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Understanding the Effect of 3D Layering Methodologies on the Production Profile of Tidal Estuarine Reservoirs

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Abstract

A typical tidal estuarine reservoir comprises inclined interbeds of sandstone and claystone, also known as Inclined Heterolithic Strata (IHS). This sub-seismic feature of naturally inclining beds, combined with considerable heterogeneity, commonly inhibits the horizontal connectivity and ultimately controls the fluid flow behavior within these systems. However, normal datasets from subsurface studies frequently restrict a full IHS characterization and lead to the construction of a conventional, proportionally layered reservoir model. Moreover, once the 3D model is carried forward for simulation purposes, any significant changes to the geomodelling parameters are commonly barred which leads to excessive manual near-well region editing. Therefore, this paper aims to showcase the importance of representing the architectural elements of tidal estuarine deposits in the 3D model and their relation to the 3D layering methodologies and reservoir performance through 3D outcrop studies and multi-scenario reservoir simulation approach.

To demonstrate the effect of 3D layering on the production profile of IHS, 3D scanned outcrops of the Blackhawk Formation, USA, have been studied to produce several realizations of 3D models, including one that matched the morphological features of the outcrops as the truth case. All realizations were then simulated, and history matched to the truth case result as comparative studies.

Using 3 matched realizations to simulate 5-years forecasts, significant divergences prevailed. Cumulatively, there was up to 9% variation in total productions with only 3 producers and 1 injector wells in all realizations. More importantly, evident on both well by well production plots and visually over the time steps, the timing of water breaking-through the producer wells were faster and more uneven on the truth case, contrasting the results from proportionally layered realizations. Naturally, these required varying development strategies and proved that different3D layering methodologies produce quite variations in production forecasting albeit historically matched.

The novelty of this work is to integrate geological concepts, in a form of 3D layering methodology, as one of the most influential variables when modelling tidal estuarine deposits with under-informed conditions. This work can be implemented further in most fields with layering uncertainties to enable an optimum flow estimation, for a better investment decision.

Keywords: Geomodelling; History Matching, Reservoir Simulation; Tidal Estuarine, 3D Outcrop.

Introduction

Estuaries are primarily transgressive features that represent the flooding of incised valleys during the periods of lowstand (McIlroy et al., 2005). These features are known to host economically important deposits in hydrocarbon provinces such as the Athabasca oil-sand in Alberta, Canada (Nardin et al., 2013).

A typical tidal estuarine reservoir shared the similar overall architecture and the inclining nature of the beds to those of prograding point-bars from a fluvial environment. But there is a considerable heterogeneity inherited from the tidal influences which commonly inhibits the lateral connectivity of these reservoirs. Whilst point-bars are sandy and homogenous, the estuarine intertidal deposits are typically heterogenous with rhythmically stacked sandstone and claystone interbeds (figure 1).

The contrasting heterogeneities between the two depositional systems ought to present different 3D grid constructions, particularly the layering. However, this often overlooked, and understandably so, due to the typically insufficient subsurface dataset to fully characterize these geometries.

In a subsurface study, the occurrence of naturally dipping configurations on the other depositional environments, such as the carbonate platforms and delta clinoforms, are likely to be resolved through micro-faunal dating, sequence stratigraphy techniques and seismic imaging (figure 2). In the other hand, IHS are typically sub-seismic and resolved through borehole imaging or dip-meter which are expensive and rarely run while only providing 1D observation. When translated into 3D grid construction, the delta and reefs clinoforms are usually represented in the model as vertical segmentations (zones) whereas the IHS are likely to be represented as dipping-curvilinear layers usually irrespective to the zone boundaries also due to their much smaller scales compared to the previous stratigraphic features. Yet theoretically, the layer configurations will mostly define the production profiles and the reservoir performance of tidal estuarine reservoirs.

This study documents an approach of solving the stated problems with an outcrop-based reservoir analogues study coupled with dynamic simulations from the outcrop-based models. The presented workflow may be replicated in most fields with layering uncertainties to enable an optimum flow estimation, for a better investment decision.

Data and Method

The exposure of rock formations at Blaze Canyon, which located in the southeastern Book Cliffs - Central Utah (USA), is ideal for building reservoir model with 3D outcrop-based data using LiDar and Drones in roughly 1km^2 of area. The location was chosen because it offers a combination of outcrop and well logs observations of the tidal estuarine deposits (figure 3). The Blaze Canyon outcrop itself, represents highly prograding shoreface parasequences and the overlying transgressive incised valley fill deposition of the Campanian Desert Member of the Blackhawk Formation.

