COMBINED BURIAL AND ROCK PHYSICS MODELLING TO DETERMINE COMPLEX VELOCITY AND AVO DEPTH TRENDS OFFSHORE CANADA

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Summary

A comprehensive rock physics and AVO feasibility study, where we combine burial and rock physics modelling, has been conducted for the Tablelands and North Tablelands area, offshore Newfoundland. The burial history was assessed in 3D from seismic velocity information, calibrated to selected wells in the area. There is a natural ambiguity between the temperature and burial histories. We therefore introduce the term "pseudo-uplift" referring to deviations from normal compaction for a given temperature gradient. The "pseudo-uplift" cube can be used to constrain 3D rock physics and AVO feasibilities away from the selected wells within a selected area of interest. We model different scenarios, including a "pessimistic" one (P90) with respect to reservoir quality and fluid sensitivity, an "optimistic" one (P10), and an "expected" one (P50). These AVO scenario-cubes could be used to screen, rank and derisk leads and prospects in the area from real AVO data.

Combined burial and rock physics modelling to determine complex velocity and AVO depth trends offshore Canada

Introduction

The Orphan Basin offshore Canada is a frontier area where tectonic and burial history is relatively complex and not fully understood (Cawood et al., 2021). Likewise, the expected rock physics and seismic properties between the few wells drilled in the area can be quite challenging to predict. In this study, the main motivation is to combine burial and rock physics modelling, calibrated to key wells, and constrained by seismic velocities, petrographic observations, and regional geological understanding. The main goal is to perform geologically constrained rock property and AVO feasibility modelling in 3D away from wells. The area of interest includes the Tablelands and North Tablelands in the Orphan Basin, offshore Newfoundland,.

Methodology

The methodology applied in this study was first presented by Avseth et al. (2020a), and further developed by Avseth et al. (2020b), and includes the following four major steps: 1) Combined burial and rock physics modelling of sands/sandstones and shales at selected well locations; 2) Quantification of maximum burial and net erosion from seismic velocity cubes; 3) AVO feasibility modelling away from wells; and 4) Prospect and lead de-risking using multi-scenario AVO feasibilities calibrated to observed wells. In this paper, we focus only on the first three steps.

A general rock physics diagnostic screening of key intervals in selected wells is conducted during the first step. The burial and temperature histories are also assessed at the well locations. Mechanical compaction can be modelled by combining Athy's empirical porosity with depth (or effective stress) function and Hertz-Mindlin contact theory. Based on burial and temperature history, the Walderhaug (1996) model predicts quartz cement volume (Avseth and Lehocki, 2016). The quartz volume will affect the porosity depth trends of the sandstones. Using the Hertz-Mindlin contact theory for the mechanical compaction domain and the Dvorkin-Nur contact cement model combined with modified upper bound Hashin-Shtrikman for the chemical compaction domain, the corresponding rock physics properties can be modelled corresponding to the burial, packing and quartz cement growth. Shale rock physics properties as a function of burial depth can be modelled either with physical models or empirically from the well log data. In the second step, shale depth trends are also used to quantify burial uplift for key intervals. Seismic velocities will effectively represent the upscaled shale properties away from wells. In the third step, the sandstone and shale properties are modelled as a function of the burial history in 3D for different scenarios. The resulting AVO feasibility cubes for different scenarios can then be used in the fourth major step (not included in this study), to directly compare with real seismic amplitudes and/or inversion data for the purpose of de-risking leads and prospects.

Combined burial history and rock physics modelling

We applied the methodology of Avseth and Lehocki (2016) to perform 1D burial constrained rock physics modelling of sands and sandstones at four selected well locations in the area of interest (Publicly released wells Lona O-55, Great Barasway F-66, Margaree A-49, Cupids A-33; see www.cnlopb.ca). Detailed burial history curves for these wells are also publicly available (BeicipFranlab, 2018). The main goal was to investigate how burial history affects the rock physics properties, and see if there are deviations between the forward modelled rock physics properties and the observed elastic properties in the wells. This could shed light on uncertainties in the burial history away from wells. Furthermore, this approach allowed us to create AVO feasibility models at the well locations that could be directly compared with observed AVO signatures.

