Introduction

Field appraisal and development plans aim to provide the best technical solution for optimizing the production and require integration between various disciplines including geology, geophysics, engineering, well planning and environmental sciences. Of course this is a broad definition and the geophysics loop itself can consist of many studies. On that note, one could argue that seismic inversion is the fundamental, and perhaps the most critical, step in the quantitative interpretation (QI) workflows (and generally in the seismic discipline) to provide the final deliverables for field appraisal and development evaluations. It is therefore of significant importance in seismic inversion to assess all the possibilities and incorporate all the uncertainties involved in the reservoir definition and extension.

The case study in this paper centres on a recent Paleocene discovery, known as Avalon, in block 21/6b of the UK Central North Sea located at the north-western edge of the Central Graben just south of the Buchan Field. The reservoir sands lie within the proximal part of the prolific northwest to southeast late Paleocene Forties and Cromarty depositional trend. Generally, Cromarty and Forties members have high porosities, high net-to-gross and, as a result of these rock properties, the reservoirs provide a natural laboratory for applying AVO-based inversion techniques. Zabihi Naeini and Exley (2017) presented a facies-based inversion to delineate the discovery and to optimize the location of a further appraisal well, the third well on the structure (well-3 in this work) after a dry well (well-1) and a successful discovery well (well-2; 85 ft column of oil in good quality sands). In this study we assess the success of the new well, and further employ the same facies-based seismic inversion method as in the previous study, albeit this time in a probabilistic mode to assess uncertainties to optimize field development. I.e. whilst the previous work was focused on de-risking via QI for a successful exploration toward drilling appraisal well program, this paper is dedicated to the application of facies-based inversion for field appraisal studies toward development planning.

The appraisal well (well-3) was mostly consistent with Zabihi Naeini and Exley's results. The new well showed the oil water contact as predicted, the presence and thickness of a local gas accumulation in a small four-way-dip closure, a better definition for the top and the base reservoir layer, and an overlying supercharged shaly sand referred to as "ratty sand" here. Figure 1 presents a multi-well panel used in this study along with the classified facies and the corresponding petrophysical logs. It is therefore possible to fine tune the model further with the new well information, i.e. update the depth trends and also quality control (QC) the inversion with an extra well. The probabilistic approach allows one to compute various scenarios. We have categorically selected, amongst others, most-likely, optimistic and pessimistic scenarios based on our knowledge and calibration at the wells. Furthermore, we have performed a statistical analysis of all the analyzed scenarios to help identifying the uncertainties.

Method

The work presented here is a QI study with application to the field development plan. A typical QI study often consists of rock physics analyses, fluid substitution, and seismic forward modelling, followed by well to seismic tying, inversion to elastic properties, with subsequent derivation of facies. For the sake of brevity, we will only show the updated depth trends as a result having new well information, followed by multi-scenario inversions for statistical multi-scenario analysis. These concepts are explained below.

Depth trends and facies-based inversion

Facies based seismic inversion, in which the low frequency model is a product of the inversion process itself, was introduced by Kemper and Gunning (2014). The low frequency model is constrained by per-facies input depth-trended Rock Physics Models (RPM) including Vp, Vs and Rho, the resultant facies distribution and the match to the seismic (Zabihi Naeini and Exley, 2017). Undoubtedly, these depth-trended RPMs are at the heart of facies-based inversion and ultimately lead to the optimum construction of a low frequency model which now becomes an output of the inversion (rather than input). In summary, a per facies compaction curve is fitted to the impedance log data belonging to that facies, as a function of depth below an appropriate datum, complete with an assessment of uncertainty. Then, the inversion first derives models of impedances (from the seismic) given facies, and then facies (from the impedances) at each iteration of the optimization loop. The main outputs of the inversion are therefore the most-likely elastic properties and facies given by the so called maximum-a-posteriori (MAP) estimates (Dashti et. al 2013).

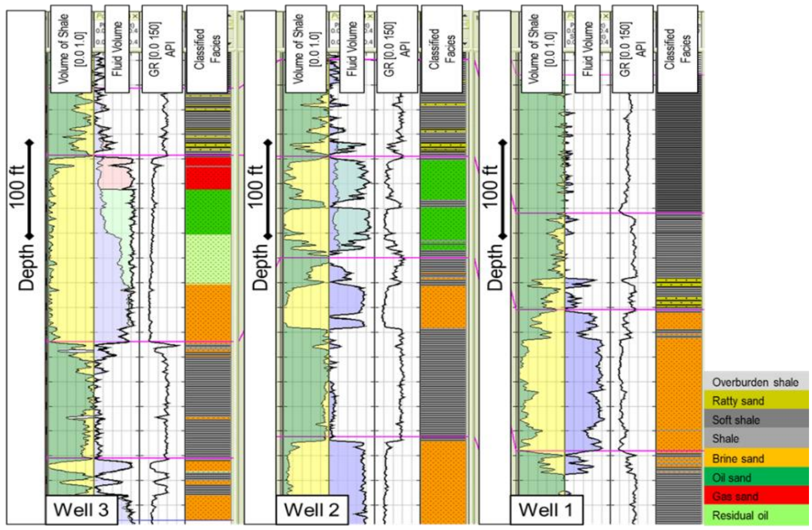

Figure 1 *Multi-well view summarizing the petrophysical logs and the classified facies. Note the presence of shaly sand classified as "ratty sand" just above the reservoir*

