The application and value of AVO and spectral decomposition for derisking Palaeogene prospects in the UK North Sea

N. Loizou¹* and S. Chen²

Abstract
Perhaps over a billion barrels of oil, distributed over dozens of mostly small prospects, remain trapped in Palaeogene reservoirs in the UK sector of the North Sea Basin. Here we consider whether traditional amplitude versus offset (AVO) analysis, augmented by spectral decomposition, can provide a useful tool in helping to evaluate which of these prospects are worthwhile targets for drilling. In recent years, exploration drilling in the Palaeogene play fairway of the UK Northern North Sea has had mixed results. Eighty percent of wells drilled since 2000 have failed to encounter hydrocarbons, for reasons that include poor interpretation and evaluation of prospects, lack of AVO analysis, and positioning of wells on poor quality seismic data. Our analysis suggests that AVO analysis and spectral decomposition can be very useful and powerful tools for predicting the presence or absence of hydrocarbons in undrilled Palaeogene prospects in the North Sea. However, the validity of the results depends upon the availability of good quality seismic data with broad frequency content that have been acquired with cable lengths greater than 3 km.

Introduction
Since 2000, 25 exploration wells drilled in the UK Northern North Sea and the Outer Moray Firth, excluding the Central North Sea and the East Shetland Platform, have targeted prospects in Palaeocene or earliest Eocene reservoir formations. Surprisingly, only five of these wells encountered significant hydrocarbons, even though the operators had predicted their chances of success to be greater than 25% for each of the 25 wells drilled. Fewer than half of the 25 exploration wells were sited on an amplitude anomaly (not to be confused with an AVO anomaly). All of the exploration wells were located within mature play fairway areas, and most were close to previously drilled wells. The majority of the 25 wells encountered high-quality reservoir with porosities between 24% and 33%. The target reservoirs were located from 1700 m to 2500 m subsea, at depths where AVO analysis should have been viable. Given these factors, the overall drilling success rate should have been significantly better than one in five.

Pre-drill AVO analysis had not been carried out for the majority of the 25 wells UK Northern North Sea and the Outer Moray Firth (Figure 1). Here we describe the results of a programme of post-mortem AVO analysis and spectral decomposition, commissioned by the UK Department of Energy and Climate Change and carried out by the British Geological Survey (BGS), on eight of the 25 wells. Our purpose is to evaluate whether AVO analysis of the data available to the operators could have influenced their decisions on whether to drill their target hydrocarbon prospects. We focus on results from AVO analysis and spectral decomposition for five of the eight analysed wells. The results of the other three wells (9/10b-5A, 15/13b-8, and 16/23-6) are very similar to those described here.

AVO processing and analysis procedure
The basic principle of the AVO technique has been described in many papers (e.g., Castagna et al., 1993, 1998). The processing sequence and analytical procedures used for this study are outlined here, and are identical to those described by Loizou et al. (2008) in a previous study of the AVO characteristics of Tertiary reservoirs in four UK west of Shetland wells.

All of the seismic data were pre-processed to zero phase prior to AVO analysis, so that positive amplitudes on shaded wiggle traces correspond to increases in impedance. However, the data supplied by the operators are of variable quality, with some datasets containing residual multiples and residual moveout on primary events in common midpoint (CMP) gathers. Although these seismic processing issues are not addressed here, we stress their importance in achieving unambiguous AVO results.

The amplitudes of events on selected CMP gathers in the vicinity of each well location were first inspected visually.

¹ Department of Energy and Climate Change, 3 Whitehall Place, London SW1H 2HH, UK.
² CNPC KeyLab of Geophysical Prospecting, China University of Petroleum, Beijing 102249, China.
* Corresponding author, E-mail:nick.loizou@decc.gsi.gov.uk
Longer cable lengths would also be required to provide comparable AVO analysis for deeper targets. In this study, conventional stacking of NMO-corrected data was done with the full range of offsets (full offset stack). Then stacks of near, middle and far-offset data were generated to analyse the relative seismic amplitudes for different offset ranges.

**AVO attribute analysis**

In this study, AVO attribute analysis was carried out by computing the standard attributes of AVO intercept and gradient. The basic principle has been described by Castagna and Smith (1994), Foster et al. (1997), Sams (1998), and Pan et al. (2006), amongst others. A very useful way to interpret AVO attributes is to construct cross-plots of intercept, $A$, versus gradient, $B$. Castagna et al. (1998) give an excellent overview and a framework for interpretation of AVO gradient and intercept. A comparison of results derived from two-term and three-term AVO using the Aki–Richards equation did reveal some differences, but are not shown here. It would also have been interesting to investigate the role of different fluid factor methods (Smith and Gidlow, 1987), but the required shear-wave data were not available.

