Modelling seismic response from North Sea chalk reservoirs resulting from changes in burial depth and fluid saturation

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Abstract: Changes in seismic response caused by variation in degree of compaction and fluid content in North Sea chalk reservoirs away from a wellbore are investigated by forward modelling. The investigated seismic response encompasses reflectivity, AVO and acoustic impedance. Synthetic seismic data are calculated on the basis of well data from the South Arne and Dan fields, Danish North Sea and compared to field records. Seismic response predictions are based on three main tools: (1) saturation modelling, (2) compaction/decompaction modelling and (3) rock physics.

Hydrocarbon saturation in North Sea chalk is strongly affected by capillary forces and transition zones in the order of 50 m are common. Advanced saturation height modelling is applied, which has proved robust for the prediction of saturation profiles in Danish chalk.

Compaction modelling relies on exponential decay of porosity with depth, where abnormal fluid pressures are accounted for. A new set of compaction parameters is presented based on a normal velocity–depth trend and a velocity–porosity transform for North Sea chalk. The parameters appear to allow fairly precise predictions of abnormal fluid pressures from observed average porosity. Based on this, the relative contribution to porosity preservation by abnormal fluid pressure and early hydrocarbon invasion may be estimated.

Rock physics theory is applied to obtain all necessary parameters for the complete set of elastic parameters for seismic modelling.

Modelling results of importance in the search for subtle traps include: (1) correlation of reflectivity with porosity; (2) primary sensitivity of acoustic impedance to porosity variation rather than hydrocarbon saturation; (3) the Poisson ratio is very sensitive to hydrocarbon saturation at high porosity, depending on fluid density contrasts. In addition, compaction modelling shows a clear effect of porosity preservation by hydrocarbons in the South Arne Field, whereas this effect is negligible in the Dan Field. In both fields seismic signatures in field records originating from fluid changes are identified.

Keywords: chalk, seismic attributes, North Sea, reservoir properties, compaction, oil–water contact

Zero offset seismic response at a well site may be readily modelled, provided reliable calibrated sonic and density logs are available. If shear velocity logs are available amplitude versus offset (AVO) response may also be modelled. However, questions may arise as to what causes changes in the response away from the well site. This paper develops methods for creating forward models of the seismic response away from the well site. The models simulate the effects of hypothetical changes in degree of compaction and hydrocarbon saturation away from a wellbore. For this purpose three main tools are applied: compaction modelling, saturation modelling and rock physics. These tools then create input for seismic modelling. Work flows for studying either saturation or compaction changes are outlined in Figure 1. It is noted that a change in degree of compaction may also involve changing the saturation due to the strong dependency of saturation on porosity, as will be discussed below.

The models are developed for North Sea chalk and applied to two wells: Rigs-2 and M-10x drilled in the South Arne and Dan fields respectively (Fig. 2). Both wells have oil reservoirs in the Danish Ekofisk Formation and the Maastrichtian Tor Formation.

Compaction modelling

Compaction is modelled by applying empirical compaction laws in which excess fluid pressure is accounted for in a simplistic way. This approach is favoured over deterministic modelling, because pressure development is very hard to model due to inherent uncertainties in the geological development of basin-wide hydraulic connectivity.

The goal of the compaction/decompaction modelling is to calculate porosity logs as a function of changes in burial depth and/or changes in effective stress caused by changes in excess fluid pressure.

Basic assumptions are:

- in the absence of overpressuring and early diagenesis, porosity decay follows a simple exponential law according to depth;
- depth is considered a proxy for effective stress in the absence of overpressure;
- general deviations in porosity are due to late overpressuring;
- local deviations in porosity from the average function are due to minor textural, mineralogical or very early diagenesis inherited from the time of deposition (or shortly after);

where $\phi$ is porosity at depth $z$, $\phi_0$ is the surface porosity in fractions and $a$ is the decay parameter. Some relevant parameters are listed in Table 1 and the porosity–depth trend for chalk is shown in Figure 3a. Compaction exceeding the normal trend has proved to be irrelevant for the cases in this paper, only sub-normal trends are encountered. The equation can be developed to allow correction of the layer thickness as a function of burial or change in effective stress and, thereby, preserve rock mass (e.g. Sclater & Christie 1980; Jensen et al. 1985). However, in the main application of the model, compaction/decompaction of porosity logs, the interest is in changes away from a well site, and not in what has happened to the succession at the well site. It was, therefore, decided not to change thickness during the compaction/decompaction calculations. The compaction model is, however, also applied to calculate the subsidence and porosity developments, as shown in Figures 4 and 5. These curves include thickness changes and are derived by applying the parameters listed in Table 1. In this modelling, porosity decays with depth until present observed porosity is reached. This then represents the time when overpressuring is assumed to have started.

In the case of chalk, Sclater & Christie (1980) suggest values of 0.7 for $\phi_0$ and 1408.5 m for $a^{-1}$. These values correspond to average normal pressured chalk, but are not consistent with velocity data (Japsen 2000). A compaction trend for North Sea chalk was constructed by transforming the revised normal velocity–depth trend of Japsen (1998, 2000; Fig. 3b) into a porosity–depth trend. The normal velocity–depth trend for chalk was based on an analysis of data from 845 wells throughout the North Sea Basin and ODP data (Fig. 3b). Burial anomalies relative to this trend were found to agree with estimates of erosion along the basin margins and with measured overpressure in the centre of the basin. The trend was transformed into a porosity–depth trend by converting velocity to porosity via a constructed velocity–porosity trend for chalk (Fig. 3c). The velocity–porosity trend was established from two segments.