Scenario analysis

Given the probabilistic nature of facies-based inversion, it is possible to divide the interval of interest into different zones in which one can constrain the inversion in those zones more effectively by assigning appropriate facies probability proportions. Although good prior information (e.g. sufficient number of neighbouring wells) would inherently help to reduce the number of scenarios, however, one can intuitively imagine that such an approach can still lead to many scenarios. As an example, tuning the shale content in the reservoir, calibrating the ratty sand and different hydrocarbons proportions led to 13 different scenarios in this study. After reaching a sensible overall calibration (identified based on regional geology and calibration at the wells), one can compare various scenarios based on different hydrocarbon probability proportions, of course constrained in the reservoir zone. In this study, oil-sand probability of 3% as the prior information is recognized as the most-likely choice and is compared to when it is set to more optimistic and pessimistic scenarios, 5% and 2% accordingly.

It is also possible to analyse all the scenarios statistically and compute the mean and standard deviation of the elastic properties, the most probable facies (the one that occurs most across all different scenarios) as well as the fractional probability of each facies. In other words, we would like to compute the most frequently occurred facies among all the scenarios that were originally derived by MAP. This analysis allows us to rank the scenarios and consequently derive low, mid and high probability estimates corresponding to scenarios exceeding the 10%, 90% and 50% probability (Monte Carlo type evaluations).

North Sea Case Study

In this study the input seismic has been broadband processed and prestack depth migrated using a tomographic velocity model. As expected, the pre-imaging de-ghosting technique, for broadening the bandwidth of the conventionally acquired towed streamer data, removes the frequency notches caused by ghost wavelet interference. Improved low frequencies within the seismic are especially important for seismic inversion as they reduce the dependency on the initial low frequency information. Subsequently we performed a thorough well tie analysis to capture the effective seismic bandwidth in the wavelet, especially the low frequencies, which is of critical importance to achieve high validity for seismic inversion.

After well tie and computation of wavelets for all angle stacks, the next critical step for facies-based seismic inversion is to derive depth trended RPMs for each facies. Separating the various shales and including the ratty sand facies into different facies types proved a critical factor to improve the inversion accuracy and distinguish it from oil sands as well as a more accurate top reservoir definition. The depth trended RPMs is shown in Figure 2.

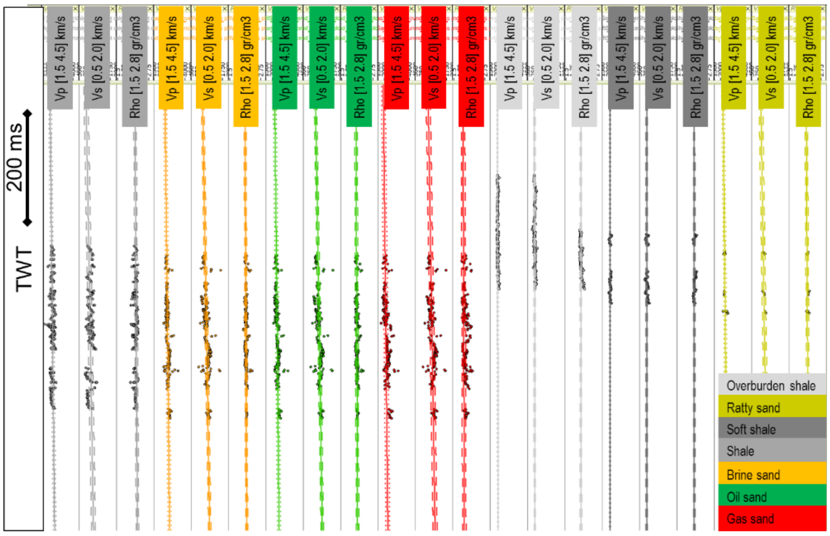

Figure 2 *Depth trended RPM's for each facies displayed in the time domain. Dashed lines show the error bounds for each of the depth trends and also represent the constraints for which any given facies may be inverted to. Correlations between Vp and Vs and between Vp and Rho were derived also as part of the RPM's (not shown).*

