Reducing Drilling Risk on Culzean using WAVI-VSP

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Abstract

Critical to the successful delivery of ultra-HPHT production wells on the Culzean gas development project has been the placement of the production liner. To ensure correct depth of the liner a combination of GeoWave II® and the look-ahead Walkalong Vertical Incidence VSP (WAVI-VSP) technique have been deployed. Underpinning this has been detailed planning and close collaboration between operator and contractor.

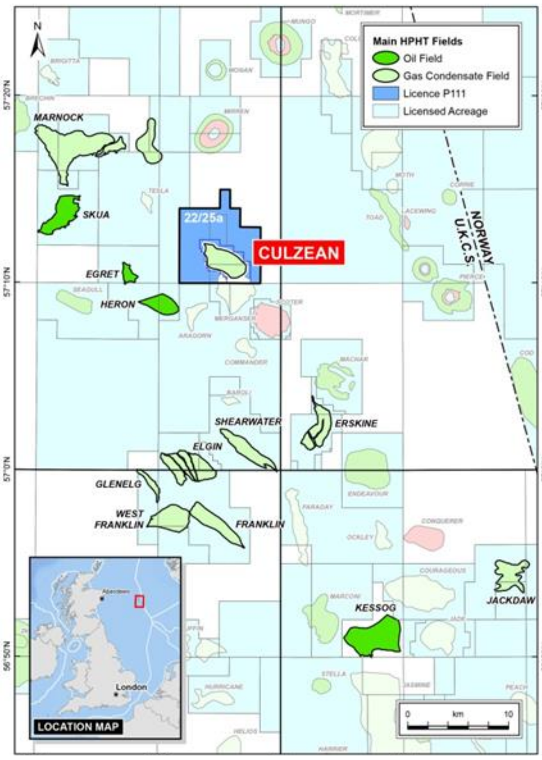


Figure 1: Location Map

Introduction

The Culzean field is an ultra-High Pressure, High Temperature (uHPHT) gas-condensate field located in block 22/25a of the UK sector, Central North Sea (Figure 1). The primary reservoir is Triassic and combined with a secondary reservoir in the Jurassic (Figure 2). Total recoverable resources are estimated to be between 250 and 300 MMBOE.

From both the Exploration and Appraisal phases it has been demonstrated that placement of the production liner, at ~4,100m, within the Lower Cretaceous Valhall formation (and ideally the Tuxen Limestone member) is a critical component of successful well, and thus development project, delivery. Failure to achieve an optimum setting depth for the production liner would have resulted in either the production liner set too shallow or drilling into the reservoir section with insufficient mud weight. Both scenarios have significant detrimental project implications.

If the section TD had been too shallow, then the cementing of the production liner might have been compromised. Additionally, this would have resulted in a lower than expected leak off test (LOT) in the subsequent hole section and would have required the setting of a drilling liner. Drilling too deep into the section would have resulted in a number of negative impacts. Initially reservoir pressure would have been encountered with insufficient mud weight, resulting in a potential well control incident, once under control it would have necessitated the setting of a drilling liner.

The requirement for a drilling liner would have reduced the hole size over the reservoir interval with a significant impact on well, and project, deliverability and thus economics. The potential for the total loss of a uHPHT well was also a realistic possibility, and given that Culzean is a six-well, multi-billion dollar development, the risk of such a loss was significant.

The delayed or lost production would have a large impact on the overall project economics thus significant effort was made in ensuring correct placement of the production liner was achieved. The margin between the optimum Lower Cretaceous formation for TD and Top Reservoir was only 80-150ft TVD (25-45m). Therefore, a multi-disciplinary approach was utilised. Logging while drilling (LWD) and biostratigraphy were useful for correlating the drill bit position but the use of Walkalong Vertical Incidence VSP (WAVI-VSP) was key to understanding how far to drill to ensure optimal production liner placement.

