Introduction

Amplitude vs Angle (AVA) analysis has been practically utilized in oil exploration since the 1980s after Richards and Frasier 1976, and Aki and Richards 1980 approximated the Zoeppritz equations which calculate the partitioning of seismic wave energy at a physical boundary as a function of incidence angle. AVA testing now forms a key component of the identification of potential hydrocarbon drilling prospects and risk assessments thereof. AVA has become a staple component of the exploration process and many rock physics models and workflows exist within the public domain and within Oil companies.

In 2011 a study was published by Loseth et al which began to explore the possibility that shales or "Thick <20m Claystones" exhibit a number of seismic characteristics which could be used to assist interpreters in the identification and characterization of marine source rocks on seismic data in the absence of wells. This study was broadly based on the observation that kerogens have approximately half of the density of otherwise non organic shales for an equivalent volume, and therefore increases in TOC (Total Organic Carbon) reduces the bulk rock density and therefore Acoustic Impedance of a rock non-linearly as shown in Figure 1.

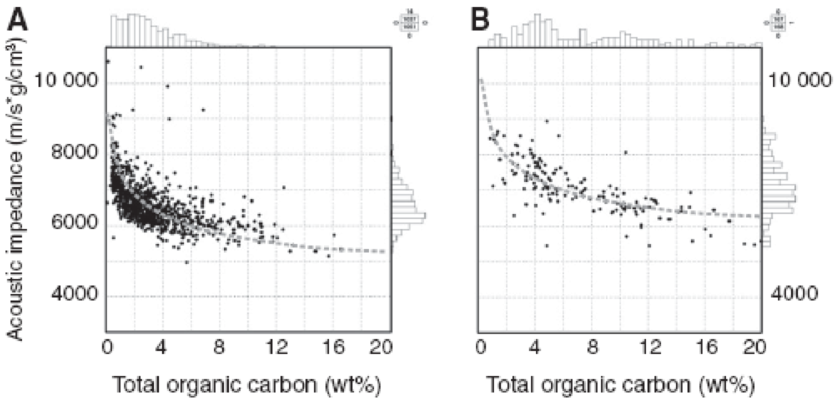

Figure 1: The relationship between Total Organic Carbon % and Acoustic Impedance. From Loseth et al 2011.

One characteristic of shale source rocks proposed by Loseth et al 2011 was that the top and base of a thick high total organic content (TOC) claystone should show a class 4 AVA response. Class 4 AVA anomalies show a decrease in amplitude with increasing reflection angle. This is distinctly different to the conventional use of AVA which looks for increases in amplitude with increasing offset as an indicator of hydrocarbons within reservoir rocks. Class 4 AVA responses are relatively uncommon in clastic sequences and the confirmation of the presence of one can be a quantitative indicator of source presence.

Subsequent publications including Avseth and Carcione 2015 have expanded upon the initial work by Loseth et al and demonstrate the relationship between rock properties such as Acoustic Impedance (AI), Shear Impedance (SI) and Vp/Vs ratios amongst others, with TOC and other shale rock properties. Similarly, Yengu and De-hua Han 2013 calculate the effect of maturity within the Bakken Shale onshore USA and the predicted p wave reflectivity (R) (Figure2) as a function of angle. These studies give credit to the statement that High TOC claystones will exhibit a class 4 AVA response, and that AVA attributes and derivative attributes such as Gradient, Intercept and Vp/Vs ratio should vary as a function of both TOC and maturity due to the changes in rock properties as a result of variations in kerogen content, fluid content and porosity.

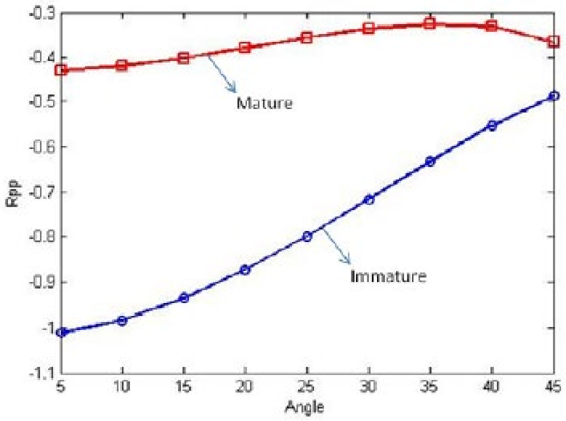

Figure 2: Variation in Rpp vs incidence Angle modelled in the Bakken Shale US. Reflectivity profiles presented for mature vs immature shale. From Yengu and De-hua Han 2013.

