Improving AVO modeling using geological knowledge, 4 examples from the Norwegian Continental Shelf

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Summary

AVO has been used extensively to identify hydrocarbon accumulations. However, numerous examples of false positives and false negatives exist. Modeling may help set expectations for AVO interpretation, however, understanding the geological framework in key to getting the modeling right. This paper focuses on how data in the overburden may control the AVO response. The geology if the overburden must be well understood to enable extrapolation of modeling results away from well control. Also, data in the overburden may be affected by drilling technical issues, which must be accounted for. This paper presents 4 examples from the Norwegian Continental Shelf, discussing of how poor understanding of the geology of the cap rock and overburden may be provide misleading AVO strategies.

Introduction

AVO half-space models are very useful for understanding the seismic signal, and are an important part of developing an exploration strategy that involves AVO. Simple two-layer models are instructive if the reservoir of interest is thick and homogenous, and the cap rock is thick and homogenous. Wedge models considering the thickness of the reservoir are also useful for determining how the reservoir geometry impacts the AVO signature (e.g. as a function of tuning).

Equally as important as the reservoir parameters and geometry is the geology of the cap rock. The cap rock is often not homogenous, and considering the cap rock as such may lead to false positives or false negatives in terms of AVO classification. Therefore, it is of utmost importance to consider geological features of the cap rock, and immediate overburden, such as unconformities, presence of sand stone stringers, and fluid properties. When such geological features are identified they may be incorporated into the AVO modeling exercise. By considering geological features (e.g. unconformities), the AVO modeling becomes richer, by providing a broader understanding of the limitations of AVO, thereby reducing the possibility of misinterpretation.

Furthermore, critical use of measured data is vital; careful editing of elastic logs above the reservoir, and consistency between elastic logs and petrophysical logs is an often neglected necessity for accurate AVO modeling.

Four examples are presented in this paper, one demonstrates the importance of high quality input data, and three demonstrate various geological features in the Norwegian Continental Shelf. However, these examples illustrate the importance of understanding the input data and geology, and thus have universal relevance.

Example 1, Data Quality

The first example is from the Norwegian Sea. The 6608/10-3 well was drilled in 1993 to appraise the Norne discovery in the Fangst and Båt Groups. The well was drilled with water-based mud, and casing was set immediately above the reservoir. The well was cored, logged extensively, and also tested. Over 100m of hydrocarbons were encountered, 25m of which comprised a gas cap.

AVO analysis may be done on this well to develop a exploration strategy. One approach is to develop a half-space model by averaging the elastic properties of a zone above the reservoir and a zone within the reservoir, and use these average properties in the Zoeppritz (1919) equation. This was attempted for the 6608/10-3 well using the well logs uncritically, as found in the NPD database. Three fluid cases were made: 100% wet, 80% gas, 80% oil. The results (Figure 1) indicate that Class I AVO is expected for the wet and oil case, and class IIP for the gas case.

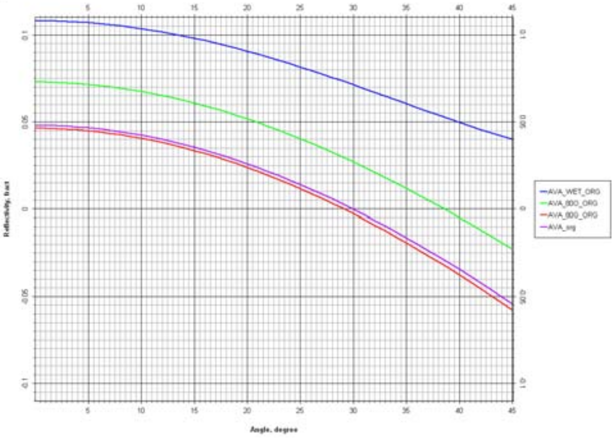

Figure 1: AVA crossplot for well 6608/10-3 using unedited input data. Wet case in blue, oil case in green, gas case in red. Wet case gives Class I AVO, and gas case gives Class IIP.

We could now use this as a strategy for further exploration. However, we find that the synthetics do not make sense geologically, and that the well tie is unsatisfactory. Further examinations of the well logs indicate that there is a severe washout zone associated with the casing point directly above the reservoir. This has given rise to an erroneous density curve, as evidenced by the crossplot of density vs. velocity.