Delivery of multiple production wells required a drilling campaign approach. Thus, over the course of one year, four 12.25in. and three 8.5in. sections were delivered. This required significant planning of all activities prior to the commencement of drilling. A central element of this planning was the selection of the correct intermediate Vertical Seismic Profile (VSP) data acquisition methodology and its subsequent design. The main objective of the VSP acquisition was to provide a high quality seismic image with frequency uplift, compared to the surface seismic data that had been used pre-drill. This allowed a better prognosis of the Top Reservoir depth and reduction in the uncertainty of its shallowest possible occurrence. This article outlines what methodology was selected and how its employment ensured success for this critical hole section in a difficult uHPHT well.

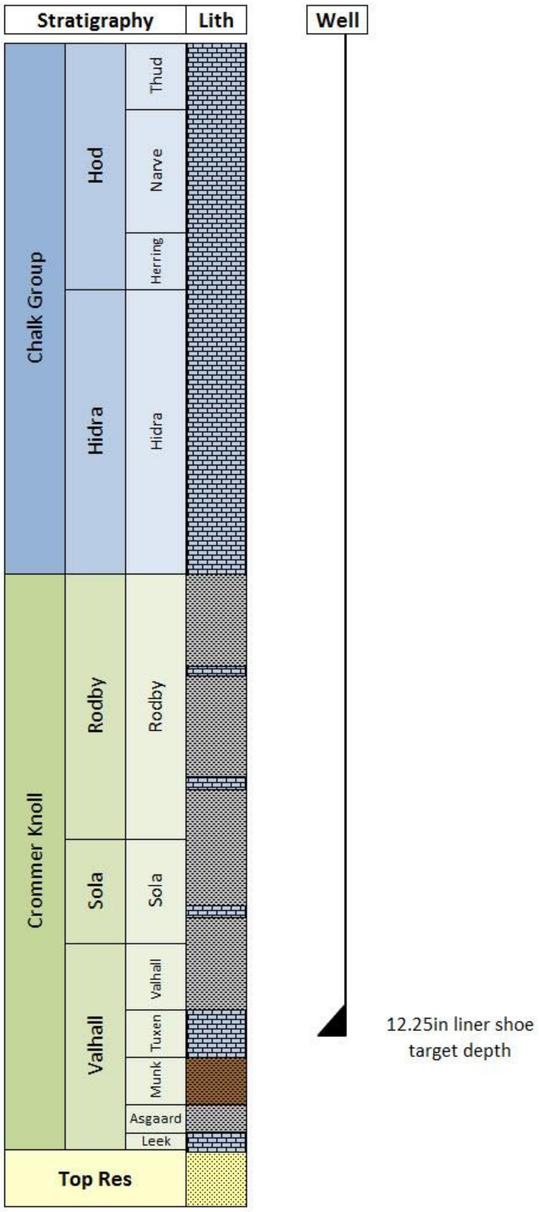


Figure 2: Stratigraphy

Pre-survey modelling

Pre-survey modelling is a critical part of the planning and design of any significant borehole seismic project. It aims to determine whether the project will be successful from a safety, geophysical and economical point of view. In order to derive an appropriate VSP design, all relevant information is assessed: the surface seismic and its interpretation; local well data; archive VSPs acquired in the area; the availability of equipment needed to acquire the data.

In the Culzean field, borehole seismic technology had been used previously by recording VSPs in four wells, and using two of the datasets to attempt to predict the depth of the BCU. Limitations in these initial surveys had been previously identified and these included: errors in the choice of method for the prediction; poor communication between the parties involved; an underestimation of the uncertainty associated with the results.

The pre-survey modelling on the new Culzean campaign was designed to improve on previous surveys, make a clear prediction of uncertainties, and derive a detailed protocol for executing the job. This last point was pertinent given the limited time available for data processing, interpretation and overall quality control.