Loizou et al. (2008) discussed the effects of dispersion and attenuation on AVO responses. Figure 3 summarizes the variation of P-wave reflection coefficients with saturation and frequency modelled for typical Class I and Class III AVO anomalies. For a Class I interface, associated with low to high impedance contrast, frequencies above the transition frequency enhance the AVO effect due to the increase in impedance contrast across the interface. Therefore one would expect that for a Class I AVO, amplitudes would increase as frequency increases – the high frequency ‘bright’ spot. For a Class III AVO, an interface with high to low impedance contrast, exactly the opposite should occur. Amplitudes would be expected to dim as frequency increases.
hydrocarbon detection. In the present study, comparisons were made of the spectral data from selected CMP gathers in and outside the target reservoir zones. Following the methods of Castagna et al. (2003) and Chapman et al. (2007), iso-frequency sections were generated from the stacked data for each of the wells. It became apparent that some of the wells exhibit frequency anomalies that are associated with a Class III AVO response.

**Figure 3** Variation of P-wave AVO with fluid saturations in the high and low limits for typical Class I and Class III type AVO (after Chapman et al., 2006)

above the transition frequency, producing a low frequency ‘bright’ spot. The variation of AVO with frequency is also heavily dependent on the presence of saturated fluids.

**Spectral decomposition**

Spectral decomposition was also performed for all eight wells in the study, and produced some intriguing results. The main use of spectral decomposition has been in delineating tuning phenomena (e.g., Castagna et al., 2003). The modern instantaneous spectral analysis technique, or spectral decomposition, is an ideal test for detecting the effect of frequency-dependent AVO. It has been shown that spectral characteristics can also be used to differentiate fluids (Chapman et al., 2003; Odebeatu et al., 2006).

Loizou et al. (2008) extended the application of spectral decomposition analysis to AVO studies in the framework of the method of AVO analysis proposed by Rutherford and Williams (1989), and concluded that spectral decomposition could be used in conjunction with AVO analysis for direct

**Analysis of five exploration wells**

The eight wells analysed (Figure 1) include three that encountered hydrocarbons (15/19b-10, 16/23-6, and 16/23-7) in low-relief anticlinal structures with small associated amplitude anomalies. Wells 9/5b-5A, 9/10b-5A, 9/27a-4, 15/13b-8, and 15/30a-14 are all dry holes, and had targets with limited or no conformance to structure and no unambiguous hydrocarbon-related amplitude anomaly. Well 16/23-6 was drilled in 2000, while the other seven wells were drilled between 2005 and 2008.

Here we focus on the evaluation of wells 9/5b-5A, 9/27a-4, 15/19b-10, 15/30a-14, and 16/23-7. The five seismic datasets analysed are of variable quality. For three of the five dry holes, the operator had supposedly undertaken an AVO analysis that indicated a Class III (hydrocarbon-related) anomaly. The present study revealed that, with the exception of the
Well 16/23-7 was positioned on a low relief four-way dip closure at the top of the Palaeocene Balmoral Sandstone (Mey Sandstone Member), located above a Middle Jurassic tilted fault block and immediately northwest of the 1971 16/23-1 well that had encountered oil shows within the Balmoral Sandstone reservoir (Figure 4). The 16/23-7 well proved 52 m of oil-bearing Balmoral Sandstone reservoir with an average porosity of 26% at a depth of 2450 m (Figure 5). Modelling shows a Class I AVO anomaly. This is verified on the CMP gathers at the level of the Balmoral Sandstone (2.345 s) where there is little to suggest a dramatic increase in amplitude with offset (Figure 6).

On seismic profiles, the top of the Balmoral Sandstone is represented by a low-amplitude, hard event with normal polarity (Figure 4). Despite the data being acquired with a cable length of only 3 km, examination of the near (0–15º) and far (15–34º) offsets indicates some increase in amplitudes on the far-offset traces (Figure 7). However, the AVO cross plot shows principally a Class I type AVO response, but with a small area of data within the red ellipse that could ideal for robust AVO studies, and that the frequency content of the data was no more than 30–40 Hz.