Thus using the density log uncritically for AVO modeling will give wrong results. Instead, the density log was edited and modeled in the washout zone, using Gardner's (1974) equation. This modeled data was now used for the AVO modeling (Figure 2). The results now suggest that wet reservoir should have a Class II response, oil may be weak Class III, and gas Class III. Note that an exploration strategy based on the edited and modeled curves is vastly different than one using the input log data uncritically.

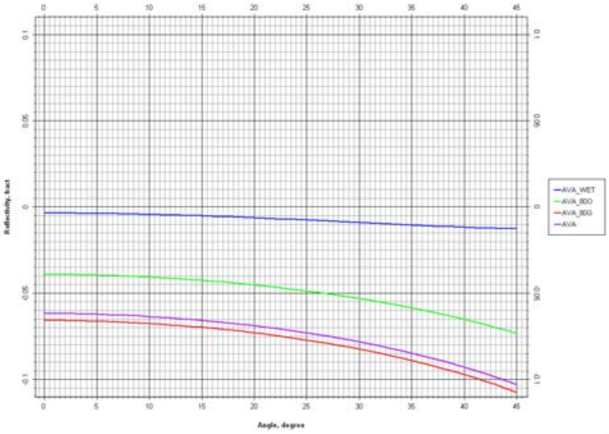

Figure 2: AVA crossplot for well 6608/10-3 using edited and modeled data. Wet case in blue, oil case in green, gas case in red. Wet case gives Class IIP AVO, and gas case gives Class III.

In conclusion, careful editing of the elastic logs is essential for developing a robust exploration strategy based on AVO.

Example 2, Cap Rock Stratigraphy

The 7121/5-1 well was drilled in the Barents Sea in 1985 to appraise the Snøhvit gas field. Much work has been done on understanding the rock physics of the reservoir (Selnes et al. 2003), however, this example will illustrate that the cap rock stratigraphy is equally important for the AVO response. The main reservoir in the Snøhvit field is the lower Jurassic Stø Formation. Unconformably above the reservoir lies the Jurassic Fuglen Formation, which provides the cap rock. The Fuglen Formation is some 10m thick in the 7121/5-1 well, and is a hard, fast shale. Unconformably above the Fuglen Formation lies the Hekkingen Formation. This is also a Jurassic shale, but has very different elastic properties; the Hekkingen formation is much less dense, and is sonically much slower.

AVO models may be made using the cap rock properties of the Fuglen Formation, and an exploration strategy may be formulated on that basis. Figure 3 illustrates the expected AVO response for the Stø Formation (gas filled and wet) underlying the Fuglen Formation. Both gas and wet cases are expected to yield Class IIP AVO signatures. However, the synthetic seismograms do not display any Class IIP's at the top of the reservoir. In fact, the top of the reservoir is not associated with a reflector at all. Due to the thin nature of the Fuglen Formation in this well, and the elastic contrast with the overlying Hekkingen Formation, the top of the reservoir is not expected to yield a clear cut reflector. Thus, quantitative interpretation of the strong reflector associated with the Hekkingen/Fuglen interface will not yield information about the Stø formation.

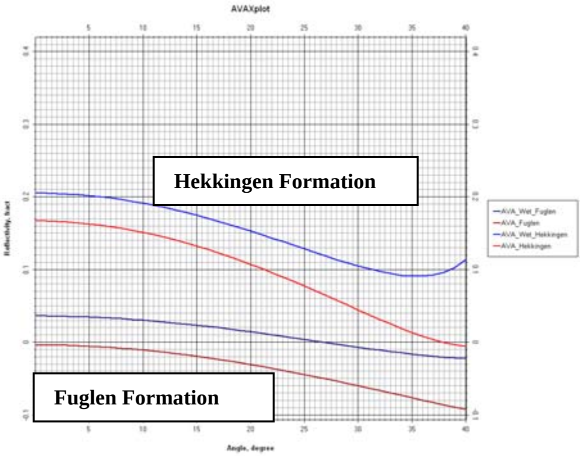

Figure 3: AVA crossplot for well 7121/5-1 for Stø Formation under Fuglen Formation and Hekkingen Formation respectively. Wet cases in blue, gas cases in red. Note Stø under Hekkingen yields Class I AVO, whereas Stø under Fuglen yields Class IIP AVO.