Looking ahead of the bit using VSP data is a simple process whereby formation tops directly below the intermediate TD are interpreted as a function of time on the VSP corridor stack and then converted to depth using an accurate velocity model. The complexity of the workflow and most of the uncertainty is in generating the velocity model.

Previous VSP surveys on Culzean predicted the depth ahead of the bit used a Sparse Spike Inversion algorithm which inverts seismic data from the VSP corridor stack into interval velocities below the intermediate TD. This method is most effective in areas with little *a priori* knowledge of the geology where there is a low confidence in migration velocities. Unfortunately it often comes with a substantial uncertainty in the results, and can be described as a method with a great qualitative but poor quantitative solution. Given the limited depth window for setting the production liner, high-confidence quantitative results were required on this project.

After reviewing the available log data from the Culzean prospect, it was identified that the interval velocities of each formation in the Rodby – Sola – Tuxen - BCU sequence had maximum variations of only 4% to 6% across the four wells. Therefore if these tops could be confidently identified in time on the planned intermediate VSP corridor stack, then they could be accurately predicted in depth using their known average interval velocity. This technique cannot be directly applied to the surface seismic data because it lacks high frequency content, and the Tuxen and BCU formations often exhibit seismic tuning effects which make their interpretation in time difficult and inaccurate.

As a proof of concept, the four VSPs already acquired were reprocessed using data down to 60ft within the Rodby formation, consistent with the depths of the future intermediate VSPs. These new corridor stacks were interpreted in the time domain, and the Sola, Tuxen and BCU formation top depths were predicted, then compared with their known true depths. Average absolute errors of 4ft, 6ft and 12ft for the Sola, Tuxen and BCU respectively were calculated confirming the new look-ahead method was valid and sufficiently accurate to satisfy the defined objectives. The reprocessing also confirmed that sparse spike inversion could not provide accurate interval velocities, although their variations correctly identified the top Tuxen, confirming the method as a good qualitative tool to help identify the formation tops as a function of time.

A look-ahead VSP in a deviated well can be used to predict the target depth vertically below the well track and not the depth subsequently drilled along the well path. A geometrical correction is applied using the local dip of the targets to calculate the predicted measured depth. To estimate the dip of the target formations, the surface seismic interpretation can be used, but also the high-resolution vertical and horizontal images generated by the look-ahead VSP below the well deviation.

The VSP therefore had to satisfy the following criteria:

- an accurate time depth relationship to position the well on the surface seismic
- a high horizontal and vertical resolution 2D image below the wellbore
- data which can be processed on a fast turnaround basis

- a VSP tool string which can be deployed in open hole with acceptable risks for the challenges associated with uHPHT conveyance (Owens 2012).

Equipment & Technology

The most practical VSP geometry to satisfy these criteria is a vertical incidence VSP, where the seismic source is positioned vertically above each downhole geophone in turn. This is a long-established technique, and works well for a single geophone in the well with a single source, recording successive depths in turn. However, the development of long geophone arrays, driven by the economics of minimising rig time, has resulted in the use of many geophones deployed in the well simultaneously. To record VIVSP using these long arrays, for convenience a single source located vertically above the middle of the array has been commonly used, instead of positioning the source above each individual geophone. This has led to incorrect sampling of the subsurface, with a distinct acquisition footprint remaining in the data, degrading the data. (See Figure 3).