Figure 1 shows the combined burial history and rock physics modelling at the Lona well location. The upper left subplot shows the burial history curves for selected key horizons ranging from Late Jurassic (J148/J145 in cyan and dark blue) to Cretaceous (K100 in green) and Cenozoic (C54/C34 in red and orange). The log displays are also coloured by chronostratigraphic intervals (Blue=Jurassic, Green=Cretaceous, Red/Beige/Yellow=Cenozoic). The seafloor is currently at 2602 m. The temperature gradient at the target level (Late Jurassic sandstones) is found to be around 40 ^{o}C/km based on inputs from basin modelling. The Late Jurassic sandstones (cyan interval just below the J148 marker) in this well are reported to be relatively homogeneous, well-sorted, and fine-to-medium grained (0.2-0.3 mm on average). The clay content is around 10%, whereas the porosities are within the 0.3-0.35 range. Based on the textural information and temperature/burial history, the elastic properties are modelled by combining the Walderhaug diagenetic model with rock physics contact theory. We obtain an exceptionally good match between the observed reservoir sandstones in all elastic domains, as seen in the three rightmost upper subplots in Figure 1. Shale depth trend modelling is also performed. We propose a novel method for burial constrained shale modelling that honours the same burial and temperature history as the ones we use for the sandstone modelling (work in progress). However, shale data are abundant in the four wells used in this study, so empirical shale trends are also derived, honoring varying degree of marliness in the shales. We can also evaluate the match between the modelled and observed sandstone properties in the rock physics template plots shown in the lowermost two subplots (Lower left: V_P/V_S versus acoustic impedance; Lower right: V_P versus porosity). The Lona well is a "dry" well, and the pore fluids included in the modelling are brine with a salinity of 83000 ppm.

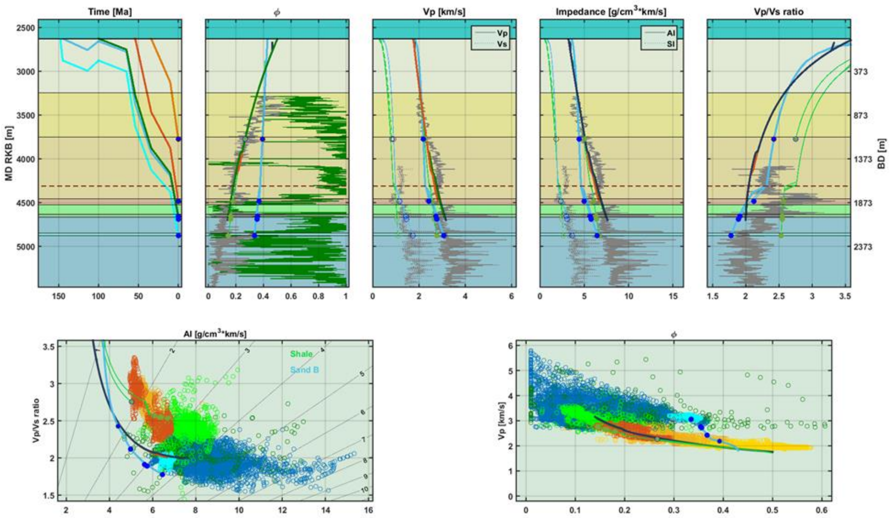

Figure 1 *Combined burial history and rock physics modelling of sand/sandstone and shale depth trends for Lona well. A detailed set of burial history curves for selected key markers is used to constrain the modelling. The temperature gradient for this well is 40.5 °C/km. The different colours of the zones refer to different chronostratigraphic intervals (pale yellow and red=Cenozoic; green=Cretaceous, blue=Jurassic). The cyan coloured curves and data points represent the key Late Jurassic sandstone unit, with the J148 marker as the top horizon. Note the good match between the rock physics modelling and the observed well log data, honouring both mechanical and chemical compactions during burial. Overall, there is a good match between the sandstone and shale modelling for different stratigraphic intervals and the well log data.*

