Using rock physics for constructing synthetic sonic logs

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ABSTRACT: Knowledge of velocity-depth trends in shales is important for determining background velocity, interpreting seismic data and for predicting abnormal pressures for drilling purposes. However, the existing log data on shale formations is often unavailable or unreliable. Hence, we have used both empirical and effective medium theory based rock physics models for constructing synthetic sonic logs for mudstone sequences at North Sea wells. Our approach is to use resistivity or porosity as the independent variables. The RMS errors for the resistivity based Faust (1953) and Hubert (2008) models are 3.2-11.6 % and 4.2-11.7 %, respectively. The RMS errors are 4.4-7.9% and 4.4-12.7% for the porosity-based Wyllie (1951) and Holt & Fjær (2003) models, respectively. In terms of model complexity it is the Faust (1951) model that provides the best fit to the measured sonic data since it has the fewest number of fitting parameters.

1 INTRODUCTION

Detailed knowledge of velocity-depth trends is essential for constructing well-to seismic ties (White & Simm 2003), determining background velocity (Japsen 1993, Snieder et al. 1989) and generating synthetic seismic traces for interpreting seismic amplitudes in terms of porosity, lithology and pore fluid type (Smith and Sondergeld 2001). The acoustic properties of shales are of particular importance in the exploration setting as shales constitute more than 80% of sediments and rocks in siliclastic environments (Avseth et al. 2009). Seismic and sonic log data may be used for estimating overpressure in shales (Lubandazio et al. 2006, Dutta et al. 2002, Bowers & Katsube 2002, Hermandud et al. 1998). Such information is essential for maintaining borehole stability and safety during drilling. In addition, velocities in shales can be used for predicting its mechanical properties and hence, to foresee borehole collapse (Horsrud 2001).

Despite of the apparent importance of understanding shale acoustics, the oil industry has paid relatively little attention into acquiring detailed log data and core samples at subsurface shale formations. As a consequence, sonic or density logs are frequently unavailable especially for older wells. Furthermore, the existing data can be unreliable due to adverse borehole conditions. Yet, proper analysis of pore pressure or lithology requires good quality logs for the entire well interval. Hence, it is essential to compute pseudo-velocity logs from other available information such as density, gamma ray or resistivity data (Japsen 2007, Lubandazio et al. 2006, Dræge et al. 2006, Faust 1953). This can be accomplished by using empirical relationships or rock physics transforms (Hubert 2008, Hacikoylu et al. 2006). In this study we will use rock physics relationships in order to predict velocity-depth trends for North Sea shales.

Rock physics transforms can be used for predicting reservoir properties (porosity, lithology, clay content) from seismic or sonic data. They can also be utilized for predicting seismic properties from observed reservoir properties. The time-average equation of Wyllie et al. (1956) represents one of the earliest models for relating sonic velocity to rock porosity. The empirical velocity-porosity relationship is given by

$$\frac{1}{V_p} = \frac{\phi}{V_{pf}} + \frac{(1-\phi)}{V_{pr}} \tag{1}$$

where V_p = velocity in the fluid saturated rock, V_{pf} =velocity in the pore fluid; and V_{pr} =velocity in the minerals that make up the rock. It is called the time-average equation, as it considers the transit time as the sum of the transit time thought the minerals and the transit time thought the pore fluid. Equation (1) assumes that the rock is composed of a single homogeneous mineralogy and it works best for intermediate porosities. It is an empirical model and it cannot be justified theoretically (Mavko et al. 1998).

The rock physics model of Holt & Fjær (2003) provides an alternative way of computing acoustic properties from knowledge of rock porosity. It is specifically designed to describe the acoustic properties of shales. The model is based on the work of Hashin & Shtrikman (1963) and it considers shale to be made up of mineral grains, free water and bound water. According to the formalism of the Holt & Fjær (2003) model the bulk (K_W) and shear (G_W) moduli of the effective pore water are given by (2) and (3), respectively

$$K_W = K_{BW} + \frac{(1-f_{bw})}{\frac{1}{K_{fw}-K_{bw}} + \frac{f_{bw}}{K_{bw}+\frac{4}{3}G_{bw}}} \tag{2}$$

$$G_w = G_{bw} + \frac{(1-f_{bw})}{-\frac{1}{G_{bw}} + \frac{2f_{bw}(K_{bw}+2G_{bw})}{5G_{bw}(K_{bw}+\frac{4}{3}G_{bw})}} \tag{3}$$