A post-mortem analysis has been carried out on the five failed wells. It revealed that the majority of the well failures resulted from poor target trap definition, whilst some of the traps were mapped partly on the basis of AVO artefacts and spurious amplitudes. The three wells that encountered hydrocarbons were positioned on robust structural closures. Two key problems recognized whilst carrying out the analysis were that some of the 3D seismic datasets were acquired with cable lengths of only 3 km, and hence data were not atypical 15/30a-14 well, none of the dry holes showed strong amplitude anomalies on the far offsets. With the exception of 15/30a-14, the dry holes instead conform to a Class I type AVO anomaly (essentially water-bearing). For the hydrocarbon-bearing reservoir encountered in the 15/19b-10 well, the analysis confirms the presence of a Class III AVO anomaly. The other two wells with hydrocarbons, 16/23-6 and 16/23-7, gave somewhat anomalous results, primarily because the 3D seismic dataset supplied by the operator for the analysis was acquired with a cable length of only 3 km. In the case of well 16/23-7, the hydrocarbon column commences at a depth of 2.45 km, i.e., below the maximum depth deemed acceptable for reliable AVO analysis, with a cable length of 3 km.

Figure 5 Well logs through the top of the Balmoral Sandstone reservoir in well 16/23-7. Depths are in feet subsea.

Figure 6 AVO responses modelled for well 16/23-7, and CMP gather across the top of the Balmoral Sandstone reservoir. Here, and in later figures, \( R(\theta) \) is the reflectivity of the P-P wave at angle of incidence \( \theta \), \( \rho \) is density, \( a \) is P-wave velocity, and \( \beta \) is S-wave velocity.
be interpreted as showing a partial Class III (hydrocarbon-bearing) response, or alternatively as being within the noise data cloud (Figure 8). In summary, the overall analysis is inconclusive, largely because of the data quality and the need for a seismic dataset with longer offsets.

Iso-frequency displays (10–40 Hz) of stacked seismic sections for the 16/23-7 well are shown in Figure 9. At 2.3–2.4 s depth, corresponding to the oil column, there is no sign of any anomaly at the different frequencies, but what is intriguing is the zone of abnormal energy centred at 2.5 s that is particularly prominent at 30 Hz. It could possibly indicate a frequency-dependent phenomenon associated with the presence of oil (Odebeatu et al., 2006), or it could be a function of lithological variation within the underlying Ekofisk Formation chalk. In order to substantiate this type

Figure 7 Near-offset (0-15°) and far-offset (15-34°) stacked sections for well 16/23-7. Top reservoir is highlighted in blue.

Figure 8 AVO cross plot for well 16/23-7.

Figure 9 Iso-frequency displays of stacked seismic data for well 16/23-7. The oil zone is within the red ellipse.
of occurrence, spectral analysis of data around other North Sea Palaeogene wells associated with reasonable oil columns will need to be evaluated.

Well 9/5b-5A was drilled on the Eagle prospect, targeting the lower Eocene Hermod Sandstone Member as the key reservoir. The Top Hermod Sandstone time map and seismic profile (Figure 10) shows that an earlier 9/5b-2 well was positioned on an up-dip feature that encountered high net-to-gross Hermod Sandstone, but no hydrocarbon shows. Well 9/5b-5A also encountered high-quality Hermod Sandstone reservoir with porosity of 28% (Figure 11). The AVO curves for this well show a clear Class I AVO response, again verified by the gathers which display an obvious decrease in amplitude at approximately 2.1 s (Figure 12) (Figures 10–15 about here). Comparison of the near-offset and far-offset stacked sections in Figure 13 shows the far-offset traces are much weaker in amplitude. The AVO cross plot in Figure 14 confirms a distinct Class I AVO response that is very similar to that of the 9/27a-4 well. The iso-frequency displays of stacked sections at the Eagle site (Figure 15) suggest that there is no anomaly at either the low or high frequencies. This is consistent with the well results, which recorded no trace of hydrocarbons.
Figure 13 Near-offset and far-offset stacked sections for well 9/5b-5A. Top reservoir is highlighted in blue.

Figure 14 AVO cross plot for well 9/5b-5A.

Figure 15 Iso-frequency displays of stacked seismic data for well 9/5b-5A.

Figure 16 Depth map for the top of the Skadan Sandstone Member, showing the locations of wells 9/27a-2 and 9/27a-4 (courtesy of Century).
Figure 17 Two-way time to the top of the Flugga Sandstone Member, and interpreted seismic profile through wells 9/27a-2 and 9/27a-4 (courtesy of the British Geological Survey).

Figure 18 Well logs through the top of the Skadan Sandstone reservoir in well 9/27a-4. Depths are in feet subsea.

Figure 19 AVO responses modelled for well 9/27a-4 and a CMP gather across the top of the Skadan Sandstone reservoir.