Figure 1 also shows the modelled response for all the markers representing the tops of different chronostratigraphic intervals. Interestingly, the predictions explain the transition from soft sands in the Cenozoic interval to slightly cemented sandstones in the Late Jurassic, as the critical temperature of 70 °C is reached at around 1700 m burial depth, that is, in the lowermost part of the Cenozoic interval. We repeated this exercise for three other wells and obtained a good match between modelled and observed elastic properties, using the burial curves provided from basin modelling (BeicipFranlab, 2018), except in one well, the Cupids well. Here we needed to apply a tectonic uplift of ca. 500 m to explain the observed velocities in the Late Jurassic sandstone interval. This could be because the Cupids well is located closer to the Atlantic rift margin (i.e., oceanic-continent transform), where significant uplift is expected due to increased heat convection/advection associated with crustal thinning (Vågnes, 1997). An alternative explanation is that elevated heat flux during or right after the rifting could have caused temperatures to exceed 70 °C even at relatively shallow burial depths at that well location.

Tectonic uplift/heat anomaly maps from rock physics

Based on seismic velocity cubes (PSTM velocities) from the area, the next step is to create uplift maps. Using the empirical shale trends extracted from the local wells, showing continuous subsidence in 3 of the wells (Lona, Great Barasway, Margaree), we can create uplift volumes/maps from the deviations from the shale reference trend for normal compaction. Deviations from these could be related to uplift, heat flux anomalies, and/or lithology variations. However, concentrating on shaly intervals, lithology effects should be accounted for. One such interval is the Early Cretaceous. Figure 2 shows an uplift map for the J145 horizon. We identify an uplift anomaly towards the northeast, in the direction where the Cupids well is located (just outside the northeastern corner), and where we identified possible uplift from the well log data. Still, we refer to this map as “pseudo-uplift”, as the anomalies could be related to heat flux anomalies during/after the rifting period. From an elastic point of view, doing Walderhaug modelling as input to rock physics models, higher temperatures or deeper maximum burial will have similar effects on the velocities.

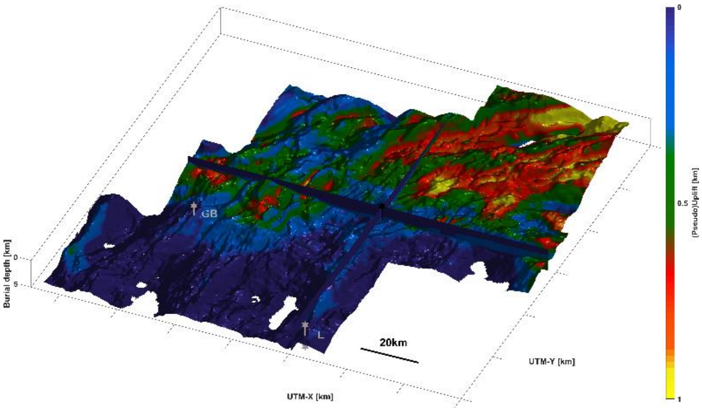

Figure 2 *Pseudo-uplift map along Top Jurassic horizon (J145) over the area of interest, showing potential uplift of several hundred meters (or alternatively heat flux anomalies) towards the northeast. Great Barasway well is indicated with a “GB” on the map, whereas Lona is indicated with an “L”. Both these wells are located in areas where the pseudo-uplift is close to zero, meaning continuous subsidence since Jurassic (c.f. figure 1).*

AVO feasibility modelling

Based on the combined rock physics and burial modelling results at selected well locations and the pseudo-uplift maps for target intervals, we can perform 3D AVO feasibility modelling away from well locations. The expected contrast between sands and shales can be estimated at any location and depth point within the area of interest. Different scenarios can be tested, yet constrained by well log data observations. We define three major scenarios, referred to as pessimistic (where key input calibration parameters are making the rock stiffer and the reservoir in general poorer), expected (where key input calibration parameters are according to what is observed/calibrated in key well locations), and optimistic (where key input parameters are making the rock softer and the reservoir in general better). For convenience, we refer to these as P90, P50 and P10 scenarios, respectively.

