Identification of hydrocarbons in chalk reservoirs from surface seismic data: South Arne field, North Sea

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Seismic data are mainly used to map out structures in the subsurface, but are also increasingly used to detect differences in porosity and in the fluids that occupy the pore space in sedimentary rocks. Hydrocarbons are generally lighter than brine, and the bulk density and sonic velocity (speed of pressure waves or P-wave velocity) of hydrocarbon-bearing sedimentary rocks are therefore reduced compared to non-reservoir rocks. However, sound is transmitted in different wave forms through the rock, and the shear velocity (speed of shear waves or S-wave velocity) is hardly affected by the density of the pore fluid. In order to detect the presence of hydrocarbons from seismic data, it is thus necessary to investigate how porosity and pore fluids affect the acoustic properties of a sedimentary rock. Much previous research has focused on describing such effects in sandstone (see Mavko *et al.* 1998), and only in recent years have corresponding studies on the rock physics of chalk appeared (e.g. Walls *et al.* 1998; Røgen 2002; Fabricius 2003; Gommesen 2003; Japsen *et al.* 2004).

In the North Sea, chalk of the Danian Ekofisk Formation and the Maastrichtian Tor Formation are important reservoir rocks. More information could no doubt be extracted from seismic data if the fundamental physical properties of chalk were better understood. The presence of gas in chalk is known to cause a phase reversal in the seismic signal (Megson 1992), but the presence of oil in chalk has only recently been demonstrated to have an effect on surface seismic data (Japsen *et al.* 2004). The need for a better link between chalk reservoir parameters and geophysical observations has, however, strongly increased since the discovery of the Halfdan field proved major reserves outside four-way dip closures (Jacobsen *et al.* 1999; Vejbæk & Kristensen 2000).

A link between reservoir porosity and sonic velocity in the South Arne chalk

Acoustic properties of the chalk of the Danish South Arne field have been investigated at three scales by analysing core data, log readings and surface seismic data (Japsen *et al.* 2004). The South Arne field is located in the central North Sea and chalk porosities of up to 45% are found in the reservoir at almost 3 km depth (Fig. 1). The velocity–porosity trend for pure chalk samples from the South Arne field matches a modified upper Hashin-Shtrikman (MUHS) curve fitted to Ekofisk field chalk (Walls *et al.* 1998). The curve was smoothly extended to 45% porosity using core data from the high-porosity South Arne chalk. Based on this curve, the acoustic properties of chalk may be calculated as a function of water saturation. This is done by applying Gassmann's equations, which relate the elastic properties of a rock saturated with one fluid to those of the same rock saturated with a different fluid (cf. Mavko *et al.* 1998). The results indicate a pronounced change in the relationship between P- and S-velocities for chalk saturated with light oil for porosities above *c.* 30% (Fig. 2). This relationship is described by the Poisson ratio, and this can provide information about lithology and fluid content of hydrocarbon-bearing reservoirs. For a rock of a given porosity, high pore fluid density results in high P-wave velocity and high Poisson ratio, whereas hydrocarbons with low fluid density result in low P-wave velocity and almost unchanged S-wave velocity and a low Poisson ratio.

These results from the model of the acoustic properties of the chalk indicate that light oil in the high-porous chalk of the South Arne field may be detected through Amplitude

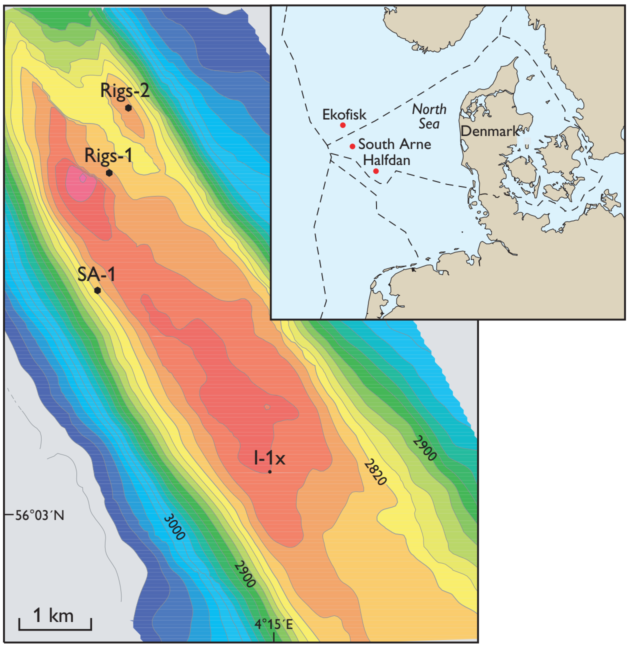

Fig. 1. The South Arne field; top chalk structure with location of selected wells.