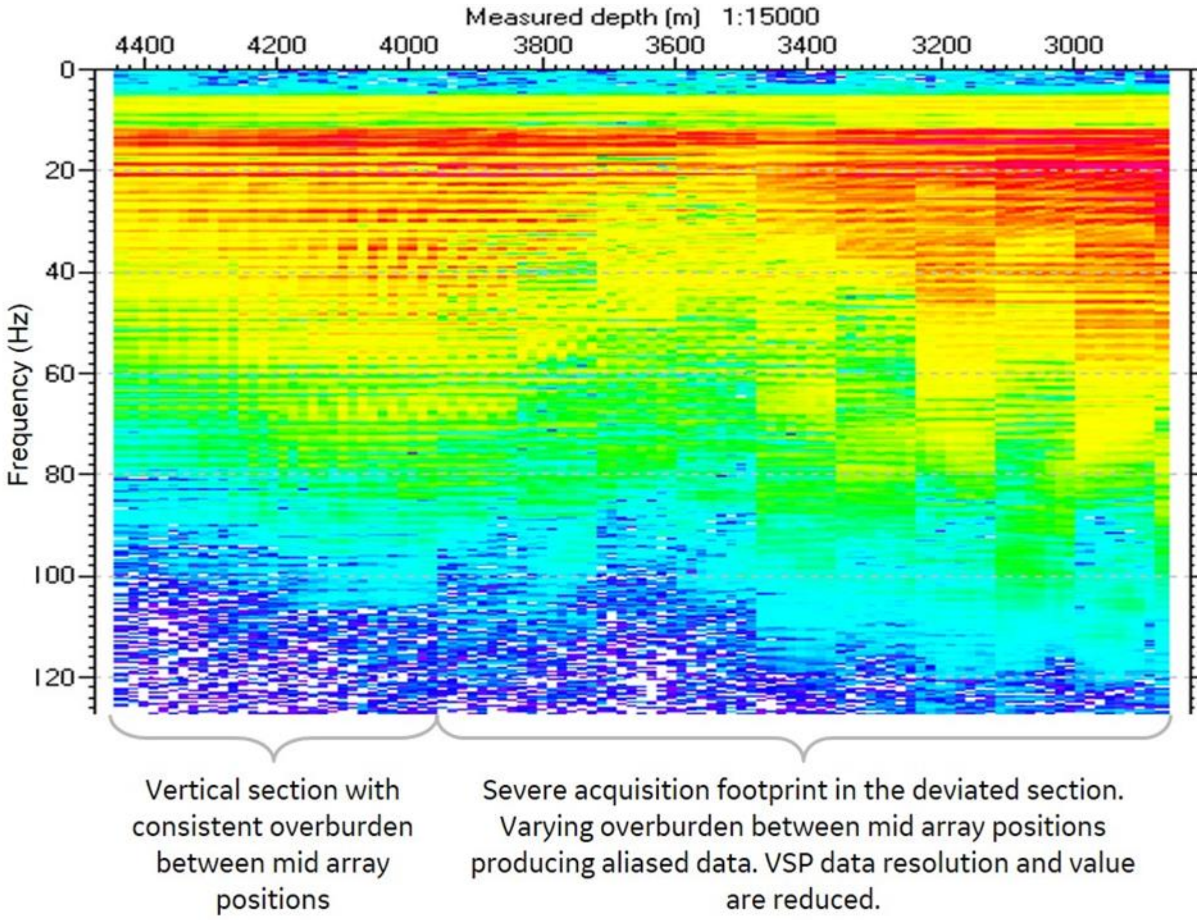


Figure 3: Acquisition Artefacts in Standard VIVSP Field Data (Frequency Domain)

In order to improve on this, a new technique of acquisition has been developed, the walkalong vertical incidence VSP (WAVI-VSP), in which, instead of acquiring shots above the middle receiver of the tool string, short walkaway lines are acquired above each tool string location (See Figure 4). This generates data from the vertical source-geophone pairs as before, but also generates data from all the other geophones in the string. The result is a large amount of data, densely sampling the subsurface, giving greater reflection point coverage and improved final images. The volume of data allows the VSP data processor to group the data into common-offset gathers, and enables imaging at a much finer trace spacing than usual, revealing more detail of the subsurface (Figure 5).