where the f_{bw} = the fraction of bound water, K_{bw} = the bulk modulus of the bound water; and G_{bw} = the shear modulus of the bound water. It is assumed that the bound water has ordered structure and hence, rigidity. The bulk and shear moduli K and G can be calculated from

$$K = K_w + \frac{(1-\phi_{tot})}{\frac{1}{K_s-K_w} + \frac{\phi_{tot}}{K+\frac{4}{3}G_w}} \tag{4}$$

$$G = G_w + \frac{(1-\phi_{tot})}{\frac{1}{G_s-G_w} + \frac{2\phi_{tot}(K_w+2G_w)}{5G_w(K_w+\frac{4}{3}G_w)}} \tag{5}$$

where ϕ = the total porosity, K_s = bulk modulus of mineral grains and G_s= shear modulus of bound water; K_w = the bulk modulus of free water. Hence, the shear wave velocities can be computed from the knowledge of K, G and density by using standard formulae (Fjær et al. 2008). This velocity porosity model has the advantage that is based on sound physical principles. It has however the disadvantage that the properties of the bound water are not known.

Alternatively, the acoustic properties can be computed from measurements of the electrical properties of rock. The Faust (1951, 1953) empirical formulae represent one of the earliest studies into computing a velocity-depth trend from resistivity logs. The original Faust (1951) formula relates sonic velocity to time, depth and a lithological factor. However, in the (1953) paper the lithological factor is replaced by the true formation factor F so that

$$V_p = \gamma(ZF)^{1/6} \tag{6}$$

where γ=parameter and F = formation factor that is given by

$$F = R_0 / R_w \tag{7}$$

where R_0 = resistivity of a water saturated rock; and R_w = the water resistivity (Ikwuakor 2007, Archie 1941). More recently, Hacikoylu et al. (2006) suggested that the Faust equation is only applicable to consolidated sandstones that exhibit porosities ranging from 5 to 20 %. Hacikoylu et al. (2006) presented a rock physics model for relating V_p to resistivity in unconsolidated sediments. The Hacikoylu (2006) model is given by

$$V_p = \frac{F}{(0.9 + cF)} \tag{8}$$

where F = the formation factor and c = a coefficient that ranges from 0.27 to 0.32. In a recent article, Hubert (2008) pointed out that the Hacikoylu (2006) model does not account for the electrical properties of clay minerals. Hubert (2008) suggested a modification of equation (8) that is given by

$$V_p = \frac{F - A}{0.9 + c(F - A)} \tag{9}$$

where A = coefficient that is related to the cation exchange capacity of clays. Hubert (2008) reported that the above velocity to resistivity transform (9) provided a better fit to Ormen Lange and Vøring basin well data than the Faust (1) or Hacikoylu (8) formulae. The empirical formulae of Rudman et al. (1975) and Brito dos Santos (1988) provide alternative ways of calculating sonic log from the resistivity data for water saturated sediments.

Large scale field studies also suggest that resistivity and acoustic velocities may be correlated. Meju et al. (2003) observed a power-law relationship between resistivity and seismic velocities in a field setting. Similarly, deep crustal studies have shown a correlation between low velocity zones and anomalous electrical conductivities (Marquis & Hyndman 1992). Such cross-property relationships are of great importance: they can be used for an improved structural and petrophysical characterization of the subsurface as well as for joint inversion of seismic and electromagnetic data (Gomez et al. 2008).

The aim of this study is to compare the predictive power of resistivity and porosity based models for computing synthetic P-wave velocity logs. We have used wireline log data from mudstone intervals at three North Sea wells. The wells 6507/2-1, 6507/2-2 and 6507/2-1 are located at the Haltenbanken area at the Norwegian Sea as shown in Figure 1. The wells targeted hydrocarbon potential at the upper Cretaceous and lower Tertiary sandstone sequences. The sandstone beds are overlain by thick Tertiary and Cretaceous sequences of mudstones as shown in Figure 2 (Peltonen et al. 2008, Storvoll et al. 2005). Since our primary goal is to model acoustic velocities in shale, we used wireline data from the Nordland, Rogaland and Hordaland groups that are mainly composed of mudstone. The model parameters are compared and discussed.

2 METHODOLOGY

The mudstone beds were identified from the well log data by using natural gamma log, sonic and resistivity data as well as information from the Norwegian Petroleum Directorate website (NPD, 2009). The volume of shale was estimated from the natural gamma log by using the following equation

$$VSH = \frac{GR - GR_{clean}}{GR_{shale} - GR_{clean}} \tag{10}$$

where VSH = the shale volume in volume fraction, GR = the gamma ray reading in API, GR_{clean} = gamma ray reading in sand; and GR_{shale} is gamma ray reading in shale.