(1) The modified Hashin–Shtrikman model for chalk, with porosity in the range from 10% to 41%, following Japsen et al. (2000) and based on Dan Field data (dry bulk and shear

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**Fig. 1.** Work flow for modelling either of the two assumed causes for change in seismic response away from a wellbore: saturation change and compaction change. Due to strong capillary forces in the chalk, porosity changes during compaction also result in saturation changes.

- the overpressure as of today has not dissipated significantly since onset: Overpressure ‘arrests’ porosity as it is at the time of onset.

The basic approach follows the original proposition by Athy (1930) and is detailed in e.g. Sclater & Christie (1980) and Jensen et al. (1985):

$$\phi = \phi_0 \cdot e^{-aq}$$

(1) The modified Hashin–Shtrikman model for chalk, with porosity in the range from 10% to 41%, following Japsen et al. (2000) and based on Dan Field data (dry bulk and shear

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**Fig. 2.** Top chalk depth structure map with locations of wells and fields referred to in this paper. Chalk fields are also shown.
Table 1. Depths and compaction constants for the Rigs-2 and M-10x wells

<table>
<thead>
<tr>
<th>Rock unit</th>
<th>Base (M-10x) (TWT ms)</th>
<th>Base (Rigs-2) (TWT ms)</th>
<th>Base (M-10x) (m below m.s.l.)</th>
<th>Base (Rigs-2) (m below m.s.l.)</th>
<th>Surface porosity (fractions)</th>
<th>Decay length (1/a) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Pliocene-Recent</td>
<td>Na</td>
<td>Na</td>
<td>432.0</td>
<td>453.5</td>
<td>0.56</td>
<td>2560.16</td>
</tr>
<tr>
<td>Lower Pliocene</td>
<td>Na</td>
<td>Na</td>
<td>600.2</td>
<td>794.0</td>
<td>0.56</td>
<td>2560.16</td>
</tr>
<tr>
<td>Messinian</td>
<td>Na</td>
<td>Na</td>
<td>812.2</td>
<td>809.4</td>
<td>0.56</td>
<td>2560.16</td>
</tr>
<tr>
<td>Tortonian</td>
<td>Na</td>
<td>Na</td>
<td>1144.6</td>
<td>902.4</td>
<td>0.56</td>
<td>2560.16</td>
</tr>
<tr>
<td>Mid Miocene</td>
<td>Na</td>
<td>1430</td>
<td>1210.6</td>
<td>1411.6</td>
<td>0.56</td>
<td>2560.16</td>
</tr>
<tr>
<td>Aquitanian</td>
<td>Na</td>
<td>1805</td>
<td>1820.5</td>
<td>1772.4</td>
<td>0.71</td>
<td>1960.02</td>
</tr>
<tr>
<td>Palaeogene</td>
<td>1868</td>
<td>2705</td>
<td>1895.5</td>
<td>2745.6</td>
<td>0.71</td>
<td>1960.02</td>
</tr>
<tr>
<td>Ekofisk Fm.</td>
<td>1888</td>
<td>2741</td>
<td>1927.5</td>
<td>2796.1</td>
<td>0.7097</td>
<td>1818/1029.3</td>
</tr>
<tr>
<td>Tor Fm.</td>
<td>~1967 (td)</td>
<td>2766</td>
<td>2063.8 (td)</td>
<td>2829.1</td>
<td>0.7097</td>
<td>1818/1029.3</td>
</tr>
</tbody>
</table>

Note that this listing mode means that, for instance, top chalk in Rigs-2 is at 2705 ms. No checkshot survey is available for M-10x, so TWT values are approximated on the basis of the integrated sonic log. TWT values for some horizons are not available (Na) due to missing sonic logs.

Fig. 3. Porosity–velocity–depth relations for chalk. The normal compaction (porosity–depth) trend for chalk is combined from velocity–porosity and normal velocity–depth trends for chalk. (a) Resulting normal compaction trend. The dashed line shows an example porosity–depth path for a rock that followed the normal compaction trend until the depth at a when overpressure was initiated due to rapid burial to the present depth b without reduction in porosity. The distance a–b is the burial anomaly; (b) Normal velocity–depth trend for chalk, $V_{50}^{Ne}$, derived from 845 wells studied by Japsen (1998, 2000), of which a selection is shown here. The shallower part of the trend is constrained by sonic data from Recent pelagic carbonate deposits drilled at ODP site 807 (Urmish et al. 1993). The steeper part of the trend is defined by the upper bound for interval velocity data from wells where the chalk is buried beneath significant thicknesses of Neogene and Quaternary sediments, and where only the highest velocities below 2 km depth are believed to be free from under-compaction or overpressuring effects; (c) Porosity–velocity relationship for the chalk. Points in this diagram are derived via bulk and shear moduli calculated from Dan Field log data and fluid substituted into fully brine saturated using the Gassmann equation. Although velocity and porosity are affected by overpressuring, the interrelationship between the two is assumed not to be. The model is derived as a modified upper Hashin–Shtrikman trend for $\phi < 41\%$ based on Japsen et al. (2000) and on extrapolation to velocity of chalk at 70% porosity (cf. Walls et al. 1998).
moduli at zero porosity, $K_0$ and $G_0$ estimated at 55 and 20 GPa and the moduli at the high porosity end-member, $K_0$ and $G_0$, as 2.6 and 3.0 GPa for $\phi_{\text{max}} = 45\%$.

