1998; Anderson, 1999; Vejbæk & Kristensen, 2000; Gommesen & Fabricius, 2001, Røgen *et al.*, *in review*). This combined with the ambiguity of using AVO analysis in carbonates in general, support the need for continued research aimed at understanding and predicting the elastic behaviour of North Sea chalk.

Rock physics modelling indicates that e.g. amplitude versus offset (AVO) behaviour is controlled by the presence of porosity and hydrocarbons. Thus predicting elastic properties of reservoir rock from their dependence of porosity and saturating pore fluid are key aspects when modelling seismic reflectivity and interpreting seismic data.

However, several important issues should be considered before seismic modelling is carried out.

A rigorous elastic model is fundamental for the seismic modelling of reservoir rock. The elastic properties of a rock are described by its elastic moduli, which may be calculated from the compressional velocity, the shear velocity, and the bulk density of the rock, if the rock is assumed to behave linearly elastic and therefore obey Hooke's law of elasticity.

An elastic model may be established from different types of data such as e.g. data measured in the laboratory on plugs sampled from core material or from wire-line logging data measured *in situ* or both. Although both types of data have advantages, the continuous data sampling in the logging interval and the relatively higher availability of logging data make it useful to base an elastic model on logging data.

Effective medium theory indicates that porosity is the dominating parameter controlling the elastic properties of porous media such as sedimentary rocks (Voigt, 1928; Reuss, 1929; Hashin & Shtrikman, 1963; Kuster & Toksöz, 1974; O'Connell & Budiansky, 1974; Berryman, 1980). Upper- and lower bounds predict limits of elastic behaviour of porous rock as function of porosity without specifying the pore geometries (e.g. Hashin & Shtrikman, 1963). However, Nur and co-workers introduced the critical porosity concept, making the predicted the upper bounds of elastic behaviour significantly lower than e.g. the upper Hashin-Shtrikman bound (Nur *et al.*, 1991; Yin *et al.*, 1993; Nur *et al.*, 1995; Gal *et al.*, 1998). Accordingly, a chalk model should be porosity dependent and based on an upper critical porosity.

Other factors may also contribute to the effective elastic properties of porous reservoir chalk. Recent studies indicate that an increased presence of contact cement in the chalk matrix can increase the acoustic velocity without a significant change in porosity (Fabricius, 2002). Because the progress of cementation in chalk may be debilitated by hydrocarbons trapped in the reservoir (Scholle, 1977), one should study the elastic properties of both fully brine-saturated and hydrocarbon/brine-bearing chalk to look for differences and ideally map the potential influence from contact cement.

For porous rocks, variations in the elastic properties of the saturating fluid also influence the effective elastic properties. In this context the fluid substitution method is an important tool, because it makes it possible to predict the elastic response of a rock saturated with one type of fluid from the elastic response of the same rock saturated with another fluid. Successful use of the often-applied Gassmann (1951) theory has been reported for permeable granular rock (e.g. Murphy, 1982), but the Gassmann's theory has also been applied to carbonates (Marion and Jizba, 1997; Wang, 1997) and to North Sea chalk (Borre, 1998). However, for low permeability rocks, such as the North Sea chalk one could argue that inclusion based scattering theories (e.g. O'Connell & Budiansky, 1974; Kuster & Toksöz, 1974; Berryman, 1980) would be more appropriate. Sørnes and Brevik (2000) specifically discussed this issue for carbonates by comparing the Gassmann predicted estimate with the estimate predicted by the non-self-consistent scattering theory given by Kuster and Toksöz (1974), although a question remained unanswered: How well does the fluid substitution estimate of respectively the Gassmann and e.g. the Kuster-Toksöz theory actually correlate with the acoustic log response of a hydrocarbon-bearing chalk?

The fluid effect on the elastic rock properties may potentially be predicted from the compressional- and the shear velocity, and the bulk density. However, shear wave logging is not applied routinely. Thus the fluid effects on the compressional velocity have to be predicted from different rock physics theories without the shear velocity, or the shear velocity has to be predicted from the data available by either rock physics theory or empirical relations. In either case, one must verify the respective applicability for the actual type of rock, before such procedures are followed.

AVO analysis has traditionally been applied to clastic environments but has within the last decade been used as a successful porosity predictor in carbonates (Landrø *et al.*, 1995; Santoso *et al.*, 1995; D'Angelo *et al.*, 1997; Li & Downtown, 2000). However, AVO analysis as a fluid prediction tool in carbonates has only been successfully applied in a limited number of cases (Megson, 1992; Chiburis, 1993; Adriansyah & McMechan, 2001). Unique hydrocarbon signatures are only found at extraordinary conditions of very high porosity and gas saturation because the hydrocarbon effect is believed to overlap the changes caused by variations in porosity (Megson, 1992). However, is it possible from seismic modelling to separate the effects from hydrocarbons and porosity, respectively?