Figure 1. The location of the three wells at the North Sea (NPD 2009).

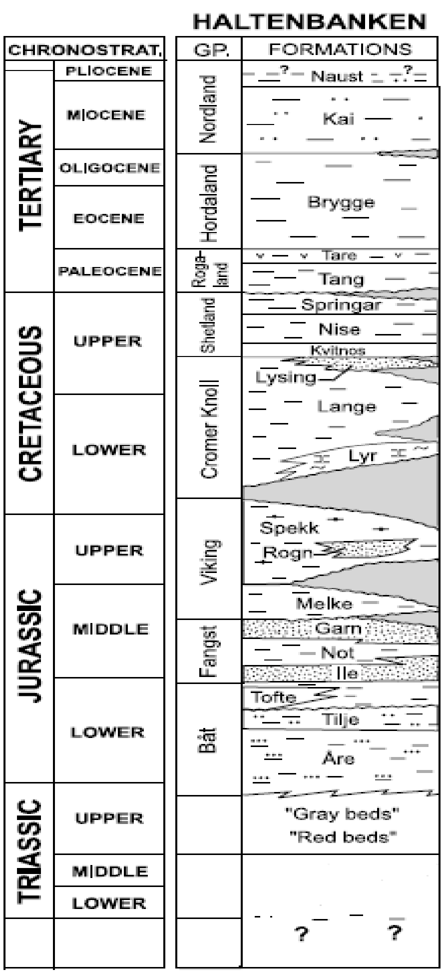

Figure 2. The general lithostratigraphy of the studied wells (Modified from Storvoll et al. 2005).

The appropriate parameters that were used for calculating shale volume were chosen from histograms of the gamma-ray values. It is important to note that some Jurassic sandstones can exhibit high gamma ray values amounting to more than 40 API due to the potassium feldspar that they contain (Lubanzadio et al. 2006). Hence, the shale volume cannot be used alone for discriminating between sand and shale. It is for this reason that we used the Schlumberger parameter for discriminating between mudstones, sandstones and limestones (Schlumberger 1972) that is given by

$$M = \frac{\Delta t_f - \Delta t_{LOG}}{\rho_{LOG} - \rho_f} \times 0.01 \qquad (11)$$

where Δt_f = the sonic transit time and density ρ_f is in g/cm^{-3}. We used values of 187 s/ft and *1.05* g/cm^{-3} for Δt_f and ρ_f respectively. The data points with values higher than 0.65 were discarded. Similarly, the data points with shale volume less than 40 % were discarded. Furthermore, exceptionally high resistivity values amounting to more than 6 Ohm m were not included in the data analysis. The numbers of data points that were used for the analysis are listed in Table 1. The lithology analysis was checked against NPD reports (NPD 2009).

Table 1. Numbers of data points that were selected for each well.

Well	Nordland	Hordaland	Rogaland	Sum
6507/2-1	4265	969	785	6019
6507/2-2	1853	1094	777	3724
6507/6-2	5030	732	363	6125

Porosities were determined from the density log by using the following equation (Rider 1986)

$$\phi = \frac{RHOB - \rho_f}{\rho_r - \rho_f} \qquad (12)$$

where ϕ = porosity, *RHOB* = the density log reading, ρ_r = matrix density and ρ_f is the fluid density. Ideally, one would use grain density obtained from core measurements for porosity calculation. However, we did not have access to any core data on the mudstone beds since such intervals are rarely cored. We used 2.7 and 1.05 g/cm^3 for matrix and fluid densities, respectively. The depth that was used for calculating Vp from (1) was the depth below mudline. This is the true vertical depth (TVDss) minus the water depth. This kind of practice allows the comparison of well data from wells that have been drilled at different depths (Hubert 2008).

In modeling p-wave velocities with the porosity-velocity model of Holt & Fjær (2003) we used the elastic properties of illite. Since illite has no bound water it was chosen to represent the bulk mineral properties with K_s and G_s amounting to 62.2 and 25.7 GPa, respectively (Wang et al. 1998). The bulk modulus of free water was assumed to be 2 GPa (Batzle & Wang 1992). For modeling based on resistivity measurements using equations (7,9) we used formation water resistivity Rw of 0.2 Ohmm which corresponds to salt water with a concentration of 35000 ppm (Rider 1986). Such value for the water resistivity was indicated by a more detailed analysis of water saturation and porosity based on neutron, density and resistivity data.