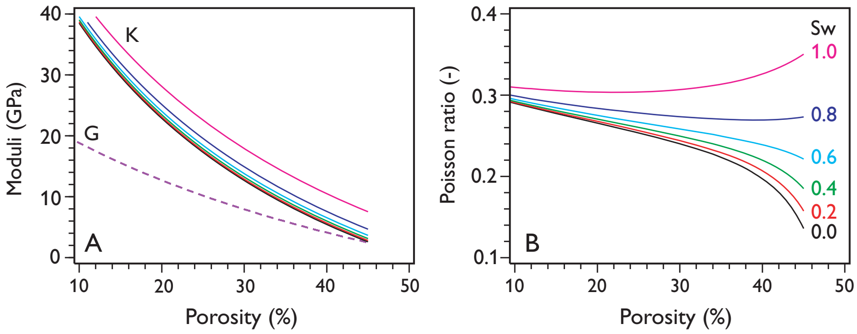

Fig. 2. Acoustic properties of chalk as a function of porosity and water saturation (**Sw**). **A**: Bulk (**K**) and shear modulus (**G**); **B**: Poisson ratio. Note the pronounced difference in the Poisson ratio between brine and oil for porosities above *c.* 30%. MUHS prediction based on fine-scale mixing and fluid properties for the South Arne field. Modified from Japsen *et al.* (2004).

Versus Offset (AVO) inversion of surface seismic data. This is because the variation in seismic reflection amplitude with change in distance between shotpoint and receiver may indicate differences in rock properties above and below the reflector. Changes in AVO can be directly related to changes in the Poisson ratio and thus to differences in pore fluid properties.

The uppermost part of the chalk of the South Arne field is rich in clay (the Ekofisk Formation). Core data indicate that clayrich chalk has significantly smaller P- and S-velocities and a higher Poisson ratio than observed for pure chalk (see Japsen *et al.* 2004, fig. 2). The relatively small velocities for a given porosity are probably an artefact due to a reduction in porosity because clay fills up the pore space without affecting the acoustic properties of the chalk matrix. However, the amount of silicates (typically quartz and clay) cannot always be predicted from the gamma log, because the chalk may be rich in very fine-grained silicates which are not all radioactive. In water-wet chalk the amount of very fine-grained material may be estimated from the water saturation (cf. Fabricius *et al.* 2002). The MUHS model of the acoustic properties of the chalk is therefore scaled according to silicate content estimated from the water saturation.

Comparison of well log data and core data

The link between the surface seismic data and the reservoir properties in the South Arne field is complicated by difficulties in interpreting the sonic log, because mud filtrate has invaded the reservoir near the well bore where the sonic log is registered (Fig. 3). The water saturation can be estimated at intermediate and long distances from the bore hole based on resistivity logs, but not adjacent to the well bore. However, the sonic waves travel close to the well bore and it is thus difficult to perform ‘fluid substitution’ of the data, i.e. to transform the acoustic data from the pore fluid environment where they are measured to the fully hydrocarbon-saturated environment of the reservoir (the virgin zone; cf. Gommesen 2003).

Comparison of P-wave velocity and porosity from log and core data clearly shows that the logging data record conditions close to the well bore, where mud filtrate has almost completely flushed the reservoir (Fig. 4). Core porosities match log porosities estimated from the density log assuming full invasion of mud filtrate (Fig. 4A) and P-wave velocities of brine saturated cores generally correspond to readings of P-wave velocity in the borehole (Fig. 4B). Estimation of invasion effects is usually difficult because of the lack of different types of data, and this study underlines the importance of having access to core data.

