Facies-dependent AVO prediction: a Rock Physics framework for prospect de-risking in the Flemish Pass and Orphan Basins

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Summary

A predictive framework has been defined that relates geological processes to seismic AVO response away from well control in the Flemish Pass and Orphan Basins, offshore Labrador. A balanced approach is taken using both empirical trends and analytical rock physics models to ensure that the behavior of each facies is captured in the most appropriate manner. The facies dependent predictions made by the framework are used to develop synthetic AVO models for different scenarios, which can then be compared to seismic AVO anomalies identified within the basins.

Introduction

Recent success in the Flemish Pass (e.g. the 2009 Mizzen, 2013 Harpoon and 2013 Bay du Nord oil discoveries) and new insights in the Orphan Basin has led to increasing interest in these under-explored frontier basins. To de-risk seismic amplitude anomalies away from well control we need a mechanism that allows us to understand the elastic properties of the underlying facies, and the contrasts in those properties between facies. The elastic properties of rocks depend on a number of basin-wide geological properties and processes that include: burial depth, lithology, temperature, porosity and compaction regime, stress and the saturating fluid. The predictive framework is defined with the aim of investigating seismic AVO anomalies at leads across the basins. While the focus in this study is on amplitude interpretation, such a framework also has uses in terms of velocity model building and the construction of low-frequency background models for seismic inversion in areas of sparse well control.

Theory and/or Method

A study well database was collated from the available well penetrations on the Labrador Shelf and in the Flemish Pass and Orphan Basins. Wells that sample the quartzose depositional system encountered in the deep-water are of particular interest, as a number of prospective amplitude anomalies have been identified in this environment.

A rock physics model was calibrated to capture the elastic behavior of the reservoir sandstone facies. Non-reservoir facies elastic behavior are captured via the use of empirical trends. Overpressures are modelled via the calculation of Vertical Effective Stress (VES) based on pore pressure profiles for the study wells, and the derivation of empirical trends that relate elastic properties to VES.

Defining the Framework

The modelling framework was constructed as follows:

1. Facies identification.
2. The definition of porosity-depth trends for the reservoir facies.
3. Capturing the reservoir sandstone velocity-porosity relationship.
4. The determination of the empirical elastic property trends for each non-reservoir facies.
5. The derivation of empirical trends to relate elastic properties to VES.

Facies Identification
The facies were identified based on the study well database: where four shale types and one reservoir facies were identified. The reservoir facies was approximated as a quartz rich sandstone, with available well penetrations being of early Cretaceous and late Jurassic (Tithonian) age. The sands have highly variable porosity and cementation, and are representative of a range of compaction states. The shale facies identified was divided based on the petrophysical interpretation and the observed elastic responses.

Porosity-Depth Trend
For the reservoir sandstone facies, the first step of the work was to establish a robust porosity-depth trend. The porosity of normally compacting sandstones is expected to reduce with depth, in the shallow section by mechanical processes such as grain crushing and sorting, and in the deeper section by diagenetic processes such as grain contact cementation and quartz overgrowth (e.g. Ramm and Bjørlykke, 1994).

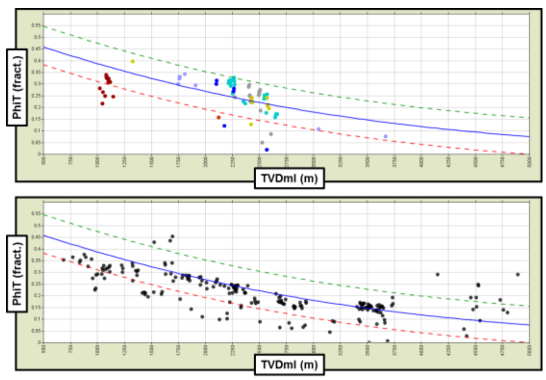

Figure 1: Porosity (PhiT) - depth (TVDml) trend for clean sandstone. The upper plot shows the data from the Flemish Pass and Orphan Basins, the lower is analogue data from mid Norway. The blue trend is the mid-point porosity case, the green is the high porosity case, and the red the low porosity case.