Inversion sensitivity for field appraisal and development

As mentioned before various scenarios were computed (typically by first running over some QC 2D lines and at wells before completing in 3D) to allow us understand the sensitivity of inversion and the inverted facies in different zones as a function of prior facies probability proportions. Here we summarize our analysis into two sections. First, we categorically select what we think is the most sensible, optimistic and pessimistic results in terms of oil- and gas-sand proportions relative to shale and brine sand (one could say this is the interpreter's choice). Second, we run a statistical analysis of different scenarios to allow us understand the uncertainties more broadly and quantitatively (here the computer can select alternative cases to the interpreter's choice based on the statistics of all scenarios). We only show the latter in this paper due to lack of space. Although each individual scenario was performed with specific targets in mind (i.e. analyze the impacts of various facies), but having all these scenarios can be difficult to comprehend quantitatively due to the fact that each scenario is originated from an individual MAP which is based on different prior information . Therefore, statistical analysis of all the scenarios can be useful where one can compute the mean and standard deviation of the elastic properties, the most likely facies (the one that occurs most across all different scenarios) as well as the fractional probability of each facies. This sort of analysis allows one to compute the low, mid and high probability estimates (Monte Carlo type evaluations) ranked based on volume of reserves, here volume of oil sands, and consequently the probabilities exceeding 10%, 90% and 50% (known as P10, P90 and P50 where P50 is considered a good middle estimate). This can be considered as a transition from MAP (based on Bayes' probability) to the frequentist probability. Coincidentally, the P50 outcome turns out to be the sensible scenario we flagged based on our interpretation which consequently gives us confidence on this scenario as a good middle range choice. Also our two pessimistic and optimistic end members are specified as P0 and P100 in this analysis. So from the probabilistic point of view, amongst all the generated scenarios, it is guaranteed that the estimated volume of oil exceeds the pessimistic case volume, and vice versa for the optimistic case. Finally, the most-likely facies (and also other attributes such as the mean and standard deviation of the elastic properties which are omitted here for the sake of brevity) could be computed from all the scenarios. That is the facies that occurs most at every sample location. As an example, Figure 3a and 3b compares the most-likely facies with the sensible scenario, in this case scenario P50. The two examples are rather comparable with some subtle differences on the shale content around the reservoir zone. Furthermore, we can compute the fractional probability of each facies which is the fraction that each scenario satisfies being a specific facies. This is shown in Figure 3c and 3d for oil and gas sand probabilities. The probability of the oil sand, Figure 3c, clearly indicates the reservoir extensions as well as some satellite targets. Moreover, for gas sand probability in Figure 3d, the gas accumulations are visible and marked with ellipses whilst the two smaller gas anomalies marked with arrows demonstrate a variable probabilistic nature which indicates the uncertainty for their presence.

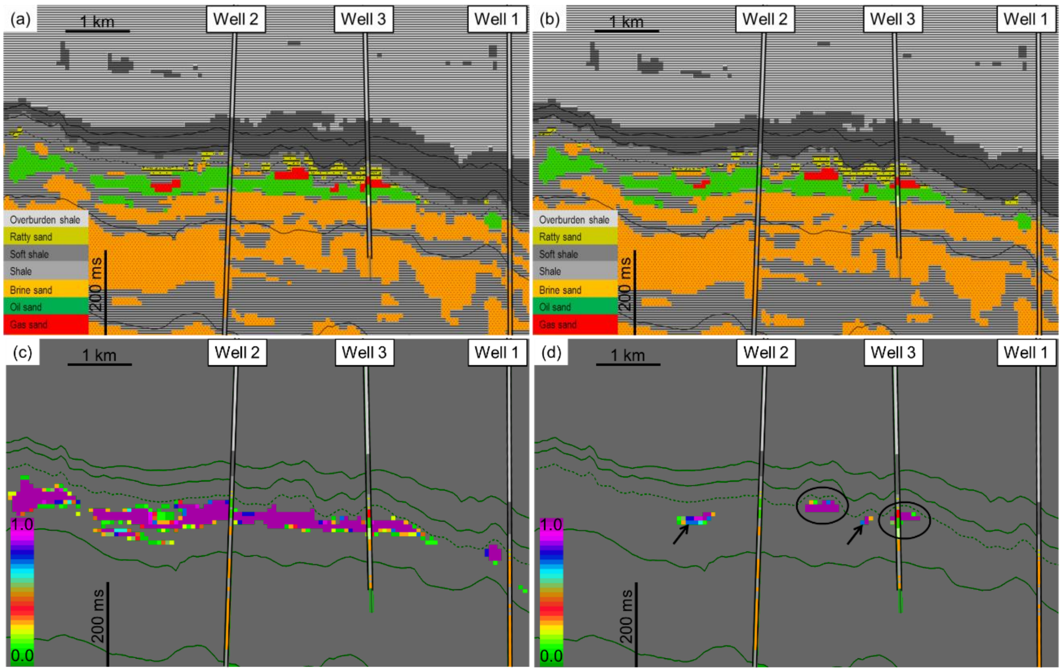

Figure 3 *(a) most-likely facies, (b) sensible P50 scenario, (c) oil sand probability, and (d) gas sand probability. The arrows in the gas sand probability section indicate the uncertain nature of those small packages. The gas accumulation confined by small 4-way dip closure marked with ellipses however are confidently visible and also match at well-3.*

Conclusions

A QI workflow dedicated to a field appraisal and development planning has been demonstrated via a North Sea case study. We took full advantage of the probabilistic nature of facies-based seismic inversion to explore a range of possibilities and understand potential inversion errors and uncertainties. It was observed that a sensible scenario as well as optimistic and pessimistic end members can be selected by well calibration and geological knowledge or by statistical multi-scenario analysis. We showed that these two approaches complement each other and can help in building confidence for the best possible scenario. Another important factor which led to achieve better facies model was the updated depth trended RPMs based on the newly drilled appraisal well and accurate well ties.

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