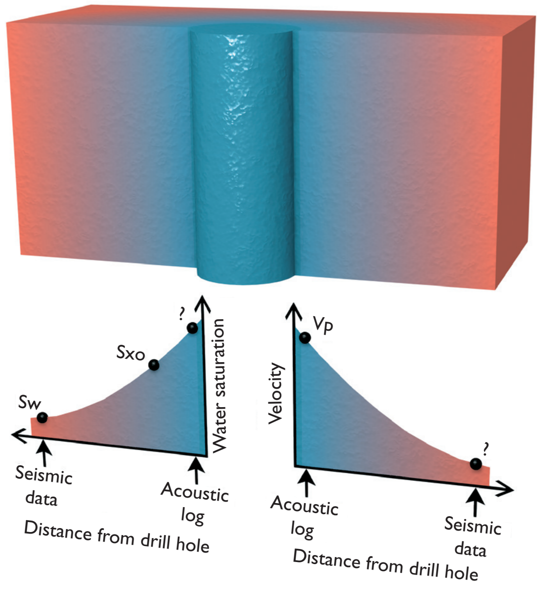

Fig. 3. Illustration of the effects of invasion of mud filtrate (**blue**) into a reservoir saturated with hydrocarbons (**red**). Lower left diagram shows how water saturation (**Sw**) increases towards the bore hole. Lower right diagram shows how the P-velocity also increases towards the borehole due to the higher density of the mud filtrate compared to the hydrocarbons. The seismic data are influenced by water saturation in the virgin zone (**Sw**, registered by the deep resistivity log), and the acoustic log by the properties close to the well bore, whereas the shallow resistivity log registers the water saturation at some distance from the well bore (**Sxo**). Water saturation and sonic velocity are thus not known at the same di-stance from the bore hole, and therefore the acoustic properties of the virgin zone cannot be easily estimated.

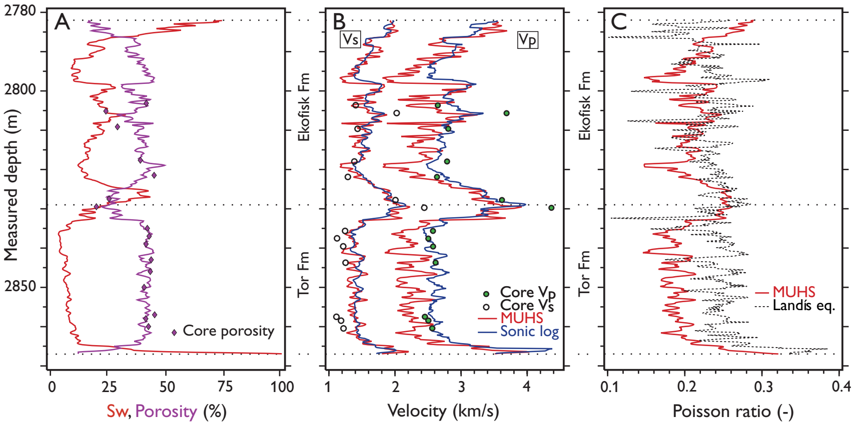

Fig. 4. Log data and predictions from the corrected MUHS model based on porosity and water saturation for the chalk section in the Rigs-2 well. **A**: Porosity (estimated from the density log) and water saturation (**Sw**). **B**: P- and S-wave velocity (**Vp, Vs**). Data (**blue curves**) and predictions from the corrected MUHS model (**red curves**). **C**: Poisson ratio in the virgin zone; prediction of the corrected MUHS model (**full red curve**), prediction based on Land's (1968) equation (**black dashed curve**). In the high-porosity oil zone of the Tor Formation, the oil is predicted to be almost completely flushed. This is indicated by the closeness of the measured Vp log (**blue curve**) and measured Vp for the brine saturated cores (**green circles**), whereas the predicted Vp for the virgin zone is low (**red curve** based on the MUHS model and **Sw**). Modified from Japsen *et al.* 2004.

Comparison of well log data and seismic data

Two approaches may be followed to estimate the acoustic properties of the virgin zone in order to compare well data with seismic data (both are based on Gassmann's equations):

1. Transformation of the sonic data to reservoir conditions based on an estimation of the water saturation near the well bore. This can be done using Land's (1968) equation that gives a smooth estimate of the water saturation some distance from the well bore (corresponding to the more scattered registrations by the shallow resistivity log).
2. Estimation of the acoustic properties of the reservoir from the MUHS model with porosity and water saturation as input (based on the deep resistivity log).

Estimation of the Poisson ratio versus depth in the reservoir depends very much on the approach taken (Fig. 4). In the first approach, moderate invasion is assumed and a featureless variation of the Poisson ratio results (Fig. 4C, dashed black curve). In the second approach, forced displacement of the hydrocarbons near the well bore is assumed and forward modelling results in a characteristic pattern with pronounced peaks at top Ekofisk Formation and top Tor Formation, and low values in the highly porous Tor reservoir (full red curve). The latter pattern is in good agreement with the inverted seismic data (Fig. 5B, blue AVO curve). The AVO attributes were calculated from the angle-dependent impedance inversions combined with information on the absolute level of chalk velocity which is not contained in the seismic data (Bach *et al.* 2003). Acoustic impedance, shear impedance and the Poisson ratio were extracted at the location of the Rigs-2 well. The AVO results show a good match with the well log data. A low Poisson ratio in the Tor Formation near the Rigs-2 well is in agreement with the presence of light oil in the highly porous chalk of the South Arne field.