Namibia Kudu Shale

The Barremian-Aptian sequence shale is interpreted as present throughout the West African offshore margin, referred to locally in Namibia as the 'Kudu shale' due to its presence as the seal and source component at the Namibian Kudu gas field. It has, subsequently been high graded as a potential oil source due to the presence of type I and II kerogen, and has been de-risked by subsequent exploration activity in Namibia including at the three exploration wells drilled by HRT in 2013 namely; Moosehead-1, Wingat-1 and Murombe-1, which each encountered the Kudu shale at different stages of maturation and light oil was also recovered from thin intraformational sands at Wingat-1.

The Moosehead-1 well drilled offshore Namibia intersected approximately 200m of *"dark grey high gamma organic shales"* interpreted as the Barremian-Aptian age "Kudu" shales. The final well report also assessed that the Kudu shale was present day mature for oil due to an observed increase in pore pressure and elevated background gas.

The Kudu shale and its time equivalent have been intersected and interpreted in neighbouring South Africa, and it forms a major source play element. The ability to confidently map this unit and subsequently assess its potential maturity forms a major component of petroleum systems analysis in Namibia.

Theory

Moosehead-1 well TOC was estimated at approximately 8% using the Vernik and Landis 1996 estimation of TOC from bulk density.

$$TOC\left(\%\right) = 67\,\frac{\rho_k\left(\rho_m - \rho_s\right)}{\rho_s\left(\rho_m - \rho_k\right)}$$

Where P_k is Kerogen density P_m is the computed average matrix density and P_s is the grain density.

The implication that the Aptian Kudu shale at Mooshead-1 is a high TOC source rock at the early stages of maturity, would imply that the Rpp reflectivity profile should be similar to the "immature" curve predicted by Yengu and De-hu Han 2013 (Figure 2) e.g. decreasing seismic amplitude with increasing reflection angle.

Classical AVA analysis of clastic reservoirs relies on the observation that when hydrocarbons are present within a reservoir, Vp changes but Vs does not. This is due to the equation of Vp being defined as:

$$V_p = \sqrt{\frac{k + \frac{3}{4}\mu}{\rho}}$$

Where μ= Shear Modulus , κ= Bulk Modulus and ρ=density
and the equation for Vs being defined as:

$$V_s = \sqrt{\frac{\mu}{\rho}}$$

For a given medium the Vp only is affected by changes in the Bulk modulus k, which is in turn affected by the saturation of fluids such as gas, brine and oil and the fluids relative density. Subsequent simplifications of the Zooeperitz equations focus on establishing reflectivity (R) as a function of angle which presents itself as amplitude in seismic data. This reflectivity is governed principally by the angle of incidence and the Vp and Vs contrast at the interface.

Castagna et al 1985 states that VP/Vs ratios for shale are typically around 2, but the Vp/Vs ratio of organic rich shale ranges from 1.5 to 1.7. Quin 2013 expands on this to describe that mineralogy and organic matter content will affect the Vp/Vs ratio. Higher TOC and kerogen content results in a non-linear reduction in density and acoustic impedance. In normal to rich source rocks (TOC to 25%) the volume of organic matter is approximately twice TOC percent which is measured in weight, because the density of Kerogen (1.1-1.4 g/cm2) *Loseth et al 2011* which is approximately half the density of otherwise non organic rich shale. Variations in density will modify Vp and Vs proportionally however Vs will be unaffected by variation in the bulk modulus, thus Vp and Vs will vary at differing rates with changes in TOC. This was demonstrated by Altowairqi, Y et. al 2015 in laboratory ultrasonic measurements of the Vp and Vs in synthetic shales with varying TOC values. The rate of variation of velocity with TOC was dependent however on the matrix composition of the shale sample.

AVA attributes and anomalies are fundamentally products of the contrast in rock physics properties between two rock units, specifically Vp, Vs and density (ρ). The elevated TOC of the Kudu shale source rock as opposed to other non-organic shales within the sedimentary sequence should result in an AVA class 4 anomaly at the top source horizon.