Figure 3 shows the resulting AVO feasibility maps/volumes for a Top Jurassic sandstone interval (J148) capped by shales (defined by seismic velocities and empirical relationships), including brine case (upper left) and oil case (lower left), for the P50 scenario. The sandstone and shale depth trends of acoustic impedance at the Great Barasway well location are shown in the central log plot, where gas (red), oil (green) and brine (blue) sandstone trends are superimposed with the seismic velocity background trend (i.e., heterogeneous shale trend; black curve), and the upscaled well log data (grey). The Jurassic sandstone interval of key interest is indicated as a yellow zone below the dashed red line in the log plots. Since the well is dry, the brine sandstone trend fits nicely with the observed impedances in the Jurassic sandstone interval. The transition from mechanical to chemical compaction is clearly seen in the depth trends, where the impedances make a significant jump at around 1.8 km burial depth. Hence, the fluid sensitivities in the Jurassic sandstones are relatively large, as the reservoir has barely entered the cementation window and is poorly consolidated. With greater depths, we expect the sandstones to become stiffer with increasing cementation, and a cross-over in the sandstone versus shale depth trends is expected at around 2.5-3 km burial depth. The corresponding depth trends in the expected AVO signatures can be seen in the rightmost log plot, where we predict AVO class III to IV for brine and III for oil at the top of the Jurassic reservoir unit. With depth, we expect the AVO classes to change. This is also seen in the AVO feasibility volumes, where the Top Jurassic horizon is located deeper (i.e., towards the southwest).

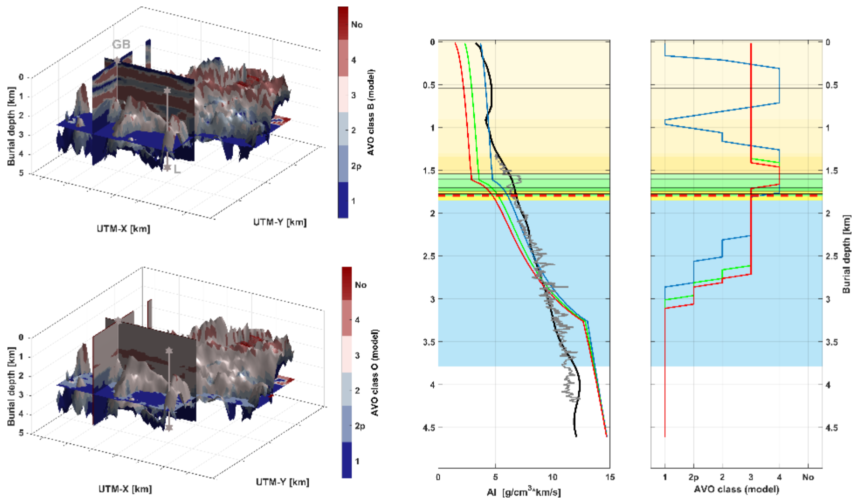

Figure 3 *AVO feasibility cubes (left) for oil (lower) and brine (upper) filled Jurassic sandstones (J145). In the centre log plot, the rock physics depth trends (acoustic impedance) of sandstones (with different fluids) and shales are superimposed. To the right, AVO class for different fluid scenarios (red=gas, green=oil, blue=brine) versus depth are shown. The yellow layer beneath the dashed red line in the log plots is the J145 sandstone interval. The other zone colours represent chronostratigraphic intervals (blue=Jurassic, green=Cretaceous, pale yellow=Tertiary).*

Conclusions

An integrated exploration workflow combining burial history and rock physics modelling has been conducted in the Tablelands and North Tablelands areas, offshore Canada. The burial history was assessed in 3D from seismic velocity information, calibrated to selected wells in the area. There is a natural ambiguity between the temperature and burial histories. We, therefore, introduce the term "pseudo-uplift" referring to deviations from normal compaction for a given temperature gradient. However, a "pseudo-uplift" anomaly could represent a thermal anomaly. The multiple rifting history and complex tectonics during the late Jurassic/early Cretaceous make it challenging to separate burial from thermal effects on elastic properties. Still, the "pseudo-uplift" cube can be used to constrain 3D rock physics and AVO feasibilities away from the selected wells within a selected area of interest. We model different scenarios, including a "pessimistic" one (P90) with respect to reservoir quality and fluid sensitivity, an "optimistic" one (P10), and an "expected" one (P50). These AVO scenario-cubes could be used to screen and de-risk leads and prospects in the area from calibrated inversion data.

Acknowledgments

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