The first approach based on Land's (1968) equation results in a mismatch between log and seismic estimates of the Poisson ratio in the virgin zone (Fig. 4C, dashed red curve versus Fig. 5B, blue AVO curve). Land's equation (and the shallow resistivity log) thus apparently underestimates the mud-invasion close to the well bore in the highly porous parts of the reservoir and probably reflects the conditions at some distance from where the sonic log P-wave propagates. This suggestion is further supported by the coincidence of log estimates of density and P-wave velocity with results from core samples saturated with brine. The content of hydrocarbons thus appears to drop to a very low value close to the well bore where the P-wave velocity reaches its maximum value restricting the propagation of P-waves to a very narrow zone, whereas the propagation of S-waves is less affected by the pore fluid content (Fig. 3).

The second approach based on the MUHS model results in a good match between log and seismic estimates of the Poisson ratio in the virgin zone (Fig. 4C, full red curve versus Fig. 5B, blue AVO curve). The best way to estimate the acoustic properties of the virgin zone is therefore to use the extended modified upper Hashin-Shtrikman velocity–porosity relation for chalk. AVO inversion of the seismic data based on such synthetic sonic logs reveals a zone of very low

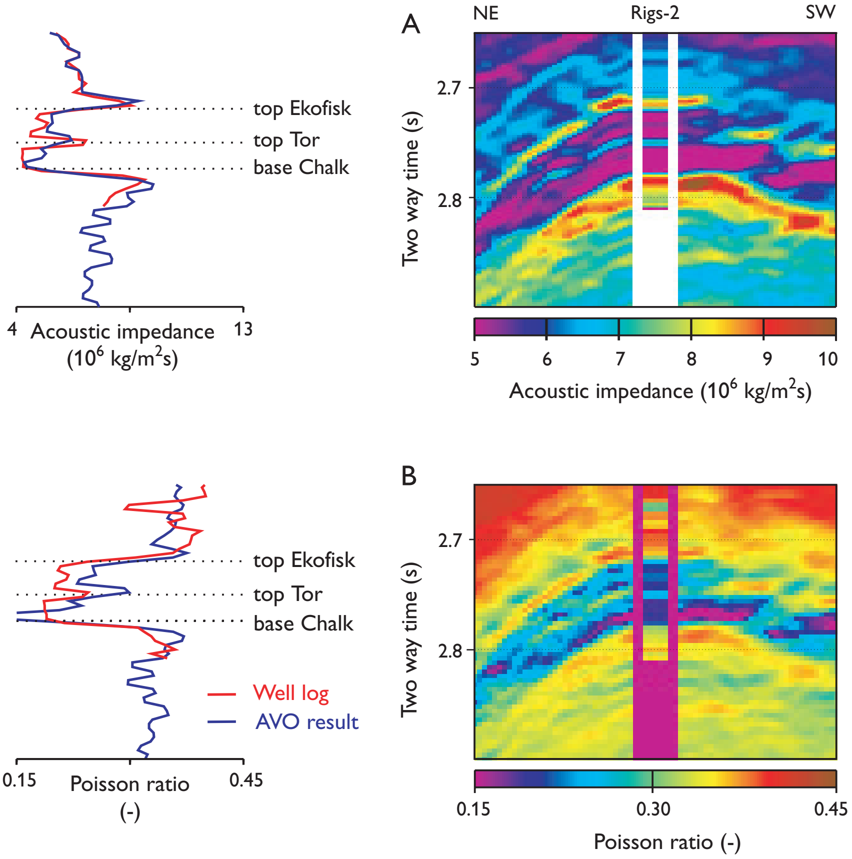

Fig. 5. Two-way time section with AVO inversion of seismic data and inserted log response for the Rigs-2 well computed from forward modelling of the corrected MUHS model (Fig. 4). **A**: Acoustic impedance (density × Vp). **B**: Poisson ratio. Very good agreement is observed between AVO and log estimates for the acoustic impedance. Note the peaks in the tight zones near top Ekofisk Formation (top Chalk) and top Tor Formation. There is also good agreement between the log and AVO estimates of the Poisson ratio, e.g. the peak at top Tor Formation and the low values within the Tor Formation. This pattern cannot be resolved by the log if the acoustic properties are estimated from the sonic log because the water saturation near the well bore is unknown. Seismic quality is severely reduced south-west of the well location due to an overlying gas cap. Modified from Japsen *et al.* (2004).

Poisson ratio that correlates with the oil reservoir in the Tor Formation. In this way AVO inversion provides direct evidence for the presence of oil in highly porous chalk of the South Arne field.

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