Figure 20 AVO cross-plot for well 9/27a-4.
Well 9/27a-4 was positioned on the Hendrix prospect, where the target was the Palaeocene Skadan Sandstone Member. It was anticipated that the well would encounter a hydrocarbon column of at least 50 m, but no AVO analysis was carried out by the operator. The nearby 9/27a-2 well had previously encountered very minor oil shows within the younger Palaeocene Lower Flugga Sandstone unit (Figure 16). The operator mapped the Hendrix prospect as a small structural closure in two-way time at top Skadan Sandstone level, but a more recent interpretation (Figure 17) and mapping by BGS shows no time closure, and more importantly no evidence of an amplitude anomaly at this location.
The 9/27a-4 well was dry, but encountered a sandstone with high porosity of 27% (Figure 18).

If there had been a significant structural closure with a 50 m hydrocarbon column in such an excellent reservoir, one would expect a significant AVO response. However, whilst the top of the reservoir is at 1.745 s, the gathers reveal a deterioration in the AVO response below 1.7 s and a marked decrease in amplitude with offset (Figure 19), despite the overall 3D data quality being rather poor. Moreover, the modelling shows a clear Class I type AVO (Figure 19). Additionally, the cross plot for this well shows the data to be concentrated within an elongate ellipsoid that is unconditionally a classic Class I wet rock trend (Figure 20).

Iso-frequency displays (10–40 Hz) of stacked seismic sections across the 9/27a-4 well site are shown in Figure 21. The plots confirm no indication of a hydrocarbon anomaly at any frequency. Furthermore, modelling suggests that in the absence of hydrocarbons, these sections should show similar energy responses for each of the iso-frequency sections.

Well 15/19b-10 drilled the Stag prospect, an elongate anticlinal trap, 3 km long, with an associated amplitude anomaly (Figure 22) (Figures 22, 23 about here). The well encountered a Palaeocene Balmoral Sandstone reservoir
The cross plot of gradient and intercept shows a somewhat complex AVO response (Figure 26). There is, however, a discrete Class III/IV type AVO anomaly that coincides with the thin hydrocarbon zone. The significance of this AVO response is difficult to judge because the thin hydrocarbon column occurs within a relatively small time interval. The iso-frequency displays for the stacked seismic sections at the 15/19b-10 well reveal a distinct anomaly (Figure 27). In this example, the gas saturation produces a clear spectral signature that is evident at all frequencies, with the strongest response occurring at 20–30 Hz, even though the gas column is quite thin.

Well 15/30a-14 drilled the Dunkeld prospect, which was mapped by the operator as a stratigraphic feature at earliest Eocene, Top Sele Formation level (Figure 28). The well encountered thick sands of 28% porosity belonging to the Beauly Member (Cromarty Sandstone Member), but with no hydrocarbons (Figure 29). Interestingly, modelling predicts a partial Class III type AVO, and this was verified by the real field gathers (Figure 30). Furthermore, the cross plot (Figure 31) also indicates a partial Class III response. However, a re-investigation of the seismic data indicates that the far-offset traces have been scaled by a factor of 2.5, which has artificially produced a much stronger anomaly, giving rise to a false AVO response. Moreover, the iso-frequency displays for the stacked seismic sections at well 15/30a-14 show little or no presence of a hydrocarbon anomaly at any of the frequencies analysed (Figure 32).
Conclusions

Although this paper presents the results of just five wells, it is clear that AVO analysis and spectral decomposition can be very useful and powerful tools for predicting the presence or absence of hydrocarbons in undrilled Palaeogene prospects in the North Sea. However, the effectiveness of the methodology and confidence in the validity of the results require the availability of good quality seismic data, notably with a cable length greater than 3 km and broad frequency content. Although some of the 3D datasets provided by the operators for the studied wells were not completely satisfactory, they did provide useful information.

The AVO analyses carried out on the dry holes predominantly show Class I AVO anomalies (limited or no hydrocarbons present). For many of the dry wells, an incorrect understanding of the geological setting was the fundamental reason for failure to find hydrocarbons. Conversely, each of the three wells that encountered hydrocarbons exhibits a Class III AVO anomaly.

Attaining the most out of AVO analysis is in direct proportion to the quality of the seismic data and detail of the model. High quality data combined with a well understood model, in the right circumstances, may allow the detection of extremely subtle hydrocarbon indicators. Used correctly, AVO has the potential to reduce undrilled prospect risk, and it can be applied in a time-efficient manner.
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References


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The potential cost benefits of avoiding the drilling of a dry hole are considerable.

Spectral decomposition is viewed as an adjunct to the more standard AVO methodology. In order to interpret and comprehend the results of spectral responses robustly, it is recommended that this be carried out in conjunction with a thorough AVO analysis.

Figure 32 Iso-frequency displays of stacked seismic data for well 15/30a-14.