(2) A second-order polynomial function estimated as a continuation of the above model from 41% (velocity 2720 m s$^{-1}$) to the parameters corresponding to the critical porosity of chalk at 70% (velocity 1550 m s$^{-1}$).

A resulting normal compaction trend was found by eliminating velocity from the above velocity–depth and velocity–porosity transform and this trend was approximated by an exponential model in two segments, where $\phi_0$ is 0.7 and $\phi_{\text{max}} = 1818$ m in the shallow portion and 0.97 and 1029.9 m, respectively in the deep portion (Fig. 3a). Crossover between the two segments occurs at 768 m (Fig. 3a).

Overpressuring is assumed in depth intervals where the porosity exceeds the porosity expected at the present depth according to the normal compaction trend. It is assumed that excess pore pressure has not dissipated at all since onset. The duration of overpressuring is the shortest possible with this assumption (hereafter called ‘pressure preserving compaction’). An alternative approach would be to assume that overpressure and, thus, abnormal porosity, has been building up gradually since deposition (hereafter called ‘gradual pressure build-up compaction’). The two assumptions may be considered as end-members of possible actual scenarios, but neither handles the case where higher overpressure in the past has dissipated to some extent.

Burial graphs for the two studied wells show rapid Central Graben burial rates only in the Neogene and modest burial rates in Cretaceous–Palaeogene times (Figs 4 and 5). Relative tranquility in Palaeogene times makes it likely that possible earlier overpressure may have dissipated and that present overpressure is caused primarily by rapid Neogene deposition.

The observed excess pore pressure is, therefore, assumed to have initiated late, and only a few million years before present. This is further supported by the correspondence between thickness of Neogene deposits and magnitude of overpressure (Japsen 1999, 2000). The pressure preserving compaction approximation, therefore, seems to be the best choice and the short geological time available further reduces the problem of modelling pressure dissipation.

In the case of overpressuring, the average currently observable porosity ($\phi_i$) in the interval is higher than predicted by the normal porosity decay function. Porosity preservation is assumed since onset of overpressuring, so the average porosity may, thus, be used to estimate the burial anomaly as given by:

$$dz_i = \frac{1}{n} \sum z - a \log \left( \frac{\phi_i}{\phi_0} \right)$$

(2) where $n$ is the number of porosity samples in the investigated depth interval. Local-scale deviations on the porosity log are attributed to local facies variation and are averaged out of the burial anomaly estimate. This anomaly is used to define which portion of the normal compaction curve to use when changes in compaction resulting from burial or overpressure changes are simulated. However, local-scale deviations on the porosity log need to be preserved during compaction and decumulation because these deviations are assumed to be inherited from the near surface, reflecting primary properties like mineralogy, clay content, etc., originating from the time of deposition. The deviations are handled by calculating individual surface porosity values ($\phi_i'$) as given by:

$$\log(\phi_i') = a(z - dz_i) + \log(\phi_{\text{obs}})$$

(3)
The result of this is that porosity variation on a log is amplified during compaction and subdued during compaction, relative to observed variation. Diagenetic processes that may cause local redistribution of material are, thus, disregarded.

The burial anomalies may be converted into an estimated excess pressure, as this is the main cause for the porosity anomaly (Japsen 1998). If the overpressure (Δp) relative to hydrostatic pressure is assumed to be caused by Neogene rapid deposition, the burial anomaly, then is equivalent to the effective stress (σ) exerted by this column:

\[ σ = Δp = (\rho_i - \rho_{br}) \cdot g \cdot dz \]

where \( g \) is acceleration due to gravity. If densities of the rock (\( \rho_i \)) and brine (\( \rho_{br} \)) are equal to 2000 and 1000 kg m\(^{-3}\), then a burial anomaly of 100 m is roughly equivalent to 1 MPa.

**Burial modelling of well sites**

The compaction model described above is applied to the Rigs-2 and M-10x well sites using the constants listed in Table 1. Moderate burial rates prevail until approximately 15 Ma when a considerable increase is noted. After 10 Ma, porosity is arrested in the Palaeogene due to overpressuring at both well sites (Figs 4 and 5). Porosity in the chalk is modelled to be arrested much earlier in the Rigs-2 well, which may reflect early hydrocarbon invasion rather than overpressuring. The M-10x shows only insignificant earlier cessation of porosity decay in the chalk, which suggests that hydrocarbon charging of the Dan Field was much later than of the South Arne Field (Fig. 4). Overpressure calculated from porosity in this well is about 6 MPa, which agrees with observations such that the high porosity may be entirely attributed to overpressuring (e.g. Japsen 2000).