Approach

How does this study approach the prediction of variations of porosity and fluid in North Sea chalk from acoustic measurements?

Seismic surveying is a central tool in exploration of hydrocarbon resources. Thus, it is the aim of the to extract as much information as possible from the seismic data. In an ideal case, analysis and interpretation of seismic data may lead to estimates of porosity and saturating pore fluid of the potential reservoir rock. However, as mentioned in the previous paragraph a range of important considerations makes the basis for proper seismic modelling such as 1) the elastic properties of the studied porous rock, 2) the influence of fluid on the elastic properties, and 3) the impact of the porosity and fluid on measurements in the seismic domain.

The Ph. D. project addresses these topics.

The resolution of the wire-line logging data is considered sufficient for studies that aim at a better understanding of seismic behaviour in relation to petrophysical parameters because of the relatively lower resolution in seismic data. The acoustic properties of chalk are therefore studied through both integrated analysis of wire-line logging data focusing on the compressional and shear velocity logs, and through modelled synthetic seismic tied to measured zero offset seismic data.

The bridging of the two types of acoustic measurements, sonic and seismic, serves two purposes in this research. First, the relatively high degree of information that logging data gives is vital for a project of this kind., Logging data provide us both with the elastic rock properties, with the petrophysical parameters such as e.g.

porosity and fluid saturation, and with additional parameters as e.g. resistivity. Integrated, the logging data makes it possible to study how parameters as porosity and pore fluid are linked to elastic rock properties and relate the observations to rock physics theory. Secondly, the bridging aim to identify to which extent the observations and results obtained from the logging domain are detectable in the seismic domain.

The approach used for this project can be subdivided into three main areas, 1) elastic behaviour, 2) influence from fluids, and 3) seismic modelling, discussed in the following.

Elastic behaviour

The elastic properties of a subsurface formation are the only properties which directly are measured in the seismic data. Because the purpose of this research is to extract porosity and pore fluid information from acoustic measurements, it is fundamental that the influence of petrophysical properties on the elastic properties is adequately adressed.

The purpose of this part of the study is therefore to establish a relationship between petrophysical parameters and elastic properties from wire-line logging data.

The elastic properties of rock are influenced by the properties of the minerals of the solid phase. Although, we generally expect the studied North Sea chalk of the Ekofisk, Tor and Hod formations to be relatively pure with a high content of calcite (e.g. Andersen, 1995), it is necessary to estimate the shale content (e.g. from the gamma ray log) in order to evaluate the elastic properties of the solid phase of the chalk.

An integrated log analysis makes it possible to study detection of cementation and its influence on the elastic properties. From the interaction of the density (ρ) and the compressional and shear velocity (v_P and v_S) data it is possible to calculate the elastic moduli, which describes the elastic properties of a rock (e.g. Mavko *et al.*, 1998). The studied moduli are bulk and shear modulus (respectively K and μ, where $K=\rho(v_P^2-4/3v_S^2)$ and $\mu=\rho v_S^2$) and Poisson's ratio (ν, where $\nu=½(v_P^2-2v_S^2)/(v_P^2-v_S^2)$).

Also Biot's coefficient (β), defined as one minus the ratio of the bulk elasticity of the dry rock (K_{dry}) relative to the bulk elasticity of the solid phase forming the rock (K_0) (Biot, 1941), can be calculated. β may vary for a given porosity, and if we assume K_0 to be constant, a decrease in β is caused by an increase in K_{dry} which can be interpreted as an increase in the amount of contact cement.

Independently of this approach we calculate the cementation factor (m) and the formation factor (F) from Archie's equation (Archie, 1942) using resistivity log data. The cementation factor indicates how well the pores of a rock are connected and is related to the formation factor so that $F=a/\varphi^m$, where a is an empirical constant and φ is porosity. The formation factor is defined as the resistivity of a fully brine-saturated formation relative to the brine resistivity. The cementation factor is considered to depend on degree of cementation and porosity.

The two sets of data, which respectively depend on acoustic properties and resistivity of the chalk accordingly gives the opportunity to discuss how detectable cementation is, and how much it influences the elastic behaviour of the chalk.