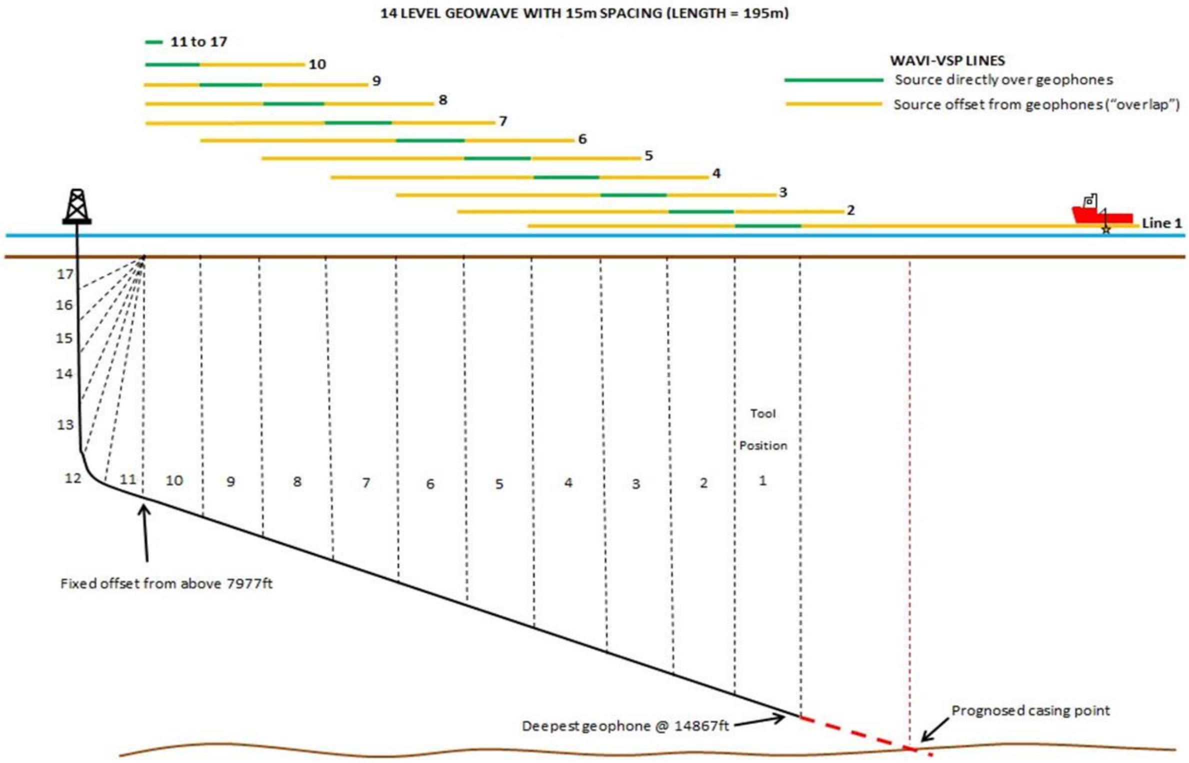
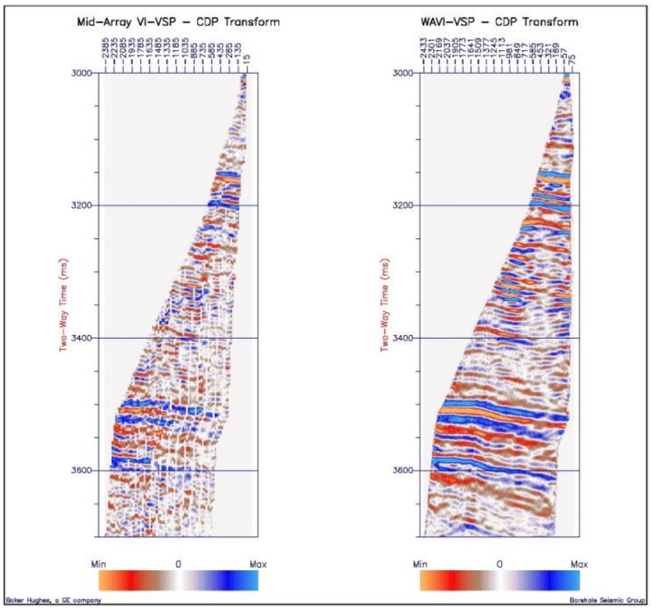