The difference between the measured V_p values and those calculated from equations (1,4-6,9) were found and the RMS error was computed by using

$$\Delta V_{rms} = \sqrt{\frac{\sum_{i=1}^{n} (\Delta V_i)^2}{n}} \qquad (13)$$

where ΔV_i = the velocity discrepancy of the *i*th data point and n = the number of data points. The results are listed in Tables 2-3. In addition, we calculated the percentage error by dividing the mean RMS error by the average of the measured V_p for the dataset to be fitted as shown in Table 4.

Table 2. The best fit parameters to Faust (1953) and Hubert (2008) models that are used for computing acoustic velocities from resistivity according equations (1) and (4), respectively. NL, HL and RL refer to Nordland, Hordaland and Rogaland formations, respectively. ALL denotes all three lithostratigraphic groups.

Well	Group	Faust (1956)		Hubert (2008)		
		A	RMS m/s	c	C	RMS m/s
6507/2-1	ALL	0.54	201	0.29	-1.2	251
	NL	0.57	293	0.29	-0.4	167
	HL	0.57	100	0.25	-0.2	107
	RL	0.51	179	0.26	-0.3	227
6507/2-2	ALL	0.55	128	0.26	-0.5	194
	NL	0.55	133	0.28	-0.3	159
	HL	0.56	94	0.25	-0.5	141
	RL	0.53	133	0.20	0	147
6507/6-2	ALL	0.54	134	0.29	-0.9	180
	NL	0.54	137	0.30	-0.4	114
	HL	0.52	70	0.22	-1.0	159
	RL	0.54	143	0.21	-0.5	272

Table 3. The best fit parameters for the Wyllie (1) and Holt & Fjær models (2-5) that are used for estimating velocities from rock porosity.

Well	GP	Wyllie (1956)			Holt & Fjær (2003)			
		V_{pr} km/s	V_{pf} km/s	RMS m/s	K_{bw} GPa	G_{bw} GPa	fbw	RMS m/s
6507/2-1	ALL	3.2	1.7	189	10.5	0.1	0.7	207
	NL	3.6	1.5	159	10.7	0.1	0.7	180
	HL	3.6	1.6	121	3.6	0.5	1.0	117
	RL	1.9	3.0	175	10.9	0.1	0.6	302
6507/2-2	ALL	3.0	1.8	146	11.1	0.1	0.7	143
	NL	3.9	1.4	132	1.8	1.8	0.7	132
	HL	3.0	1.9	116	14.3	0.1	0.7	112
	RL	2.6	1.9	163	9.6	0.1	0.7	163
6507/6-2	ALL	3.2	1.6	119	8.5	0.1	0.7	115
	NL	3.2	1.6	107	8.6	0.1	0.7	106
	HL	2.3	2.0	110	12.2	0.1	0.6	133
	RL	3.9	1.4	136	2.9	1.6	0.6	135

3 RESULTS AND DISCUSSION

In this study we have investigated the predictive power of purely empirical (1,6,9) and effective medium theories (2-5) for generating synthetic sonic logs for three North Sea wells. The best fit parameters and the associated errors for the Faust (7) and Hubert (9) models are listed in Table 2. The best estimates for the model parameters for the Wyllie (1) and Holt & Fjær (2-5) models are listed in table 3. Figure 3 illustrates the modeled velocities for well 6507/2-1. It shows that the goodness-of-fit of synthetic sonic logs is relatively similar for the different models. The RMS error for the Faust (1953) and Hubert (2008) models is 201 and 251 m/s, respectively. The RMS error for the Wyllie (1956) and Holt & Fjær (2003) models is 189 and 207 m/s, respectively. Hence, the Faust model provides the best fit to the actual sonic log for the three lithostatigraphic groups for well 6507/2-1. It is also the least complex model with only one fitted parameter γ .