The Fuglen Formation is eroded away when moving east from the Snøhvit field, and in the Goliath field, the Hekkingen Formation is the caprock for the Jurassic reservoirs. Thus the AVO effect of the Hekkingen Formation over the Stø Formation is of interest when formulating an exploration strategy. Figure 3 illustrates the expected AVO for gas and wet cases with the Hekkingen as the cap rock. In contrast to the Fuglen Formation, the Hekkingen Formation will give a Class I AVO response for both wet and gas cases.

In conclusion, the AVO response of the Stø Formation is largely controlled by the cap rock. The Fuglen Formation will yield a Class IIP response, whereas when the Fuglen Formation is eroded away, and the Hekkingen Formation is the cap rock, one can expect a Class I AVO response. Extra care must be taken when the Fuglen is so thin that the Hekkingen/Fuglen interface interferes with the Top Stø reflector.

Example 3, Reservoir Architecture

The 24/6-4 well was drilled in 2003 to appraise the Alvheim field. A ~25 meter gross gas cap was encountered over some 25 meters of oil. The Heimdal sands in the area are interpreted to be deep water turbiditic sands. Several facies are readily identifiable in the well logs. In this study we consider two main sand facies; blocky sands and laminated sands. The main reservoir is the blocky sand at 2136m MD. This sand is overlain by a 5 meters of shale, and above the shale is a 5 meter thick laminated sand, which is gas filled.

As the blocky sands are the main reservoir target it is logical to develop an AVO interpretation strategy based on the blocky sands. An AVO halfspace model is created by averaging the elastic parameters for the blocky sand and for the cap rock shale, and using this as input to the Zoeppritz equation (Figure 4). This results in a class IIP response for a wet case, and a strong class III for the gas case. Thus, the exploration strategy would suggest targeting Class III AVO anomalies.

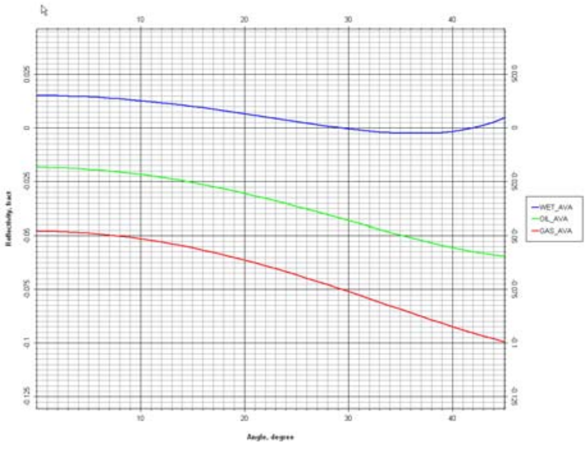

Figure 4: AVA crossplot for blocky sand in well 24/6-4. Wet case in blue, oil case in green, gas case in red. Wet case gives Class IIP AVO, and gas case gives Class III.

However, no class III AVO anomaly is present in the synthetics for the 24/6-4 well (Figure 5), suggesting erroneously that this well is wet (a false negative). Closer examination of the reservoir architecture suggests that the laminated sand 10m above the main reservoir is interfering acoustically with the main sand, masking the expected Class III response. A synthetic model of the well where the laminated sand is replaced by shale confirms the expected Class III response.

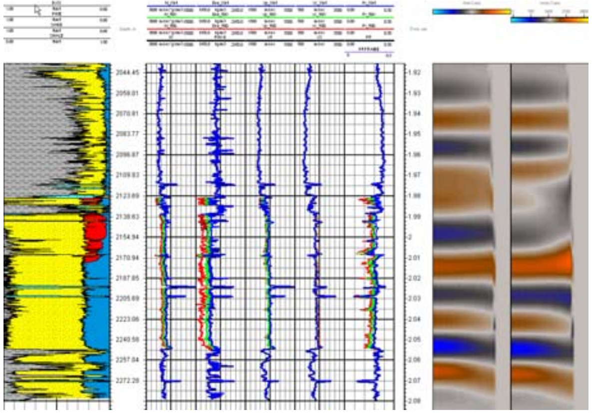

Figure 5: Fluid substituted models for well 24/6-4. Synthetic on the left is the wet case, synthetic on the right is insitu case (gas). Note no strong Class III AVO is evident in the synthetics.