Figure 4: WAVI-VSP Survey Configuration



Intuitively, one would think that sailing a line of shots instead of keeping a vessel stationary for a series of shots above the array would take considerably more rig time, but in practice, this is not the case. It can be easier for a vessel to traverse a line at slow speed, than to remain in a fixed location.

Therefore, a WAVI-VSP was selected for Culzean as the only geometry which would yield true vertical travel times for each source-receiver pair and high resolution images, since the geometry enables the unique common offset gather processing.

Figure 5: Comparison of Images from Conventional VIVSP and WAVI-VSP

The array tool chosen was the newly-introduced GeoWave II®. A system comprising a string of up to 18 orthogonal 3-component geophones was used. The high well temperature would normally severely limit the number of geophones that could be used in this environment, but the temperature tolerances of this system (continuous operations possible at 400°F) enabled a greater number of levels to be acquired in fewer stations when compared to other uHPHT solutions. Also, in the unlikely event of a geophone failure, this system has been designed to continue transmitting signals from all remaining geophones, both above and below any failed component. This advantage over other available technologies was significant in de-risking the survey, where weather conditions might result in a limited window of opportunity, in these expensive uHPHT wells where rig rates are significantly higher than NPNT drilling.

Using a seismic array tool requires thought about how many receivers to use and how they will be rigged up and deployed in the well. Several interrelated factors have to be weighed up against each other. Amongst these are:

- safety
- time taken to acquire the data
- time taken to rig-up and rig-down
- effects on the data of array size
- risk and impact of potential equipment problems

Overall, it is an optimization problem. An array with more receivers is able to acquire data over a given range of depths more quickly than one with fewer, but on the other hand will take longer to rig up and rig down. Likewise, with more receivers there will be a greater number of traces sharing the beneficial effects of identical common source signatures, but countering this is an increase in risk due to greater complexity in the well. For this survey, proprietary software was used to rigorously model the conveyance of the geophone array on wireline, taking into account the specific uHPHT challenges such as mud weight, temperature and gel strength. The decision to use the GeoWave II® tool, with its high-reliability features and fault-tolerant design, meant that with a large array the risk of a down-hole failure could be shown to be lower than with other tool designs and, effectively, negligible.

The final choice on number of receivers and deployment was therefore principally based on maximising the number of receivers, but also minimizing the total rig time the surveys would take. As part of this, the particular features of the drill rig and how well it was suited to a variety of different array tool deployment methods had to be evaluated. The conclusion was that the survey could be shot most efficiently and safely with 14 to 18 receivers, with the array rigged up and deployed by building it up in a simple way from 100ft sections.

Achieving the best possible data quality and accuracy is clearly always an objective, but for this project, where significant and safety critical decisions were to be rapidly made very soon after the survey (a matter of less than 12hours), an even greater focus was required. In particular, processes needed to be in place that would demonstrate in real-time that the data was good and therefore confirm that results from it could be trusted. Any data quality issues required early identification to decide if a particular line had to be re-run or a back-up tool string would need to be used. All in-field QC procedures were tested and checked as fit for purpose. There were many aspects to this, but two decisive ones were accurate receiver depth and source position measurement.

A process known as primary depth control was used to ensure the highest possible receiver depth accuracy and reliability. Part of this process is to use the specialist forces-modelling software used for wireline logging runs, mentioned above, while running the job. This was done in order to analyse the tension and friction factors actually seen. If these are known reliably, then then cable stretch and when and how it is occurring can be accurately accounted for. Several depth quality metrics were monitored but two of the commonly used ones in the industry showed the effectiveness of the procedures used. Depth error on pull out, i.e. the tool reference position back at surface relative to when it was run in, was an average of 3.75ft, small in comparison to the 16,000ft TD depth. Multiple comparisons were made of first arrival times between shots taken during run-in and run-out and the differences were found to be on average less than 0.3 ms.