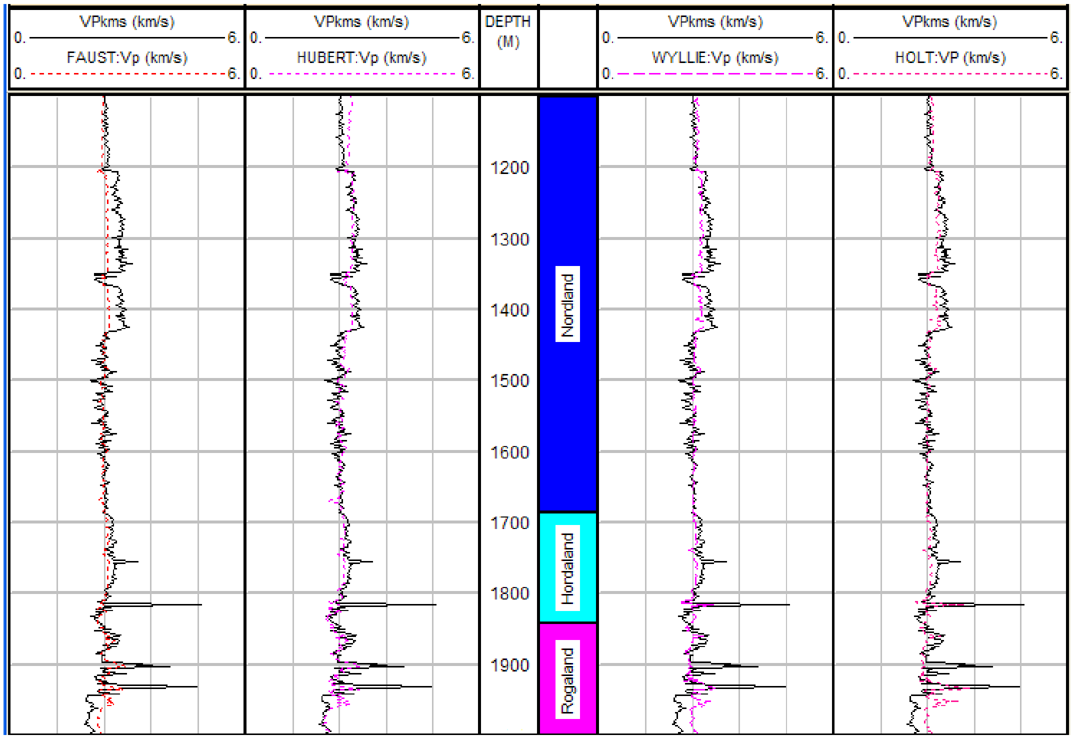

Figure 3. The modeled velocities with the Faust (1953), Hubert (2008), Wyllie (1956) and Holt & Fjær (2003) models for well 6507/2-1.

For the Nordland data the lowest RMS error of 4.4% or 106 m/s was obtained by the Holt & Fjær (2003) model for data from well 6507/6-2. At 8.6 GPa the bulk modulus that was used for the modeling of bound water properties is close to the 8.8 GPa that has been reported for ice (Davidson 1983). It is possible that bound water properties could be approximated with those of ice, since ice is a form of structurally arranged water. However, the 0.1 GPa bound water shear modulus G_{bw} is much lower than the ice shear modulus at 3.9 GPa (Davidson 1983). It is anticipated that a more detailed laboratory or modeling study involving shear wave velocities should be carried out in order to quantify the correct value for G_{bw}. However, the predicted p-wave velocities compare well with the results of a similar study by Dræge et al. (2006). By using a rock physics model based on effective medium theory they predicted the p-wave velocities for three North Sea wells with an RMS error of from to 4.4%. With an RMS error of 4.4 and 4.8 % for the Nordland group and the three lithostatigraphic groups for well 6507/6-2, respectively, the predictive power of the Fjær & Holt (2003) model compares well with the rock physics model of Dræge et al. (2006). Similarly, the bound water fraction of 70% that provided the best fit for the three wells compares favorably with the XRD data of Peltonen et al. (1999). They analyzed the smectite content for the Hordaland and Rogaland groups based on XRD data on rock cuttings from five North Sea wells. Peltonen et al. (2008) reported an average smectite content of 70% for the Hordaland and Rogaland groups for the 6505/10-1 exploration well bore, which is located relatively close to the well data that has been used in this study. Assuming that smectite is mostly composed of bound water, our assumption of 70% bound water fraction is in good agreement with the results of Peltonen et al. (2008).

For the Hordaland data the smallest RMS error was obtained by the Faust (1953) empirical model that related sonic velocities to the resistivity data. With the RMS error ranging from 3.2 to 4.0 % for the Hordaland group, the goodness-of-fit obtained with the Faust (1953) model is greater than that achieved with the Holt & Fjær (2003) model for the Nordland lithostatigraphic group. At 70-100 m/s the RMS error in modeling p-wave velocities with the Faust (1953) model is relatively small for the Hordaland group. This is probably caused by the fact that the apparent water resistivity is relatively constant for this section. The values for the empirical parameter A range from 0.52 to 0.57 for the Hordaland group. In general, the parameter A varies from 0.51-0.57 for the three wells studied here. This is generally much lower value than the 2.2888 reported by Hacikoylu et al. (2006). However, as Faust model (6) relates the sonic velocity to the formation factor, the parameter A is somewhat dependent on the value of water resistivity that is used for the modeling.