As mentioned in the previous chapter it is reasonable to consider porosity as the primary parameter to control the effective elastic properties of the rock. For an elastic model we therefore consider the upper and lower bounds to be equal to respectively the upper modified Hashin-Shtrikman bound, *MUHS*, (Hashin & Shtrikman, 1963; Gal *et al.*, 1998) and the lower Reuss bound (Reuss, 1929). The *MUHS* bound represents a principal Hashin-Shtrikman bound normalised to a critical porosity that separates the solid component from being either matrix or in suspension. The Reuss bound, which relates the constituents of the rock as a harmonic mean, represents the suspension bound for a given porosity.

We aim to predict the effective elastic bulk and shear moduli of brine-saturated chalk from a weighted summation of the two bounds mentioned above so that $K_{eff} = (1-w)K_{MUHS} + wK_{Reuss}$ and $\mu_{eff} = (1-w)\mu_{MUHS} + w\mu_{Reuss}$, where the weighting factor w may attain values between zero and one and is an increasing function of porosity for respectively the bulk and the shear modulus. The critical porosity is chosen at 70% (Lind, 1997). We consider the elastic model to be semi-empirical because w is fitted to data but always cause predictions to be within the physically possible elastic bound.

Influence from fluids

The effective elastic properties of a porous rock vary as an effect of varying pore fluid mixture because different fluid mixtures of e.g. brine-oil or brine-gas have different elastic properties.

Successful prediction of porosity and pore fluid has been reported using the P-wave impedance – Poisson's ratio domain (Avseth *et al.*, 2001; Hansen *et al.*, 2001; Mukerji *et al.*, 2001). Accordingly we wish to compare the predicted and measured responses of the hydrocarbon-bearing chalk in this domain.

A way to study the influence of fluids on elastic properties is through fluid substitution. As mentioned in the previous chapter, one can calculate the elastic response of a porous rock saturated with one type of fluid from the elastic response of the same rock saturated with another fluid. However, although some fluid substitution methods are more often applied than others, it is important to note that different methods may have different initial assumptions and may lead to different results.

Which fluid substitution theory is suitable for North Sea chalk? It may have been appropriate to compare the often-applied Gassmann theory with a self-consistent scattering theories such as e.g. presented by Berryman (1980), because the self-consistent theories are found to satisfy the Hashin-Shtrikman bounds also for high porosities (Berryman, 1980). However, because previous studies of North Sea chalk either compare the Kuster-Toksöz theory with the Gassmann theory (1951) or apply one of these two theories to predict fluid effects, we find it relevant to test how well specifically these two theories actually predict the fluid effects as they are measured in the sonic frequency domain by the acoustic logging tool. Some important differences in the assumptions of the two theories are: The low-frequency Gassmann theory assumes that isotropically distributed pores in a homogeneous solid phase are connected and communicate, whereas the Kuster-Toksöz theory assumes that the pore space can be described as isolated inclusions. The Gassmann theory is independent of pore geometry, whereas the geometry of the inclusions needs to be specified in the Kuster-Toksöz theory.

When fluid substitution is carried out the elastic properties of the fluid mixtures is an important input. Fluids behave elastically different as a function of pressure and temperature and may be described by the empirical relations presented by Batzle and Wang (1992) as cited in Mavko *et al.* (1998). However, not only is it essential to estimate the elastic properties of the different fluid types (brine, oil, and gas), it is also important to consider how the actual constituents of a fluid are mixed. One may mix the corresponding elastic moduli of the constituents by either the harmonic mean or the arithmetic mean. The harmonic mean assumes that the constituents are homogeneously mixed on a small scale whereas the arithmetic mean assumes the constituents are irregularly mixed. In this study the method presented by Berryman *et al.* (2002) is used to evaluate the type of mixture of the constituents.

As mentioned in the previous paragraph we need bulk density, compressional velocity, and shear velocity to calculate e.g. the bulk and shear modulus. However, shear velocity data are not always available thus it may be necessary to predict fluid effects from the accessible parameters (ρ and v_P) with or without predicting the shear velocity.

As a supplement to the study described above, we aim to test how well fluid effects in North Sea chalk are predicted without knowing the shear velocity and how well shear velocity is predicted from the compressional velocity using either rock physics theories or empirical relations.

Seismic modelling

This part of the Ph. D. project focuses mainly on the seismic behaviour at the interface of the commonly encountered North Sea sequence of chalk overlain by shale, but also discusses the seismic behaviour of porosity variations within the chalk.

The potential and limitation of prediction of pore fluid and porosity in the seismic frequency domain will be studied through two different approaches.

The first, general approach is based on the previously established elastic model for brine-saturated chalk. The elastic model makes it possible to perform fluid substitution on chalk within a wide porosity range so that the elastic response of hydrocarbon-bearing chalk (brine-oil and brine-gas mixtures) can be estimated. By choosing fixed elastic properties of the overlying shale and including the elastic properties of chalk saturated with different pore fluid one by one, we aim to study the seismic behaviour at the interface between shale and chalk for different angles of incidence of the down-going compressional wave.