During drilling, the Rigs-2 well encountered excess pore pressures at 1300 m, increasing to approximately 7.4 MPa at 1600 m, 12 MPa at 2600 m, and 14.8 MPa in the chalk section (Table 2). In our cases the burial anomalies for Rigs-2 are calculated as given in Table 2, with parameters given in Table 1. The observed pore pressure in the Rigs-2 well is, however, about 10% lower than the estimate based on porosity observations. If the anomalously high porosity in the well is attributed to factors other than overpressuring, such as early hydrocarbon invasion, then this may be contributing around 10% compared to pressure effects. Early hydrocarbon invasion has frequently been suggested as a cause for porosity preservation above normal (e.g. Bramwell et al. 1998).

In the Central Graben in general there seems to be roughly the same excess pressure in the water zones of the lower Palaeogene section and the chalk. However, in Rigs-2 the calculated excess pressure for the chalk is exceeding the Lower Palaeogene pressure by 3.7 MPa and the observed pressure difference is 2.8 MPa (Table 2). Only 0.7 MPa of this difference is attributable to a direct pressure effect from the hydrocarbons, so the pressure increase in the chalk suggests lateral support from deeper levels.

Within the chalk a difference of 0.9 MPa is seen between observed and calculated excess pressure. It is, therefore, estimated that the abnormally high porosity is due to a combination of overpressure and the porosity preserving effects of early hydrocarbon fill. It may be estimated that rapid Neogene deposition contributes 12 MPa, the hydrocarbon column contributes 0.7 MPa and lateral pressure support contributes 2 MPa to the observed pressures and porosity preservation, totalling the observed 14.8 MPa (Table 2). The remaining 1.7 MPa up to the estimated (but incorrect) 16.5 MPa overpressure calculated from porosity, thus, reflects porosity preservation owing to early hydrocarbon invasion.

**Saturation modelling**

In order to model the saturation realistically, the strong capillary effects in the chalk must be taken into account. The saturation height model developed by Amerada Hess (Jensennius 2003) is applied. The saturation is calculated directly from the capillary pressure (\( P_c \)) and the capillary entry pressure (\( P_{ce} \)) in this method. The predicted behaviour of the chalk with this method is illustrated in Figure 6, where capillary pressure is converted to height above free-water level (FWL). Ideally the capillary pressure is determined on the basis of downhole pressure surveys yielding the crossover depth between oil zone and water zone pressure gradients: the free-water level. The capillary pressure above the free-water level is then given by:

\[ P_c = (FWL - z) \cdot Δp \cdot Cap \]

where \( z \) is the depth of interest, \( Δp \) is the pressure gradient (or density) difference between oil and water, and \( Cap \) is the conversion factor of interfacial tension in the Hg–air system to the oil–water system at reservoir conditions. However, the base of the oil column in Rigs-2 is defined by a bottom seal (Fig. 7). For this reason capillary pressures cannot be confidently estimated directly from pressure measurements. Instead, FWL is determined by inversion of saturation log data using the saturation height model. Owing to calibration of the model to laboratory capillary pressure measurements, FWL may be placed confidently at 2900 m in the Rigs-2 well (Fig. 7). This is based on \( Δp = 0.0413 \text{ bar m}^{-1} \) (0.182 psi ft\(^{-1}\)) and \( Cap = 0.076 \). Similarly, FWL is placed at 2030 m in M-10x (Fig. 8).

![Fig. 6. Saturation height model for Danian and Maastrichtian chalk, where the capillary pressure is shown as height above free-water level for the oil–water system (Jensennius 2003).](image-url)
During modelling of seismic response to changes in hydrocarbon saturation ($S_w$), saturation height modelling is applied. Changes in $S_w$ can occur in the model by imposing changes in FWL, such that realistic vertical differences in $S_w$ are calculated. If, alternatively, the aim is to study changes in compaction, the above saturation height model will automatically impose $S_w$ changes due to the porosity dependency.

**Fig. 7.** Log data from Rigs-2. ‘$S_w$ model’ is based on the saturation height model.

**Fig. 8.** Log data from the M-10x well. ‘$S_w$ model’ is based on the saturation height model.

### Rock physics and fluid substitution

This study estimates elastic properties and changes thereof in the chalk as a consequence of changes in hydrocarbon saturation and degree of compaction. The relationships for elastic moduli and velocity versus porosity are described using modified Hashin–Shtrikman bounds and Gassmann’s relations in an approach similar to that suggested by Wallis et al. (1998).

#### Fluid substitution

Changes are estimated in acoustic properties caused by changes in fluid content as predicted by saturation height modelling. The low-frequency theory for fluid substitution by Gassmann (1951) has been shown to be fulfilled for laboratory elastic measurements on chalk and will, therefore, also apply to log and seismic data (Fabricius et al. 2002; Japsen et al. 2002). It implies that chalk is sufficiently permeable to allow pore fluid pressures to equilibrate instantaneously when sound waves propagate through the rock.