The sonic velocities in the Rogaland group are best modeled by the Wyllie (1956) time-average equation. At 5.9 to 7.9 % the RMS error of the predicted velocities is relatively high as shown in Table 4. The velocity V_{pr} that was used for modeling the rock properties according to (1) ranges from 1.9 to 3.9. These velocities are in good agreement with those reported for shale. The sonic velocities in shale can vary from 1.6 to 4.5 km/s (Fjær et al. 2008). However, at 1.4 to 3.0 km/s the fluid velocities V_{fl} are higher than that of water, which has sonic velocities in the range of 1.4 to 1.5 km/s (Batzle & Wang 1992, Kearey & Brooks 1991). It is possible that the bound water in clay contributes to the higher apparent fluid velocities in the mudstones studied here. Namely, ice has sonic velocity of 3.4 km/s (Kearey & Brooks 1991). It is possible that the effective elastic properties of the free and bound water in clays are similar to that of ice, as suggested by the Holt & Fjær (2003) model that includes a shear stiffness for the effective water properties.

This study demonstrates that both empirical formulae and effective medium based theories can be used for modeling sonic velocities at the well scale. The RMS error ranges from 70-294 m/s and 107-272 m/s for the Faust (1956) and Hubert (2008) models, respectively. These models involve the computation of sonic velocities from resistivity data. The Wyllie (1956) and the Holt & Fjær (2003) models result in an RMS error of 107-189 m/s and 106-207 m/s, respectively. These results compare well with the study of Lubandazio et al. (2006) who modeled sonic velocities from the Heather and Cromer Knoll formations at the UK sector of the North Sea. The Cromer Knoll Group is located slightly deeper than the data that was used for this study, as shown in figure 2. Lubandazio et al. (2006) generated their synthetic sonic logs based on porosity, depth, gamma ray data as well as the vertical effective stress. They reported an RMS error of 127-141 m/s for the modeled p-wave data. We obtained a similar result for well 6507/6-2 with RMS error of 107-119 m/s and 115-135 m/s for the porosity-based Wyllie (1956) and Holt & Fjær (2003) models, respectively. However, unlike Lubandazio et al. (2006) we did not penalize for the number of model parameters that were used. In the study of Lubandazio et al. (2006) the denominator of equation (13) for RMS error calculation was n-k, where k is the number of model parameters. Hence, their method of determining RMS error included an extra penalty for increasing the model complexity. In this study it is the Faust (1953) model that has the fewest number of fitting parameters, and hence provides the best fit to the data in terms of an RMS error that penalizes for the number of model parameters.

Table 4. The average p-wave velocity and the RMS error for the different models and for the different lithostratigraphic groups for wells 6407/2-1, 6507/2-2 and 6507/6-2.

Well	GP	Mean V_p km/s	Faust RMS %	Hubert RMS %	Wyllie RMS %	Holt & Fjær RMS %
6507/2-1	ALL	2488	8.1	10.1	7.6	8.3
	NL	2529	11.6	6.6	6.3	7.1
	HL	2529	4.0	4.2	4.8	4.6
	RL	2211	8.1	10.3	7.9	13.7
6507/2-2	ALL	2376	5.4	8.2	6.1	6.0
	NL	2418	5.5	6.6	5.5	5.5
	HL	2418	3.9	5.8	4.8	4.6
	RL	2218	6.0	6.6	7.3	7.3
6507/6-2	ALL	2373	5.6	7.6	5.0	4.8
	NL	2407	5.7	4.7	4.4	4.4
	HL	2166	3.2	7.3	5.1	6.1
	RL	2321	6.2	11.7	5.9	5.8

4 CONCLUSIONS

We have demonstrated that both empirical and effective medium theories can be used for computing synthetic sonic logs for mudstone sequences at North Sea wells. The RMS errors for the resistivity based Faust (1951) and Hubert (2008) models are 3.2-11.6 % and 4.2-11.7 %, respectively. The RMS errors for the porosity based Wyllie (1951) and Holt & Fjær (2003) are 4.4-7.9% and 4.4-12.7%, respectively. In terms of model complexity it is the Faust (1953) model that provides the best fit to the measured sonic data since it has the fewest number of fitting parameters.

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