In conclusion, reservoir architecture (e.g. the presence of laminated sands from the distal part of a turbidite lobe) may provide false negative results (as demonstrated in this example). Scenarios yielding false positives may also exist, though they have not been examined in this paper. Therefore, incorporating the reservoir architecture in rock physics and AVO modeling is critical for understanding the AVO response.

Example 4, Rock Physics of Organic Shale

The Draupne Formation acts as the cap rock for several fields in the Norwegian Sector of the North Sea. In many areas the Draupne Formation is an organic rich shale, providing not only a cap rock, but also the source rock. When developing an AVO strategy for reservoirs associated with the Draupne shale, it is important to carefully consider the s-wave velocities of organic shales. Many wells have penetrated the Draupne Shale, but have not measured the shear wave velocity. This may be modeled using a number of different VS predictors, such as Greenberg Castagna (1992) or Krief et al. (1990). Although both these models have been proven to work well in the Tertiary, Cretaceous and Jurassic in the North Sea reservoirs, neither of them is designed to accurately predict s-wave velocities in organic shales. Figure 6 shows a plot of measured Vp vs. measured Vs for the Draupne shale in well 34/4-10, with Greenberg Castagna’s shale line as a reference. Note that the measured data does not coincide with the reference curve.. The P-wave velocity for a given value of S-wave velocity is significantly slower for the measured data. This is due to the organic content of the shale, and is analogous to the presence of hydrocarbons in reservoir rocks.

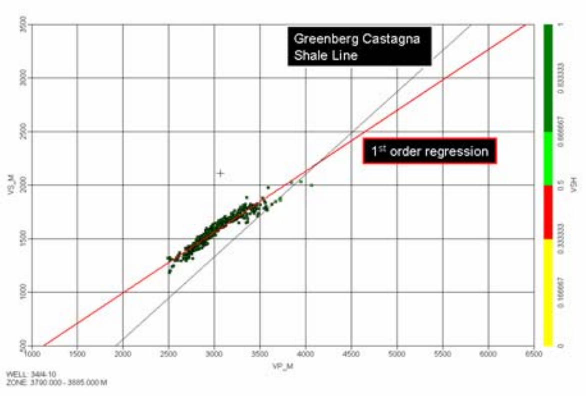

Figure 5: Vp vs. Vs for Draupne Formation in well 34/4-10, using measured data. Note that the data falls to the left of the Greenberg Castagna shale reference curve.

If modeled s-wave data is used to develop an exploration strategy using AVO, for reservoirs associated with organic Draupne shales, models such as Greenberg Castagna and Krief cannot be used, as the resulting AVO gradient is overestimated using the traditional models. Thus a local VS estimator has been generated using measured data in the Draupne from well 34/4-10. This Vs prediction model provides a robust tool for understanding the AVO associated with the Draupne Formation.

Conclusions

This paper has demonstrated that incorporating an understanding of the geology, and in particular an understanding of the geology of the cap-rock can significantly alter a exploration strategy based on AVO.

The paper showed how an unconformity may change the expected AVO, and knowing where the unconformity cuts out a given formation may be critical for getting the AVO interpretation right. Similarly, we demonstrated how a distal lobe of a turbidite introduced a thin laminated sand above the main reservoir. This laminated sand changed the AVO from the expected Class III and gave rise to a false negative. Numerous other examples due to local geology can be envisioned, such as presence of calcite stringers, fluid contrasts, mineralogical changes etc. Therefore it is important to have a thorough understanding of the geology, so geological features can be incorporated into the AVO modeling.

High quality data is also essential for accurate AVO modeling. This paper presented an example of poor data quality associated with a washout at a casing point, significantly altering the expected AVO. When modeling bad or missing data, it is important to use the correct model. The paper presented a case where inappropriate VS prediction models can lead to erroneous AVO models. Again, understanding the geology will aid in selecting the correct model.

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