Shot point location measurements were made with a source positioning system using survey grade Differential GPS receivers. The system is custom designed specifically for VSP use and automatically monitors and records a large number of position quality metrics, with relevant user alerts should one of them not meet a pre-set threshold. For example, during the surveys, it made continuous comparison between the positon measurements from two different Differential GPS receivers that were each using independent sources of differential corrections. If they had diverged significantly, then the cause would have had to have be investigated as a matter of priority. In the event, the match between the two measurements was consistently good, with an average difference of substantially less than 0.5m.

Processing & Deliverables

Because fast turnaround of the processing was of critical importance to the success of the project, special care had been taken to maximise the connectivity bandwidth between the rig and the data processing centre. At the end of each WAVI-VSP line, the data would be transmitted to the VSP processor for QC and pre-processing. Once all the lines had been acquired the full VSP processing could start.

The look ahead processing was performed on the full 3-component dataset.

First, the 'true' VI-VSP dataset was extracted from the full WAVI-VSP, the time depth relationship was calculated and the data was processed up to corridor stack, and filtered back to surface seismic bandwidth (30Hz) (Figure 6). The true VI is a dataset where for each tool only the closest source to the vertical is used, which in a deviated well often results in unique source positions for each tool with source to receiver offsets smaller than 20ft. This unique geometry provides the most accurate time-depth pairs and interval velocities.

Secondly, the full WAVI-VSP was sorted in common offset gathers (COG) and processed into a high resolution 2D image below the wellbore using the commonly used VSP-CDP transform imaging technique (Figure 7). The final image was band-limited to 5-110Hz to exclude any noise outside the seismic bandwidth, and was processed using a sampling rate of 1ms in time and a 6ft trace spacing.