Accordingly, this first approach aims to estimate the development in seismic behaviour versus angle of incidence for chalk of different saturations and different porosity.

In addition to the first approach we test if small variations (uncertainties) in the input parameters of the two fluid substitution methods of the previous paragraph (respectively the Gassmann and the Kuster-Toksöz theory) have any impact on the modelled seismic behaviour. We test the sensitivity to the inputs by Monte Carlo simulations by introducing Gaussian variations following the same approach as Sengupta *et al.* (1998).

The second, practical approach is based on case studies. Models of density and velocity versus depth, obtained from wire-line logging data from two different North Sea sites, are used as inputs for calculation of synthetic vertical seismic profiles. It is assumed that the respective models represent arbitrary horizontal stratified layered media. Accordingly, complete 3-D solutions to the wave equation will be calculated using commercial software. In order to verify the application of synthetic seismic to study porosity and pore fluid effects, the synthetic seismic is tied to measured vertical seismic profiles (VSP).

From the modelled zero offset seismic it is the aim to study porosity variations in chalk, as the two sites represent different development in porosity versus depth.

From modelled offset seismic we study the fluid effects on the interface of shale and chalk. Here we perform fluid substitution on the initial model and use the resulting model as input to calculate the synthetic offset seismic.

Results

Central results of the Ph. D. study are summarized and discussed in the follow paragraphs.

Cementation and the elastic model

Wire-line logging data from the brine zones in four different wells at four different locations in the Danish North Sea are included aiming to study cementation in the chalk and the effect on elastic properties.

A low Biot coefficient (β) will for a given porosity correspond to a high, normalised dry bulk modulus (K_{dry}/K_0), which reflects a high pore space stiffness (Mavko and Mukerji, 1995). Accordingly, a decrease in β thus reflects a strengthening of the grain contacts in the rock matrix.

From an integrated log analysis, we observe a significant porosity dependence of β. The dependence of porosity (φ) is in accordance with results from laboratory rock mechanical testing on high porous chalk presented by Engstrøm (1992). However, for porosity below c. *15%* a significant variation in β is found for a given porosity.

We relate the result from the acoustic measurements to resistivity measurements and observe an interaction between the formation factor (F), cementation factor (m), and Biot's coefficient (Fig. 1). Both the formation factor and Biot's coefficient depend on porosity and will thus be directly related, whereas the cementation factor is primarily dependent on lithology and degree of cementation. In the β-log$F$ plane we find that the gradient is related to m so that a numerical high gradient defined by low m represent cemented chalk and vice versa. Note, that for high Biot coefficients, data tends to overlap each other independently of the cementation factor, whereas

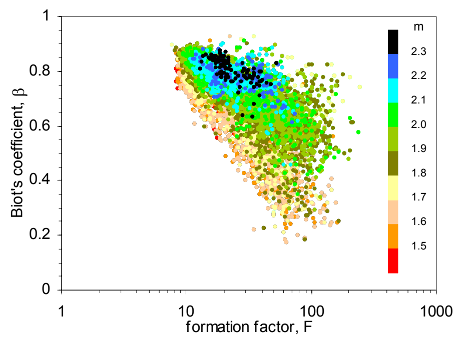

Figure 1. Biot's coefficient (β) versus the logarithm of the formation factor (F); the cementation factor (m) is given by colour. Only data of the brine-saturated chalk zone of four different wells (*A, B, C, and D*) are included. The gradient is related to the cementation factor, so that low values of m correspond to a high (negative) gradient.

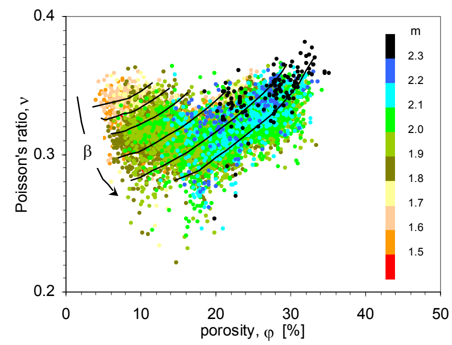

Figure 2. Correlation between Poisson's ratio (ν), cementation factor (m), and porosity (φ) for the same data as Fig. 1. Iso-trends of Biot's coefficient (β) indicate the relation to the Poisson's ratio - porosity relationship. For $\varphi<15\%$ decreasing m correlates decreasing β and increasing ν.

at lower β we observe the separation with respect to m. From the observations e.g. in the β–φ plane (not shown) and of Fig. 1 we observe that cementation only may be detected from the elastic properties for porosities below c. *15%*.