The Gassmann theory given the following relationship between rock moduli (Mavko et al. 1998):

$$\frac{K_{\text{sat}}}{K_0} = \frac{K_{\text{dry}}}{K_0} + \frac{K_{\text{fl}}}{\phi(K_0 - K_{\text{fl}})}$$

and $G_{\text{sat}} = G_{\text{dry}}$ (6)

where $K$ and $G$ are bulk and shear moduli and subscript sat, 0, fl and dry refer to saturated, mineral, fluid and dry properties of the rock. In laboratory measurements, the constant $G$ assumption does not hold for ‘dry’ conditions, but is valid as long as at least partly saturated conditions prevail (Japsen et al. 2002). However, as only ‘dry’ is encountered during calculations, it may be assumed that this part of the Gassmann theory is fully valid in this study. Bulk and shear moduli are related to density ($\rho$) and velocities ($V_p$, $V_s$) according to:

$$K = \rho(V_p^2 - \frac{4}{3}V_s^2) \quad \text{and} \quad G = \rho V_s^2.$$  

(7)

The Gassmann equation developed for substitution of one fluid with another becomes:

$$K_{\text{sat}} = \frac{K_0 \cdot A}{1 + A}$$

(8)

where $A = \frac{K_{\text{sat1}}}{K_0 - K_{\text{sat1}}} - \frac{K_{\text{fl1}}}{\phi(K_0 - K_{\text{fl1}})} + \frac{K_{\text{fl2}}}{\phi(K_0 - K_{\text{fl2}})}$ and $G$ remains unchanged. Subscripts sat1 and sat2 refer to saturated rocks before and after substitution with fluids 1 and 2 (subscripts fl1 and fl2). Bulk moduli of fluids are calculated from the properties of formation water and hydrocarbons using Reuss type fluid mixtures:

$$K_f = \frac{S_w}{K_w + (1 - S_w)/K_{\text{hc}}}$$

(9)

where $S_w$ is the water saturation and subscripts w and hc refer to water and oil (e.g. Mavko et al. 1998). This formula assumes that the two fluids are perfectly mixed considering the influence on wave propagation, which depends on frequency. Laboratory experiments show that this assumption first begins to fail at ultrasonic frequencies (Japsen et al. 2002). The consequence of the Reuss formulation is that the weak/softer fluid component will dominate the overall acoustic response such that a small hydrocarbon saturation will have a large effect. Moduli of solids and fluid in this study have been estimated during laboratory measurements (Table 3).

#### Effects of compaction–decompaction

Changes in rock moduli resulting from changes in porosity are calculated on the basis of a modified Hashin–Shtrikman model similar to the one proposed by Wallis et al. (1998) for Ekofisk Field.
Table 3. Moduli and densities of formation components

<table>
<thead>
<tr>
<th>Component</th>
<th>Bulk modulus $K$ (GPa)</th>
<th>Shear modulus $G$ (GPa)</th>
<th>Density $\rho$ (kg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcite</td>
<td>71.0</td>
<td>30.0</td>
<td>2.71</td>
</tr>
<tr>
<td>Silicates</td>
<td>25.0</td>
<td>9.0</td>
<td>2.70</td>
</tr>
<tr>
<td>lim phi = 45</td>
<td>1.5</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td>Brine (M-10x)</td>
<td>2.63</td>
<td>0.0</td>
<td>1.01</td>
</tr>
<tr>
<td>Brine (Rigs-2)</td>
<td>2.96</td>
<td>0.0</td>
<td>1.035</td>
</tr>
<tr>
<td>Oil (M-10x)</td>
<td>0.65</td>
<td>0.0</td>
<td>0.65</td>
</tr>
<tr>
<td>Oil (Rigs-2)</td>
<td>0.52</td>
<td>0.0</td>
<td>0.633</td>
</tr>
</tbody>
</table>

Note fluid differences between wells (Fabricius et al. 2002).

data. The model, developed in Appendix A, describes how bulk and shear moduli change with porosity in an interval between zero porosity and a maximum porosity encompassing the variation in the available dataset. Stiffer chalk types plot closer to the modified upper Hashin–Shtrikman (MUHS) and softer types plot closer to the lower bound, irrespective of porosity. The difference between stiff and soft chalk decreases as porosity increases towards the defined maximum porosity (Fig. 9; see Appendix A). A maximum porosity of 45% satisfies the data best, whereas Walls et al. (1998) used 40% (cf Japsen et al. in press). During compaction and decompaction, bulk moduli are changed according to the modified Hashin–Shtrikman model derived by Walls et al. (1998). During decompaction the porosity may exceed the maximum porosity, in which case the further change is set to follow the lower (Reuss) bound. If the rock is partially saturated with hydrocarbons, a change in porosity will be accompanied by a change in saturation. Therefore, compaction or decompaction calculations also involve fluid composition changes, as described in the previous section (Fig. 1). After the new water saturation is determined from the saturation–height model, the moduli for the modified rock and fluid composition are calculated.