A depth trend was fitted to the interpreted porosity logs (PhiT) from the study wells, and the variation at each depth captured by an upper and lower bound defined as being +/- one standard deviation, shown in the upper plot in Figure 1. The trend was compared and validated by the use of analogue data from mid Norway, shown in the lower plot of Figure 1. Once predictions of sandstone porosity with depth were possible, an understanding of the effects of compaction regime on sandstone velocity-porosity relationships was required.

Sandstone Velocity-Porosity
The sandstone well data from the Flemish Pass and Orphan Basins is plotted in Figure 2, here a distinct change in response is noted between the shallow and deep sections, with the change between the two groupings observed to occur at around 2km burial depth (around the 70-100℃ isotherm). Studies have identified that the shape of velocity-porosity trends in sandstones can be highly variable, and dependent on the type of processes driving porosity reduction (e.g. Dvorkin and Nur, 1996). One of the principle influences on sandstone velocity-porosity behavior is the compaction state of the rock. The effects of compaction can be sub-divided into mechanical and chemical processes, each of these compaction regimes has a different influence on the slope of sandstone velocity-porosity trends. Velocity-porosity trend variation can be investigated via comparison to published rock physics trends and models. For the rocks encountered in the Flemish Pass and Orphan Basins the Constant Cement model of Avseth et al. (2000) was found to capture the velocity-porosity behavior of the sandstone facies. This model captures the change in sandstone velocity as a function of both porosity and compaction state (both mechanical

and chemical). The model required calibration to the data in the study well database, a key calibration parameter is the grain contact cement fraction. The calibrated model is shown in Figure 2.

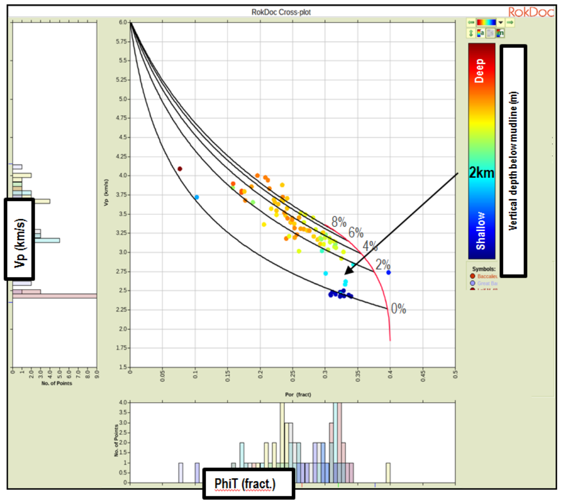

Figure 2: Velocity-porosity responses for clean sandstones in the study wells, coloured by burial depth. The blue line is the unconsolidated sandstone lines, the grey lines are lines of constant grain contact cement.

Once calibrated the model can be used to predict sandstone velocity as a function of porosity and grain contact cementation. The porosity estimates come from the defined porosity-depth trends, and the estimate of grain contact cement with depth is based on regressions of available petrographic and thin section analysis. The effects of the pore saturating fluid is modelled using the approach of Gassmann (1951).

Non-Reservoir Facies

The shale facies elastic properties were captured by the use of Vp-depth trends per identified shale type. The Vs and RhoB of the shale is determined from calibrated empirical Vp-Vs and Vp-RhoB trends.

VES Modelling

Estimates of Vertical Effective Stress (VES) were generated by subtraction of pore-pressure from the lithostatic pressure, these profiles were then used to empirically relate VES to shale elastic properties. In the sandstone the effect of overpressure was modelled as porosity preservation at depth. A RhoB-VES trend was defined for the sand, and from this an overpressured sandstone porosity calculated and input into the calibrated rock physics model allowing the prediction of elastic properties for overpressured sandstones.