Methodology

Post stack gathers from the SCOB-12 seismic dataset were imported into Hampson Russel geophysics software and an AVA analysis workflow was conducted. Pre conditioning of the gathers included AVA offset scaling and residual trim static correction. The Top Kudu Shale seismic horizon pick was used to identify the correct wavelet in the gather domain.

After cross plotting the Intercept vs Gradient attributes, the class 4 AVA trend was highlighted and plotted on a seismic stack to assess if a correlation was present between the AVA class 4 anomaly and the interpreted horizon (figure 3b).

Examples

An example AVA analysis of the post stack gathers from the SCOB-12 2D seismic dataset is shown in Figure 3a and b.

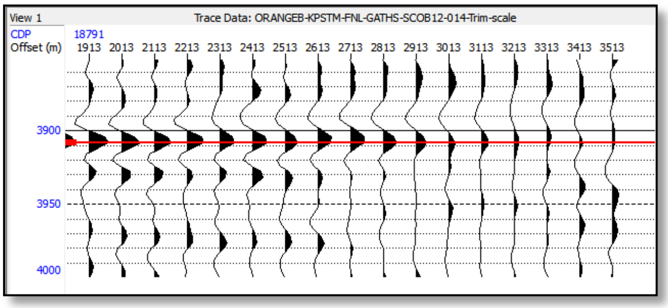

Figure 3a *An example CMP offset gather from the SCOB-12 2D seismic survey near the Moosehead-1 well, SEG Negative polarity. Red line represents the Top Kudu Shale horizon location.*

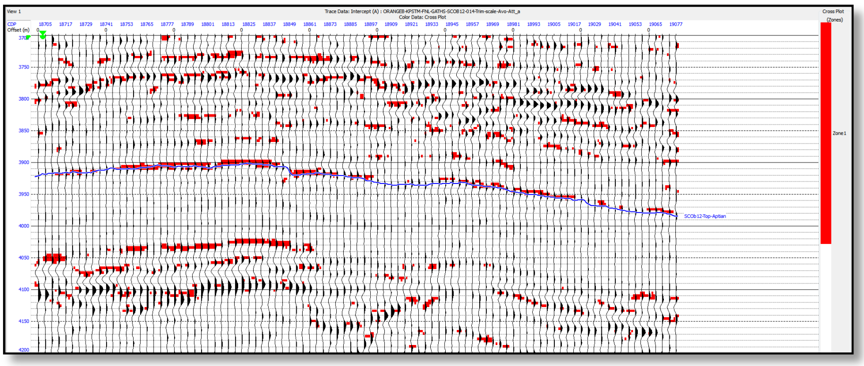

Figure 3b. *Seismic stack showing AVA class4 anomalies highlighted in Red. Blue horizon is the Top Kudu Shale seismic pick.*

Conclusions

The assessment of shales and their rock properties using AVA is a comparatively young science compared to similar processes utilized on clastic reservoirs. An AVA class 4 anomaly showing a decrease in seismic amplitude with increasing angle was predicted and observed at the top Kudu-shale level (Figure 3) and conforms as predicted with the horizon pick.

References

Altowairqi, Y. Rezaee, R. Evans, Rd B. Urosevic, Th M. (2015). Measuring Elastic Properties to determine the influence of TOC on Synthetic Shale Samples. Aseg-Pesa, 1-5.
Avseth, P and Carcione, J. (2015). Rock-physics analysis of clay-rich source rocks on the Norwegian Shelf. The Leading Edge. 34 (11), 1340-1348.
Castagna, J. Batzle,M. Eastwood, R.. (1985). Relationships between compressional wave in elastic silicate. Geophysics. 50 (4), 571-581.
Loseth, H. Wensaas, L. Gading, M. Duffaut, K. Springer, M. . (2011). Can hydrocarbon source rocks be identified on seismic data?. Geology. 39 (12), 1167-1170.
Qin, X. Han, D. Zhao, L. (2014). Rock physics modelling of organic-rich shales with different maturity levels. SEG Technical Program Expanded Abstracts 2014. , 2952-2957.
Vernik, L. Landis, C.. (1996). Elastic anisotropy of source rocks: Implications for hydrocarbon generation and primary migration. AAPG Bulletin. 80 (4), 531-544.
Yenugu, M. Han, D. (2013). Seismic characterization of kerogen maturity : An example from Bakken shale Seismic characterization of kerogen maturity : An example from Bakken shale. SEG Technical Program Expanded Abstracts. 1 (,), 2773-2777.