Introduction

Deep-water clastic systems and associated turbidite reservoirs are often characterized by very complex sand distributions with large variability in sand-shale ratio and net-to-gross (e.g. Richards and Reading, 1994). Hence, reservoir prediction and characterization based on quantitative seismic interpretation is essential in these type of reservoirs (e.g., Avseth, 2000; González et al., 2016). Moreover, in situ reservoir properties may change drastically, even within the same stratigraphic interval, due to depositional trends, compaction history and diagenetic alterations (Avseth et al., 2010; Dræge, 2019).

Figure 1 Well log profile including 4 wells penetrating the Agat Fm offshore Norway (Måløy Slope). Upper 4 subplots show porosity (gray) and clay volume (black) where Agat Fm is indicated (cyan). Middle 4 subplots show P-wave velocity (Agat Fm indicated in cyan). Lower figure is adapted from Richards and Reading (1994) showing typical changes in net-to-gross in sand-rich deep-water system going from proximal to distal settings. Note the change in thickness and log character in the 4 North Sea wells. Also note that depth scale has been adjusted for different burial history.

In this study, I investigate the rock physics properties of turbidite sequences offshore Norway, including examples from the Cretaceous age Agat Fm (Måløy Slope), see Figure 1, as a function of burial history and depositional setting. The key controlling geological factors on seismic velocities
include porosity, net-to-gross, clay volume, grain size, sorting, and diagenetic cement. Several of these factors are interdependent (e.g. presence of clay will affect the quartz cementation process). I investigate selected wells from various parts of a turbidite systems (proximal versus distal, feeder channels versus lobes) to see if there are systematic changes in the rock physics properties controlling the seismic signatures in these types of reservoirs.

A new approach is proposed where coupled burial and rock physics modelling (Avseth and Lehocki, 2016) is combined with sand-shale depositional trend modelling (Dvorkin and Gutierrez, 2002). In this way we can model/diagnose turbidite reservoirs at any location both in terms of depositional environment and burial depth. Backus averaging can be used to model the effect of scale (interbedded sand-shale sequences). Final products are geologically consistent rock physics templates than can be used for quantitative seismic interpretation. The models can also be used to augment training data away from well control during machine learning classification of seismic AVO data.

Rock physics modeling
Turbidite reservoirs are mainly composed of interbedded sands and shales. Hence, the seismic signatures of turbidite reservoirs will depend on the contrast between sands and shales at a given burial depth. Avseth and Lehocki (2016) introduced a method to combine burial history of sands and shales with rock physics modelling, in order to predict the seismic signatures of sandstone reservoirs as a function of the burial history.

![Figure 2](image)

Figure 2 Combined burial and rock physics modelling for a given well. The modelling is performed for a Cretaceous age sandstone (blue line) capped by a shale (green line). The burial history curve is shown in brown (rightmost subplot). Overburden consists of shales, silty shales and carbonates. The horizontal, dashed line represents the transition from mechanical to chemical compaction (i.e. 70 °C).

Figure 2 shows an example from a well offshore Norway, penetrating a Cretaceous turbidite reservoir zone at around 2.2 km burial below sea floor (cyan interval). These rocks have been exposed to rapid subsidence during Cretaceous, followed by a minor uplift in Cenozoic (see rightmost subplot in Figure 2). The turbidite sandstones have been exposed to chemical compaction for millions of years. The models can explain quite nicely the properties of the reservoir sandstones. However, the background well log data show in general much higher velocities for the non-reservoir rocks. This is partly explained by calcite cement in some of the Cretaceous rocks, but also the fact that mixed sands-shales often show higher velocities than the pure end-members of sands and shales.

Sands and shales can mix in two ways during deposition: 1) lamination or 2) pore-filling clays. The latter will cause a stiffening of the framework, as pore-filling clay is replacing open pore space (Marion and Nur, 1991). This effect can be modelled using the Dvorkin-Gutierrez approach, where sands and shales are mixed using Hashin-Shtrikman lower bounds. This modelling is done in two steps; first the silty sand “leg” is modelled using a pure shale end-member and mixing this end-member with silt/sand-grains until grain supported sediment is obtained (see Dvorkin and Gutierrez, 2002; Avseth et al., 2005). This is defined as the critical clay content and will vary with burial (i.e. critical clay content will equal the porosity of the well-sorted sandstone porosity at the same burial depth). Next, the shaly sand leg, representing turbidite reservoir sandstones of varying shaliness and quartz cement, is modelled using model interpolation between the point of critical clay content and the well-sorted sandstone end-member:


\[
K_{\text{sat}} = \left[ \frac{1 - C/\phi_s}{K_{ss} + (4/3)\mu_{ss}} + \frac{C/\phi_s}{K_{cc} + (4/3)\mu_{ss}} \right]^{-1} - \frac{4}{3}\mu_{ss}
\]

\[
\mu_{\text{sat}} = \left[ \frac{1 - C/\phi_s}{\mu_{ss} + Z_{ss}} + \frac{C/\phi_s}{\mu_{ss} + Z_{ss}} \right]^{-1} - Z_{ss}
\]

\[
Z_{ss} = \frac{\mu_{ss}}{6} \frac{9K_{ss} + 8\mu_{ss}}{K_{ss} + 2\mu_{ss}}
\]

where \(K_{cc}\) and \(\mu_{cc}\) are \(K_{\text{sat}}\) and \(\mu_{\text{sat}}\) as calculated from the silty shale model at critical clay content (Dvorkin and Gutierrez, 2002), and \(K_{ss}\) and \(\mu_{ss}\) are \(K_{\text{sat}}\) and \(\mu_{\text{sat}}\) as calculated from the combined burial and rock physics modelling (Avseth and Lehocki, 2016).

An example of the combined burial and sand-shale mixture modelling is shown in Figure 3. The complete modelling comprises Hertz-Mindlin contact theory (Avseth et al., 2005) combined with Lander and Walderhaug (2000) model for the mechanical compaction, Dvorkin-Nur contact cement model (Dvorkin and Nur, 1996) combined with Walderhaug diagenetic model (Walderhaug, 1996), the Dvorkin-Gutierrez shaly sandstone model, and the Dvorkin-Gutierrez silty shale model. Data from Well 1 in Figure 1 is superimposed, and we see that the Agat Fm spans a wide range of porosities along the shaly sandstone trend, reflecting the great variability in shaliness in these reservoir sandstones. Note that the high porosity end-point of the shaly sandstone trend is given by the compaction modelling (c.f., Figure 2) for the clean and well-sorted sandstone end-member.

**Figure 3** Geologically consistent rock physics modelling taking into account both burial (mechanical and chemical compaction) and depositional trends (increasing shaliness in reservoir sandstones and transition to clay-supported shales).

**Rock physics diagnostics of well log profile**

Next, we want to apply the modelling approach outlined above to the target interval (Agat Fm sandstones) indicated with blue colour in Figure 1. Figure 4 shows the superposition of the Agat Fm sandstones in all 4 wells. Well 1 has the deepest maximum burial, as this well is located most basinward where basin subsidence has allowed for thicker overburden. Well 3 has intermediate burial depth for Agat Fm, whereas Well 1 and 2 have the shallowest burial for this zone. The difference in burial between Well 1 and Well 4 is around 500m, and this has a significant impact on the velocities. Still the porosities are overlapping. However, the shaly sandstone model indicate that the sandstones in Well 4 are more characterized by shaly sandstones, whereas the sandstones in Well 1 and 2 are relatively clean and span a smaller range along the shaly sandstone model. We also include data from embedding Rødby Fm shales (green data points), and we see that the data plot nicely along the silty shale trend that connects to the shaly sandstone model. Hence, we observe an overturned V-shape in velocity-porosity values for all wells, where clean sanstones and silty shales have overlapping P-wave velocities, whereas shaly sandstones tend to have higher velocities than the end-member lithologies.
This demonstrates the ambiguities in seismic properties in these types of reservoirs, and additional information (i.e. shear wave velocities and Vp/Vs ratios) should be used during seismic reservoir characterization of these reservoirs.

**Figure 4** Rock physics diagnostic of well log data from target interval in 4 wells (Figure 1), showing the effect of burial and increasing shaliness. The trends in the data are nicely explained by the combined burial and depositional trend modelling proposed in this study.

**Conclusions**

A new modelling workflow is presented, where compaction modelling (the Avseth-Lehocki approach) is combined with modelling of depositional trends (the Dvorkin-Gutierrez models) and this modelling workflow is demonstrated on data from the Norwegian shelf. This approach can be used to create Rock Physics Templates for these types of reservoirs, and to generate augmented training data for machine learning classification of seismic AVO data in these types of reservoir rocks.

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