Deploying The Model

Deploying the framework involves the following steps.

1. Define lead depth using seismic velocities for approximate time-depth conversion.
2. Predict the elastic response of the non-reservoir facies at the depth of the prospect.
3. Predict the elastic response of the sandstone facies based on the estimated porosity, grain contact cement and calibrated rock physics model.
4. Calculate reflectivity as a function of incidence angle (θ) for all seal-reservoir interfaces using the Zoeppritz (1919) equations. Calculate synthetic AVO intercept and gradient(hence referred to as I/G) from the reflectivity.

Examples

The lead in this example is identified based on seismic amplitude anomalies associated with a rotated fault block. The potential of this play-type has been proven in the area with the discovery of oil at Mizzen. This lead is at a similar depth and within 50km of the Mizzen discovery. At the top sand, the seismic response shows weak positive intercept responses and negative gradient responses of varying amplitude, with the strongest negative gradient amplitudes observed in the up-dip location. After scaling the angle stack seismic to reflectivity, I/G is calculated. I/G is also generated from the model framework for different layering scenarios, and a comparison between the two is made. At the lead depth, the model scenario where the normal shale facies forms the seal to sandstones with expected porosity and grain contact cementation results in AVO responses that are consistent with those observed in the seismic. The model I/G responses are compared to the seismic I/G response in Figure 3.

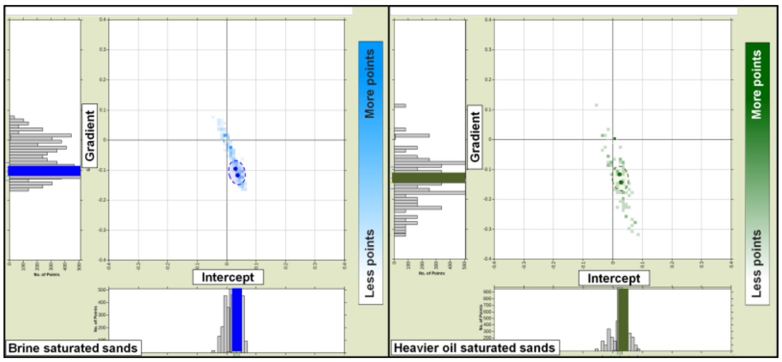

Figure 3: Seismic I/G data is shown in light blue for the down-dip location (left plot) and in light green for the up-dip location (right plot). Model points for brine bearing sands are shown in circled dark blue (left) and for oil bearing sands in circled dark green (right). The sealing shale is consistent between the two.

The change in seismic I/G response observed across the lead can be well matched by the model I/G when moving from a brine saturation in the sandstone (Figure 3, left) in the down-dip location, to an oil saturation in the up-dip location (Figure 3, right). The oil properties used in the model are equivalent to those at the nearby Mizzen discovery.

Further Lead Analysis

The example lead analysis is presented here to illustrate the deployment of the framework. The response is well captured by the normal compaction trends defined for each of the facies. However, in other locations the effect of elevated pore pressure is important, and the VES element of the framework is key when modelling the AVO response at these locations.

Conclusions

In order to understand seismic amplitudes away from well control we need to include the geological processes that drive the elastic contrasts in the subsurface within our models. Here a framework is established for the Flemish Pass and Orphan Basins that allows the prediction of elastic properties per facies as a function of burial depth, lithology, porosity and compaction regime, as well as pore pressure and saturating fluid. Once we can relate these geological processes to elastic response, reflectivity models can be defined to investigate prospective amplitude anomalies observed in the seismic. This framework provides a connection between seismic response and geological properties, which in turn allows informed interpretation of seismic amplitude anomalies away from well control.

Acknowledgements

Nalcor Energy is thanked for supporting this study, and supplying the data used. Thanks also go to Jeremy Gallop and Friso Brouwer (Ikon Science), and James Carter (Nalcor Energy) for support, review and QC.