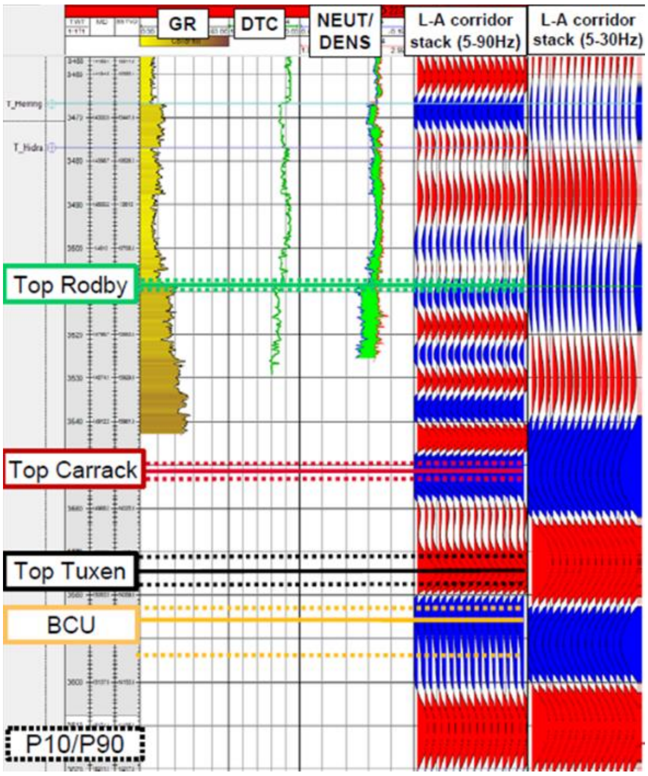


Figure 6: Interpretation of the Corridor Stacks

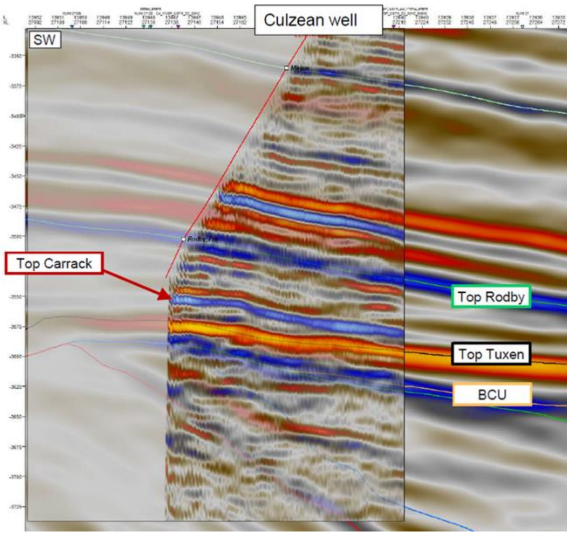


Figure 7: VSP-CDP Transform overlaid on the surface seismic image

The common offset gathers were grouped in 25ft intervals from offsets of -500ft to +1000ft from each downhole tool. In each gather, all recorded levels are present and all source to receiver pairs have about the same offset. Processing a WAVI-VSP dataset in COG, instead of in common shot gathers (CSG), vastly improves the continuity of events in the final image. The edge effects of the wavefield separation are limited only to the shallowest and deepest traces in the entire survey, instead of the top and bottom tools of each individual shotpoint as in conventional common-shot-gather processing. The CSG processing tends to create a strong acquisition footprint in the image.

Thirdly, a sparse spike inversion was performed to help interpret the VSP upgoing wavefield and VSP corridor stack below the intermediate TD, and identify the top Sola, Tuxen and BCU as a function of time.

The predicted tops in time were then converted to depth vertically below the intermediate TD before being transformed geometrically into measured depths along the well path.

For each well, the VSP operations, from rig-up and running in hole to the calculation of the predicted Sola or Carrack, Tuxen and BCU depths was completed in less than 36 hours. Within that time the complete VSP processing and analysis was finished within 6 hours of receiving the full dataset. This could only be achieved through meticulous planning of each VSP operation, and the co-location of the processing geophysicist within the customer's offices.

The three intermediate look-ahead VSPs in the new Culzean campaign resulted in extraordinarily accurate predictions. The Top Carrack was predicted, within 14ft of the true depth, the Top Tuxen within 8ft of true depth and the BCU within 13ft.

Close communication between the contractor, client, the local asset team and their international colleagues throughout the processing and interpretation was a key success factor of the Culzean VSP campaign. It enabled geophysicists and geologists on the client and contractor side to discuss ideas about the interpretation of the VSP data and ensured that each step of the look ahead workflow went through a proper peer review. After each intermediate VSP, successes and errors were analysed, lessons learned were documented, and the workflow was adapted which meant that by the third well, the BCU was predicted 13ft too shallow compared with a surface seismic prediction 75ft too deep. Without the VSP look-ahead the well could have been drilled into the BCU before setting casing, had the depth prognosis been used in isolation, resulting in a potential loss of the well.

Conclusion

Key to the safe and successful delivery of the Culzean gas development project has been the correct placement of the production liner in each production well. Behind this success has been a phase of sharing project success criteria, detailed planning, defining and agreeing protocols with close collaboration between operator and contractor throughout.

Judicious selection of appropriate downhole technology and the use of the WAVI-VSP technique defined in the planning phase have been shown to be correct in the execution phase.

The combination of downhole technology and data processing technique has resulted in a significant improvement in subsurface imaging. This increases the confidence in deciding the next steps in the drilling programme. In terms of rig-time we conservatively estimate a saving of between 0.5 – 0.75 days rig-time per well using the workscope outlined above which is significant when drilling uHPHT wells.

GeoWave II® is a registered mark of Sercel.

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