Seismic response models

The previous sections described modelling tools that allow calculation of the physical moduli for the rock, and their changes as a consequence of realistically altered degree of compaction and/or hydrocarbon saturation. Through the well-known relationships between these moduli and velocities and density, the elastic properties of the calculated models may be obtained. Based on this, zero offset seismic sections and AVO gathers are calculated, as detailed in Appendix B. Zero offset synthetic data are obtained from the reflectivity series based on P-wave velocity ($V_p$) and density ($\rho$) logs. This reflectivity series is convolved with a Ricker wavelet with a dominant frequency of 50 Hz. However, in the case where field data at Rigs-2 are modelled, a wavelet with a dominant frequency of 35 Hz was used. P-wave reflectivity for offset gathers is calculated on the basis of first-order reflectivity equations from the Zoepritz equations, as detailed in Appendix B. Offset calculations are based on a streamer length of 90% of the depth to the target. In the Rigs-2 well this equates to a 2500 m streamer, which, with fairly constant overburden velocities of around 2000 m s$^{-1}$, will produce incidence angles below 22.5° at top chalk level. Refraction in the chalk overburden is considered negligible and is consequently disregarded as well data show rather modest velocity variation. Offset examples below are shown for near, mid- and far positions, corresponding to 0°, 11.7° and 22.5°. Also calculated were the Poisson Ratios to cross-plot with acoustic impedance to illustrate effects of porosity and saturation changes that may be discernible with application of special seismic processing.

Seismic model examples

Modelling of compaction and saturation changes is exemplified with data from the Rigs-2 well, South-Arne Field and the M-10x well, Dan Field (Figs 2, 7 and 8; Table 1). Input data to the modelling are logs, where key logs like $V_p$, $V_s$ and density are restored to virgin conditions (corrected for mud invasion). The two cases illustrate different data foundations, as a $V_p$ log is available in the Rigs-2 well, but not in the M-10x well. Comparison between core analysis and sonic log data from the Rigs-2 well showed that the sonic log was measured in a zone characterized by forced displacement. Restoration of acoustic properties to the virgin zone thus proved to be performed most reliably using rock physical calculations, as described in Japsen et al. (2004). This results in an implicit self-consistency for the Rigs-2 well that causes modelled property changes calculated here to perform somewhat better than if restoration was based on shallow resistivity data (see discussion in Japsen et al. (2004)). Oil-based mud was applied in the M-10x well, so invasion problems apply to the water zone instead. On the other hand, check shots as well as shear velocity logs are missing in this well.

Change in free-water level

A range of synthetic seismograms is modelled by changing only the free-water level (FWL) and, thus, via saturation height modelling, changing the fluid composition. The FWL range for the Rigs-2 well is from 2795 m to 2990 m b.s.l., corresponding to a change from 100% water saturation to almost irreducible water saturation (Fig. 10). For the M-10x well this range goes from 1930 m to 2130 m. The best fit FWL, relative to logged $S_w$, is at 2900 m for Rigs-2 and at 2030 m for M-10x in the middle of these ranges. A conspicuous feature in the reflectivity response is the oil–water contact (lower panels in Figures 11 and 12). Reflectivity effects are also seen, and are detailed for top chalk and top Tor levels in Rigs-2 in Figure 13b. The top Tor reflector is characterized by downward decreasing impedance. It is seen that the amplitude of this reflector increases abruptly (more negative) as oil enters the formation. As FWL deepens (oil saturation increases) it gains amplitude until low to moderate oil saturation. From moderate to high oil saturation it slowly decreases again. This is a consequence of the saturation height model, which causes Tor Formation hydrocarbon saturation to increase faster than in the Ekofisk Formation, in spite of lower capillary pressures at low overall hydrocarbon saturation. This is a
consequence of lower capillary entry pressure in the Tor Formation. The top chalk reflector is also affected by increasing oil saturation (Fig. 13). The impedance contrast at top chalk is almost zero due to high porosity in the well, but also partly owing to the hydrocarbon content.

A set of plots illustrating Poisson Ratio versus acoustic impedance shows that $S_p$ changes affect both of these properties (Figs 14 and 15). However, it is clear that acoustic impedance is more sensitive to porosity changes than to saturation changes, whereas the Poisson Ratio is more sensitive to saturation changes. The sensitivity of the Poisson Ratio to saturation changes is also clearly increasing with increasing porosity. However, comparison between results from Rigs-2 and M-10x show different sensitivity in the two wells, which originates from different fluid properties (Table 3). Light oil and more saline water in Rigs-2 clearly amplify sensitivity to fluids and these tendencies would be further amplified if gas was used rather than oil in the modelling. Acoustic impedance effects from saturation change also become significant when fluid effects on the Poisson Ratio become large. In the slope–intercept plane, a tendency to a rotation occurs with changing saturation (Fig. 16b).

**Change in effective stress**
Compaction–decompaction effects are demonstrated by modelling the Rigs-2 and M-10x wells.

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**Fig. 10.** Water saturation profiles calculated by changing the free-water level (FWL): (a) Rigs-2; (b) M-10x. Note that different properties in Tor and Ekofisk formations cause the Tor to hold lower $S_w$ for shallow FWL than Ekofisk, in spite of lower capillary pressure.

**Fig. 11.** Modelled common offset gathers after normal move-out correction based on Rigs-2 data. (a) Left, middle and right panels show near, mid and far offset response to varying the degree of compaction. Compaction changes are modelled as porosity changes, but with no unit thickness change; (b) The effects of changing the free-water level for near, mid- and far offsets. Blue troughs correspond to downward decreasing impedance.