Although the actual impact of cementation on Biot's coefficient is demonstrated it may be complicated to derive β outside the wells. We therefore illustrate how a change in cementation factor affects e.g. Poisson's ratio, which is possible to extract from seismic data (Fig. 2). Generally m decreases with decreasing φ and ν, but for low porosity brine-saturated chalk, we observe that a decreasing m corresponds to an increasing ν. This observation indicates that in the ν-φ plane cemented chalk follows a u-shaped trend with a minimum around 15-20% porosity and that a change in degree of cementation is first evident in the elastic behaviour when m passes below c. 1.8.

The effective moduli are predicted from the weighted summation of the *MUHS* and the Reuss bound, where we define the weighting factor (w) as an increasing function of porosity. However, because we observe a different elastic behaviour for different degree of cementation of the chalk we choose to establish two porosity dependent elastic models representing respectively cemented and un-cemented chalk.

When predicting the effective bulk modulus at a given porosity we find that a relatively low Biot coefficient corresponds to a relatively low weighting factor. This indicates a relative high degree of contact cement, which is in accordance with the interpretation of Marion (1990). By contrast, w is constant for the effective shear modulus although β varies, which causes an increase in Poisson's ratio with a decreasing β. In other words, the shear velocity increases more slowly than the compressional velocity. We interpret this as a consequence of strengthening of the rock frame of low porosity ($\varphi<20\%$). Studies of shear velocity of highly porous calcareous marine sediments ($\varphi>45\%$) showed that v_s increases faster than v_p during early stages of diagenesis and cause a decrease in Poisson's ratio (Wilkens *et al.*, 1992). Combined these observations may explain the u-shape that brine-saturated North Sea chalk (Fig. 3).

Fluid substitution

We have tested the application of respectively the Gassmann and the Kuster-Toksöz theory as a tool for predicting the effect of hydrocarbons from the elastic properties of brine-saturated North Sea reservoir chalk.

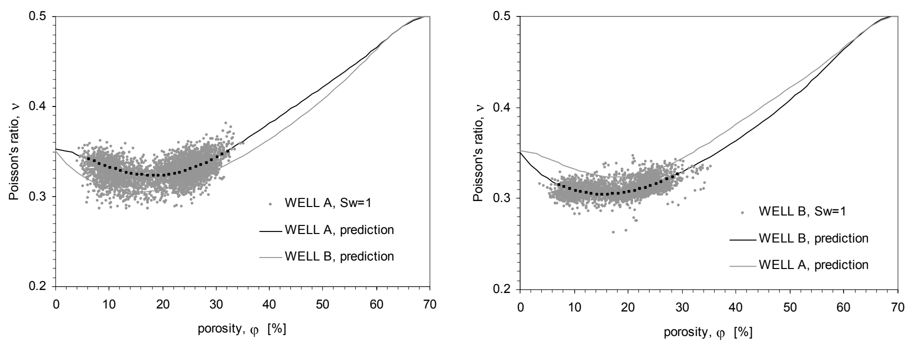

Figure 3. Elastic model for cemented chalk (left, *WELL A*) respectively un-cemented chalk (right, *WELL B*). The weighted summation of the *MUHS* and the Reuss bounds in respectively the (K-φ)- and the (μ-φ)-plane define the respective models and result in different behaviour of ν versus φ.

The fluid effect depends on the pore geometry. However because Gassmann's theory is a transformation from one fluid saturation to another, it automatically takes into account the pore geometry without having to explicitly specify any pore shape. In contrast, the Kuster-Toksöz theory needs specified pore geometry as input.

We therefore established elastic models (velocity-porosity based models) for a reference state of brine saturation, suitable for each theory. For the Gassmann theory we apply a semi-empirical model discussed in the previous paragraph, whereas for the Kuster-Toksöz theory we consider two different types of pore shapes and predict the response of the brine-saturated chalk by mixing penny cracks with spheres.

In both cases, the effective bulk modulus of the specific fluid is taken to be the Reuss average of the mixed fluids. Using the method of Berryman *et al.* (2002) this is reasonable. As an example from one of the studied sites, plotting the Lamé's parameter (λ) - shear modulus (μ) ratio versus brine saturation indicates that the oil- and brine fractions are homogenously rather than irregularly mixed (Fig. 4).

For each model, iso-curves predicting the elastic response of the hydrocarbon-bearing chalk for a given φ are compared to the measured log response of the hydrocarbon-bearing chalk in the acoustic impedance – Poisson's ratio domain (Z_p - ν) (Fig. 5). In one case we start with the semi-empirical model for brine-saturated chalk and use Gassmann's equation to compute the velocities at other saturations. In the other case, we start with the inclusion model for brine-saturated chalk and then change the fluid within the inclusions using the Kuster-Toksöz equations.