The interpreted stratigraphic surfaces on the 3D outcrop model were then brought into 3D modelling suite as polylines, surfaces, and markers. Based on the 3D outcrop data, two versions of 3D grids were created with different 3D layering methodologies, referred as the regular grid model and the dipping grid model in this study. The dipping grid model was matched to the morphological features of the outcrop with curvilinear-inclined 3D layering. The regular grid model was deliberately constructed with conventional horizontal and proportionally layered reservoir model to represent the result of an underinformed subsurface study (figure 4). Both grids are then integrated with sedimentary logs and electrical logs to fill in the grids with facies and petrophysical properties based on controlled geostatistical approach.

Dynamic simulation parameters referred the work of Howell et al (2008) including rock compressibility, equilibrium specifications, pressure and depth settings of the model while the PVT tables were built using correlations (table 1). Two producer wells in the middle and up-dip positions, B-02 and B-01 respectively, one injector well (Inj-01) placed in the down-dip position were then added to each model. After the models were successfully initialized and simulated, the dipping grid simulation result is then set as the truth case or "production history" for other models.

An additional static model based on the dipping grid was also created but with different petrophysical and dynamic properties from the truth case. This enabled direct comparison to determine whether different static parameters or the 3D layering that hold greater significance in dictating the fluid flow behavior in this study.

All in all, three realizations were made in this study, two based on the dipping grid (referred as the truth case and dipping grid model) and one based on the regular grid (referred as regular grid model). Simulated hydrocarbon volume in place for all realizations were kept constant. Figure 5 illustrates the complete workflow of this study.

Result and Discussion

The use of 3D scanned outcrop has allowed thorough observation of the tidal estuarine outcrop at Blaze Canyon, Utah. There are two main depositional environments identified within the studied interval, the wave dominated delta and tidal estuarine environment. Each exhibits different degrees of heterogeneity and architectural complexity. Whilst the stratigraphic framework of the wave dominated delta deposits are usually represented with flat flooding surfaces, the tidal estuarine deposits are encased by sequence boundary at the base and maximum flooding surface at the top but also internally complex with strata termination surfaces which indicate the flooding of the incised valley during a transgressive period (figure 6). Within these strata terminations are the naturally inclining intertidal deposits geometries which commonly hidden from a 1D log-based analysis. All realizations captured similar heterogeneity in terms of facies distributions and properties despite the different 3D layering settings (figure 7).

Simulation results from both regular grid and dipping grid models show similarly good matching quality on field production level (figure 8). However, these results are deceiving as revealed by further investigations on the well-to-well production level. On the regular grid model, well B-02 produced significantly more water compared to B-01 which positioned more up-dip (figure 9). The difference of water production from the producers in regular grid model added up in the field level and made as if the cumulative water production is within the tolerance of a matching criteria. As expected, the dipping grid model showed good matching on the field and well-to-well level despite the different petrophysical properties to the truth case (figure 9).

Sweeping profiles of both dipping grid and regular grid models further explained the phenomenon seen on the well-to-well production profiles (figure 10). By proportionally layering the regular grid, the flow simulation resulted in uniform hydrocarbon sweeping profile. However, in the dipping grid model, there is contrasting 3D layering settings between the tidal estuarine and the surrounding flat layered shoreface facies. Meaning the tidal estuarine reservoirs also rely on vertical permeabilities of the reservoir to laterally flow the hydrocarbon within a zone. This caused severe water-fingering problem and that the water broke-through the well B-01 a lot earlier in the dipping grid model compared to the regular grid model.

To replicate the early breakthrough phenomenon on the dipping grid, several manual editing efforts were conducted to the regular grid model. Relative permeabilities were adjusted and near well permeability multipliers were applied (figure 11). Whilst these history matching measures are common amongst reservoir engineering community, this meant that the geological realism captured in the original model was lost. Also, while having the 3D model redone by the geologists is possible, it usually takes a longer time and therefore often avoided in crunching project deadline. Thus, highlighting integration issue between static and dynamics modelling disciplines.

With the regular grid model historically matched to the truth case, two forecast scenarios were conducted with bottomhole pressure at the end of history matching utilized as the forecast control. The first experiment is a 5-year forecast scenario based on the current well conditions. The second scenario is a 5-year forecast scenario, but one infill wells was added. The infill well was placed where the remaining oil is the highest in both models.

For the first forecast scenario, there was up to 7% of observable difference in cumulative oil production within 5 years with the existing producing wells. The history matched regular grid model shows a rather optimistic result of oil production compared to the dipping grid model. This is due to the water production of B-01 well was still at an optimistic rate at the end of history matching. The result of the first forecast scenario is shown in Figure 12.