In both wells the present effective stress in the chalk is changed corresponding to depth shifts of ~900 m to 900 m in steps of 30 m, corresponding to 60 cases (or traces) (Figs 11, 12 and 17). This is modelled by first removing the overpressure and then changing the porosity according to the porosity–depth trend with further steps up to 900 m. The removal of overpressure is equivalent to simply shifting the log to that depth where porosity, on average, is on the normal porosity–depth trend. The entire process is chosen to occur without changing unit thickness. The chalk section is buried almost 1 km deeper in Rigs-2 compared with the M-10x well. Different fluid overpressures in the wells make the effective stress in the chalk sections almost equal. A reduction of effective burial by ~900 m, therefore, reduces the effective stress to almost zero in both wells (near-surface conditions are obtained). A markedly reduced rate of change in porosity is seen in the most decompacted porosity traces in Figure 17. This is due to the discontinuous porosity–depth trend for chalk (Fig. 3a; Table 1). The seismic response associated with changes in compaction is seen in Figures 11 and 12. A dramatic reduction in reflection strength is seen, as anticipated from the porosity log behaviour, and a change in the reflection pattern.

An interesting effect is that the variability in the porosity traces is amplified during decompaction, and subdued during compaction, which is in accordance with observations in seismic data (e.g., Britze et al., 2000; Fig. 17). Similarly, the AVO response is subdued during increasing burial (Fig. 16). Modelling a change in effective stress inevitably results in saturation changes, such that less porosity means higher water saturation. This relationship can be seen to be almost exponential (Fig. 17). The synthetic
Fig. 12. Modelled common offset gathers after normal move-out correction based on M-10x data. (a) Left, middle and right panels show near, mid- and far offset response to varying the degree of compaction. Unit thickness is, however, kept constant; (b) The effects of changing the free-water level for near, mid- and far offsets. Blue troughs correspond to downward decreasing impedance.

Fig. 13. Modelled reflector strength and sign of the top chalk and top Tor reflectors based on in the Rigs-2 well data: (a) reflection strength as a function of compaction/decompaction; (b) reflection strength as a function of free-water level (or modelled saturation distribution).

Fig. 14. Modelled Poisson Ratio versus acoustic impedance based on Rigs-2 data. Left side shows effects caused by compaction changes. Right side shows effects caused by changing the free-water level and, thus, saturation. Points in the upper right in right diagrams are from outside the chalk.

Porosity and $S_w$ logs also show that the observed $S_w$ is closer to irreducible water saturation in the Tor Formation than in the Ekofisk Formation, in spite of lower capillary pressures in Tor. This is seen from the fact that negligible reduction in $S_w$ occurs in the Tor, although porosity is almost doubled during compaction. The $S_w$ reduction during compaction in the Ekofisk Formation is more conspicuous. During compaction these differences, which originate from entry pressure differences, are amplified further.

Field data models

The modelling tools described above are designed to test hypotheses derived during seismic interpretation by forward

Fig. 15. Modelled Poisson Ratio versus acoustic impedance based on M-10x data. Left side shows effects caused by compaction changes. Right side shows effects caused by changing the free-water level and, thus, saturation.
Fig. 16. Amplitude changes with offset according to Shuey’s (1985) approximation for chalk interval data from the Rigs-2 well. (a) Compaction/decompaction modelling has been applied and colour coding refers to degree of compaction; (b) Modelled effects of changing saturation.

Fig. 17. Depth shift of the Rigs-2 well. (a) Porosity log traces corresponding to decompaction in black and compaction in green. Note that thickness is kept constant; (b) Corresponding saturation changes resulting from porosity changes are shown in the same colours.

OWC suggests that amplitude changes in the field data may also be explained by fluid effects.

Crossline 3670 through M-10x

This line is orientated S (left) to N (right) and shows part of the Dan Field SW flank. No significant change in reflectivity is seen downflank, but a slight increase in acoustic impedance is seen both in the Ekofisk and upper Tor formations. In particular, a high-porosity layer in the upper Tor Formation is seen to display an abrupt decrease in impedance downflank (arrow, Fig. 19b). Whether this reflects only porosity decay with depth, or whether saturation changes also play a role, is tested. A downdip, rather abrupt, impedance increase is produced at about the same spot by assuming a gently north-dipping free-water level. The drop occurs at the modelled oil–water contact which, according to the saturation model, is around 1950m, well above the free-water level. The FWL at the M-10x site is 2030 m, but dips away at about 5 m km⁻¹, which is not in accordance with published FWL maps. However, fluid contacts have been shown to be highly dynamic in the Dan Field west flank (e.g. Albrechtsen et al. 2001), and even a flat FWL at 2030 m is inconsistent with a closure to the south towards the Kraka Field in the investigated profile. No significant change is seen in the synthetic reflection section, only on the synthetic impedance section. Similar changes occur in the Ekofisk Formation, but are somewhat less obvious. The synthetic impedance is different from the field data impedance section due to some combination of higher frequency content, lower quality log data near the bottom, and lacking correction of log data for mud invasion (oil-based mud). However, this does not affect the possibility that an abrupt downflank impedance increase may be caused by fluid effects, although porosity effects still remain an option.