The Kuster-Toksöz theory is observed to predict

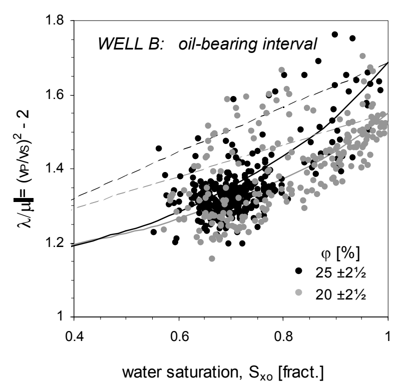

Figure 4. The Lamé's parameter (λ) - shear modulus (μ) ratio versus brine saturation for log data of the oil-bearing interval of the studied wells (*B*). Trends of chalk saturated with a homogeneous brine-oil mixture of respectively 20% and 25% porosity are included (solid line, respectively grey and black) as well as trends of the same porosity, but saturated with a patchy brine-oil mixture (dashed line respectively grey and black).

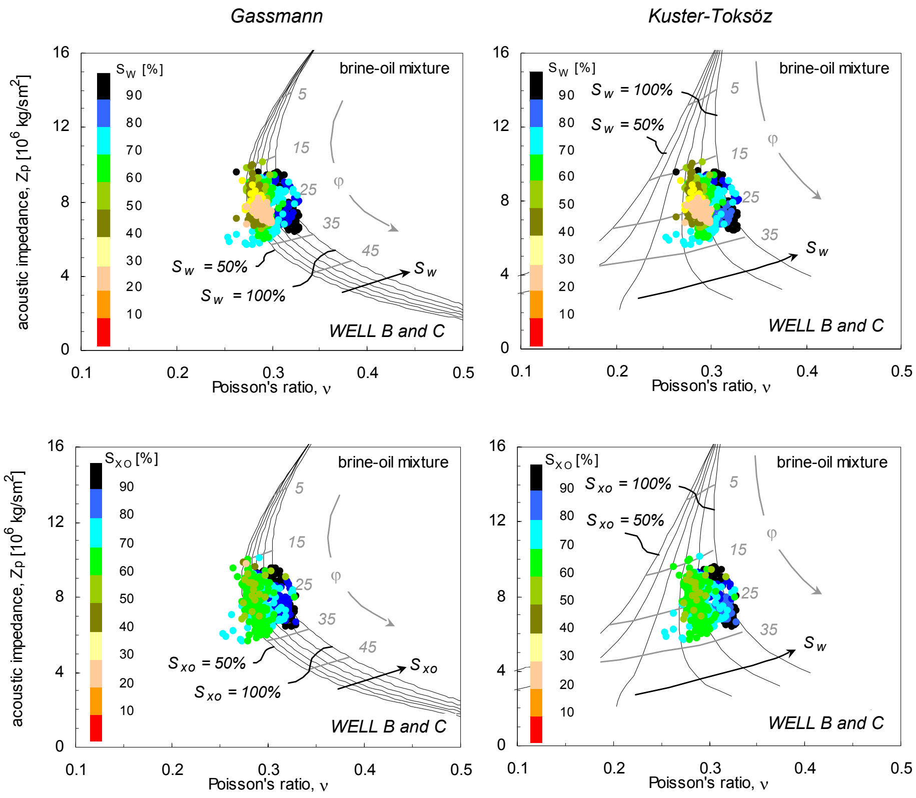

Figure 5. Acoustic compressional wave impedance (Z_P) versus Poisson's ratio (ν) for hydrocarbon-bearing chalk as predicted by the Gassmann and the Kuster-Toksöz theory. The brine saturation of respectively the virgin zone (S_w) (upper) and the flushed zone (S_{xo}) (lower) is given by colour.

a too large fluid effect and is not robust to higher oil saturations (above c. *30%*) for higher φ (above c. *30%*). The Gassmann theory provides a significantly better prediction of S_w and S_{xo} for high brine saturations (above c. *80%*). However, at low brine saturation, Gassmann predicts S_{xo} rather than S_w indicating that the acoustic response primarily originates from the invaded zone. Equivalent observations have been reported for granular reservoir rock (Walls and Carr, 2001). Taking the invasion of mud filtrate into account was observed to have significant impact on the correspondence between the predicted- and the measured elastic response which should lead to carefulness e.g. when substituting initially hydrocarbon-bearing chalk to e.g. brine-saturated chalk.