Conclusion

The forward models presented here demonstrate that oil effects and compaction effects do have direct impact on the seismic signal in chalk. Fluid effects may affect both reflectivity and seismic impedance. However, detection of fluid effects in the
South Arne Field is enhanced as compared to the Dan Field west flank. This is due to a combination of light oil, higher salinity and higher porosity in the South Arne Field. Nevertheless, it has been shown that subtle impedance changes on the Dan Field flank may be explained by fluid effects. The higher porosity in the Rigs-2 well than in M-10x, despite deeper burial, is due partly to early hydrocarbon invasion. However, this effect is estimated to be equivalent to only ~2 MPa higher fluid pressure. An increase in the degree of compaction reduces sensitivity to fluid changes. Another effect is that overall reflectivity is reduced with increasing degree of compaction, as has also been noted by Britze et al. (2000). This allows a simple first-order identification of porous zones.

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Appendix A: Hashin–Shtrikman model

The Hashin–Shtrikman model provides narrow bounds for possible variation in elastic moduli (e.g. Mavko et al. 1998). A further restriction applied to North Sea Chalk is given in a modification proposed by Walls et al. (1998). In this modification a maximum porosity (\(\phi_{\text{max}}\)) is invoked to define the upper bound of the dry rock bulk modulus \(K_{\text{eff}}^{\text{HSH}}\) and shear modulus \(G_{\text{eff}}^{\text{HSH}}\) as a function of porosity:

\[
K_{\text{eff}}^{\text{HSH}} = \frac{\phi / \phi_{\text{max}}}{K_{\text{lim}} + \frac{1}{3} G_0} \left( 1 - \frac{\phi / \phi_{\text{max}}}{K_0 + \frac{1}{3} G_0} \right)^{\frac{1}{3}} - \frac{4}{3} G_0 \tag{A1}
\]

and

\[
G_{\text{eff}}^{\text{HSH}} = \left( \frac{\phi / \phi_{\text{max}}}{G_{\text{lim}} + Z_0} \right) \left( 1 - \frac{\phi / \phi_{\text{max}}}{G_0 + Z_0} \right)^{\frac{1}{3}} - Z_0 \tag{A2}
\]

where

\[
Z_0 = \frac{G_0 9K_0 + 8G_0}{6 K_0 + 2G_0} \tag{A3}
\]

The parameter \(K_{\text{lim}}\) is the bulk modulus at the defined maximum porosity as denoted by the subscript lim. The subscript 0 refers to the solid end member. The upper bound corresponds to the presumably stiffest possible chalk type. Similarly, the lower bound is:

\[
K_{\text{eff}}^{\text{HSH}} = \frac{\phi / \phi_{\text{max}}}{K_{\text{lim}} + \frac{1}{3} G_0} \left( 1 - \frac{\phi / \phi_{\text{max}}}{K_0 + \frac{1}{3} G_0} \right)^{\frac{1}{3}} - \frac{4}{3} G_0 \tag{A4}
\]

and

\[
G_{\text{eff}}^{\text{HSH}} = \left( \frac{\phi / \phi_{\text{max}}}{G_{\text{lim}} + Z_{\text{lim}}} \right) \left( 1 - \frac{\phi / \phi_{\text{max}}}{G_0 + Z_{\text{lim}}} \right)^{\frac{1}{3}} - Z_{\text{lim}} \tag{A5}
\]

where

\[
Z_{\text{lim}} = \frac{G_{\text{lim}} 9K_{\text{lim}} + 8G_{\text{lim}}}{6 K_{\text{lim}} + 2G_{\text{lim}}} \tag{A6}
\]

The upper bound description is applied during changes in porosity, where stratigraphic lithology differences are accommodated through adjustments of the end members (\(K_0\) and \(K_0\)). During decompression the porosity may exceed \(\phi_{\text{max}}\) in which case the further change is set to follow the lower bound.

Appendix B: Seismic equations

Zero offset reflectivity \(R_{\text{p00}}\) is calculated from:

\[
R_{\text{p00}} = \frac{l_{p2} - l_{p1}}{l_{p2} + l_{p1}} \quad \text{and} \quad I_{p} = V_p \cdot \rho \tag{B1}
\]

where \(V_p\) and \(\rho\) are P-wave velocity and density (e.g. Spratt et al. 1993). Substituting \(V_p\) with the S-wave velocity \(V_s\) gives the S-wave reflectivity \(R_{s00}\). The poisson ratio \(\sigma\) is given by:

\[
\sigma = \frac{\left( \frac{V_s}{V_p} \right)^2 - 1}{\left( \frac{V_s}{V_p} \right)^2 - 1} \tag{B2}
\]

P-wave reflectivity for offset gathers \(R(\Theta)\) where \(\Theta\) is the incidence angle is calculated on the basis of first-order Zoeppritz equations:

\[
R(\Theta) = R_{\text{p00}} + (R_{\text{p00}} - \alpha R_{\text{d0}}) \sin^2 \Theta + \beta \frac{\Delta \rho}{\rho_0} \sin^2 \Theta \tag{B3}
\]

where

\[
\alpha = 8 \left( \frac{V_s}{V_p} \right)^2 \quad \text{and} \quad \beta = 2 \left( \frac{V_s}{V_p} \right)^2 - \frac{1}{2} \tag{B4}
\]

References