We find that the low frequency Gassmann theory may be applied for chalk in the sonic frequency domain of the acoustic logging tool. Consequently we expect the Gassmann theory to predict fluid saturation in the seismic domain well because it is a low frequency model, and predicts the log data satisfactorily.

Seismic behaviour

On basis on the elastic moduli model previously discussed we investigate if reflectivity versus offset plotting can facilitate the interpretation of porosity and pore fluid.

Focusing on the chalk overlain by shale we predict how the corresponding reflection coefficient behave versus offset for a wide range of φ and different mixtures of respectively oil-brine and gas-brine (Fig. 6). For the brine-saturated un-cemented chalk we find a decreasing normal incidence reflectivity (*A*) with increasing porosity. The phase reversal at zero offset from $A>0$ to $A<0$ is found at a porosity around *44%*. An increasing hydrocarbon content of the chalk causes the phase reversal to emerge at a lower porosity. For almost the entire porosity range ($\varphi<50\%$) we find a declining reflection coefficient versus offset (equivalent to $B<0$). Megson (1992) also studied phase reversal for brine-to-gas bearing chalk overlain by shale. We find a phase reversal at normal incidence for the brine-to-gas bearing chalk at approximately $\varphi=36\%$ for a *20%* gas saturation. This is c. *3 P.U.* lower than forecasted in the previos study by Megson, but by using the same Z_p for the overlying shale this difference would be even smaller.

On basis of the case studies we study variations in porosity and pore-filling fluid from modelled seismic.

From synthetic zero offset seismic we find that a discrete porosity reduction of c. 10 P.U. within the chalk interval is considerable in the seismic domain, whereas a slowly degrading porosity of c. 18 P.U. over an interval of c. 260 m appears as minor, in-distinguishable reflectors. At one site we generate synthetic offset seismographs representing chalk bearing different fractions of respectively oil and gas. We find that considerable fractions of oil have small effect on the top of chalk up-coming P-wave reflection versus offset, whereas moderate to high fractions of gas leads to a zero reflectivity with offset or even phase reversal (Fig. 7).

It is relevant to discuss the results of the two approaches, because what may be detectable in the sonic frequency domain may not be detectable in the seismic frequency domain.

From the general approach we found that chalk saturated with a fraction of only 5% gas may have the same stiffness as an oil-bearing chalk of oil saturation below 50%. For chalk with a porosity of c. 25 %, we found that the zero offset reflection coefficient at top chalk would be respectively c. 0.2 for brine-saturated chalk and 0.15 for chalk bearing a 20% fraction of gas (and an 80% fraction of brine). In the case study, the reflection coefficient for top of the chalk represents porosity just above 25% so the results in Fig. 6 and 7. are in full agreement.

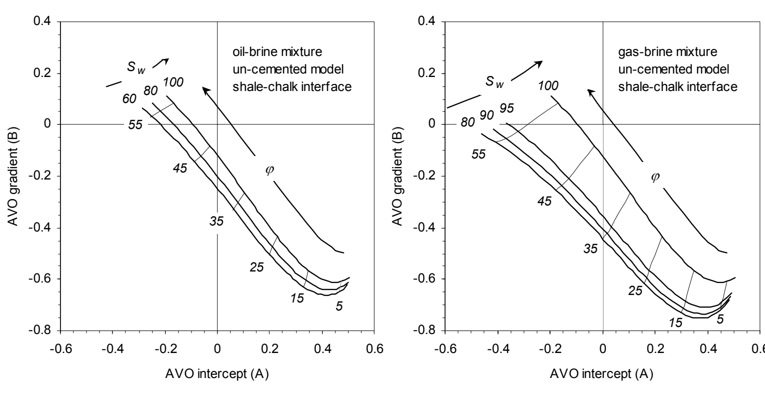

Figure 6. AVO gradient (*B*) versus intercept (*A*) for respectively oil-bearing and gas-bearing chalk overlain by shale as predicted by the un-cemented chalk model for a porosity range from *5%* to *55%*.

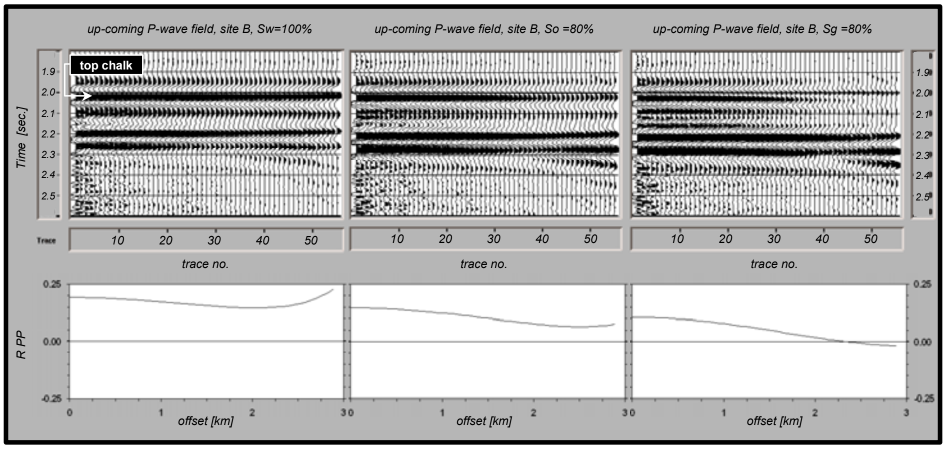

Figure 7. (upper) Synthetic, normal-moveout corrected surface seismic of site *B* displayed with a zero phase wavelet of normal polarity so that an increase in impedance is shown as a black peak. The centre frequency of the source wavelet is 35 Hz. The point source is sited 5 m below sea level. The 60 receivers are situated 10 m below sea level with equally horizontal intervals of 50 m starting 250 m from the source. The brine-saturated chalk (left), the oil-bearing chalk where (S_w, S_o) = (0.2, 0.8) (middle), and the gas-bearing chalk where (S_w, S_o) = (0.2, 0.8) (right). The overburden is identical in all three cases. (lower) Corresponding AVO behaviour of the top chalk reflection coefficient (R_{PP}) extracted from the three synthetic models.

Conclusions

In this Ph. D. study we aimed to predict variations of porosity and pore fluid in North Sea chalk from acoustic measurements. The work and the corresponding conclusions are described in detail in the four manuscripts and one expanded abstract given as Appendix A to E.

The following conclusions can be drawn:

- We show that acoustic measurements and resistivity measurements from wire-line logging surveys correspond for parameters related to cementation: We interpret a low Biot coefficient and the corresponding low cementation factor as indicators of respectively increased strengthening of the grain-to-grain contacts and decreased pore connectivity, which both indicate increased cementation. The Poisson's ratio is also affected by cementation. We show that the low porosity member of the often-appearing u-shaped trend in the Poisson's ratio – porosity cross plot with a minimum value at *15%* porosity is due to strengthening of the pore compressibility of the low porosity chalk and probably caused by cementation.

- We establish two porosity dependent elastic models representing respectively cemented and un-cemented chalk. The effective moduli are predicted from the weighted summation of the *MUHS* and the Reuss bound where we define the weighting factor (*w*) as an increasing function of porosity.

- Brine-oil mixtures tend to be homogeneously rather than patchy mixed for the one data set studied.

- We show that the Kuster-Toksöz model overestimates the log-frequency fluid effect and hydrocarbons cannot be reliably quantified by the predicted acoustic response. When fluid substitution from brine-saturated chalk was performed by Gassmann's theory, the hydrocarbon fraction of the invaded zone of the formation was satisfactorily quantified from the predicted elastic properties of the chalk, whereas the large hydrocarbon

fractions of the virgin zone were underestimated from the predicted elastic properties. Accordingly, we conclude that the fluid effect recorded by the acoustic logging tool is affected by invasion of mud filtrate.
In addition, the Gassmann model is more robust to uncertainty in the input parameters than the Kuster-Toksöz model when estimating offset dependent reflectivity.

- We find the acoustic impedance – Poisson's ratio cross plot useful for prediction of the porosity, primarily because the acoustic impedance is sensitive to porosity. The quantitative prediction of hydrocarbons is less rigorous and we stress the difficulty in separating the effects of low gas saturations from medium to high oil saturations in the reservoir chalk. Thus the cross plot is only recommended as a qualitative hydrocarbon indicator.

- In the case of fluid substitution for the studied chalk, we recommend to use either of the three rock physics methods BAM (Marion, 1990), M1, and M2 (Mavko et al. 1995) for estimating the compressional velocity without knowing the shear velocity. For prediction of the shear velocity from the compressional velocity of brine-saturated chalk we recommend to use the empirical relation of Castagna et al. (1993).

- From the established elastic model we predict the reflectivity behaviour versus offset for the interface of chalk overlain by shale presented as a function of porosity and pore fluid. In addition, we model synthetic seismic from simple models, obtained from wire-line logging data from two different North Sea well locations. From the approaches we find that considerable fractions of oil have small effect on up-coming P-wave reflection versus offset for the top of the chalk, whereas moderate to high fractions of gas lead to a zero reflectivity at moderate offsets or even phase reversal. As in the acoustic impedance – Poisson's ratio cross plot, we find it difficult to distinguish medium to high oil saturations from low gas saturations.

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