The infill case scenario shows an agreement to the first forecast scenario. The history matched regular grid is 9% higher in oil cumulative compared to the dipping grid model. The result of the infill case is shown in Figure 13.

All in all, the results show that different 3D layering schemes produced noticeable differences in the forecast productions and production profiles, probably more than the difference in petrophysical properties. In agreement with Arnold (2008) and Howell et al (2008), different interpretations with very different reservoir parameters may produce equally good history matched models but very different forecast estimates may be produced.

Nowadays, decisions for Field Development Plan are still heavily depending on reservoir simulation results. Multi-scenario approach is now a requirement to better cope the mentioned problems, particularly the lack of data to fully capture the geometrical intricacies and heterogeneities of a reservoir. With a representative range of models presented, a better investment decision is enabled. Whether to go on with acknowledged risks or to gather more data or as this paper demonstrated to do a reservoir analogues study to minimize risks.

Conclusions

An important aspect of the tidal estuarine deposits to be represented well in a model is the complex internal geometries with strata termination surfaces encasing the Inclined Heterolthic Strata (IHS). Ideally, these are then incorporated the reservoir model as 3D layering methodologies which bare as much as importance of the structural framework of the reservoir model. This study highlights the consequence of underrepresenting such features, which held 7% deviation in forecast with 2 producers and 1 injector wells in more or less 1 km2 area. The deviation is punctuated with the addition of an infill well, with up to 9% deviation of forecast from the truth case.

Whilst the importance of applying the complicated dipping grid has been raised, the implementation of such methodology in a real subsurface study is difficult. Moreover, completeness of data is such a luxury that subsurface studies commonly lack. Therefore, two alternatives are suggested based on the result of the study.

First, as this study has demonstrated. Reservoir analogues studies may provide the knowhow on the geometrical intricacies of the reservoirs of interest. In the recent years, the reservoir analogues studies have been benefited from the technological advancements such as LiDar and commercially available drones to scan outcrops which enabled the construction of outcrop-based 3D reservoir models and realistic fluid flow simulations.

Second, by building a rigorous workflow in an integrated static to dynamic modelling suites and iterating the processes in experimental run, some of the 3D model variations may exhibit the similar, or closing towards the expected, fluid flow behavior. The 3D layering uncertainty requires multiple scenarios as proposed solutions. Therefore, multiple grids with different layering scenarios are required to be set as one of the main variables in the experimental design. The second approach requires a capable integrated modelling suite which allows every static model realization to be dynamically initialized upon each iteration and then simulated. The second alternative is reserved for a further work.

Acknowledgement

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Parameter	**Value**	**Notes**
	Oil PVT	
Correlations	Standing	For Live Oil's Rs, Formation Volume Factor, and Viscosity
Temperature	100	C
Oil SG	0.8	-
GOR	142	Sm3/Sm3
	Gas PVT	
Correlations	Lee et al, Standing	For Dry Gas' Viscosity and FVF respectively
Temperature	100	C
Gas SG	1	
Z Factor	0.9	
	Water PVT	
Ref. Pressure	1.01	Bars
Ref. FVF	1	
	Rock-Fluid	
# of Saturation Regions	1	
Corey Exp	4	Water
	3	Oil-Water
Saturation End Points	0.2	Sorw (Fraction)
	0.2	Swcr (Fraction)
Rel.Perm End Points	1	Kro max
	0.4	Krw max
	Equilibrium Specifications	
Datum Pressure	145.6	Bars
Datum Depth	1327.79	Meter
Rock Compressibility	5e-6	1/bar
Rock Ref. Pressure	135.6	Bars
	Strategy	
Production History	8	Years
Well Cut Offs	90%	Watercut
# of Wells	1	Injector
	2	Producer

Table 1. Correlation parameters to generate PVT Data and dynamic simulation parameters.

Figure 1. A typical intertidal deposit characterised by rhythmically stacked Inclined Heterolithic Strata (IHS) of sandstone and shale. On the outcrop faces which are not topographically eroded, IHS is observed to have two strata terminations, top-lapping to the capping supratidal coal and down-lapping to a major erosional surface. On most of the sedimentary logs, the succession displays a fining upward pattern and is rooted in several of the logs. The rhythmical appearance suggests alternating energy of tidal influence. The strata were inclined, indicating accreting bodies. These interpretations fit the characteristics of a tidal estuary environment where the high fluvial energy is superimposed by periodical tidal floods.

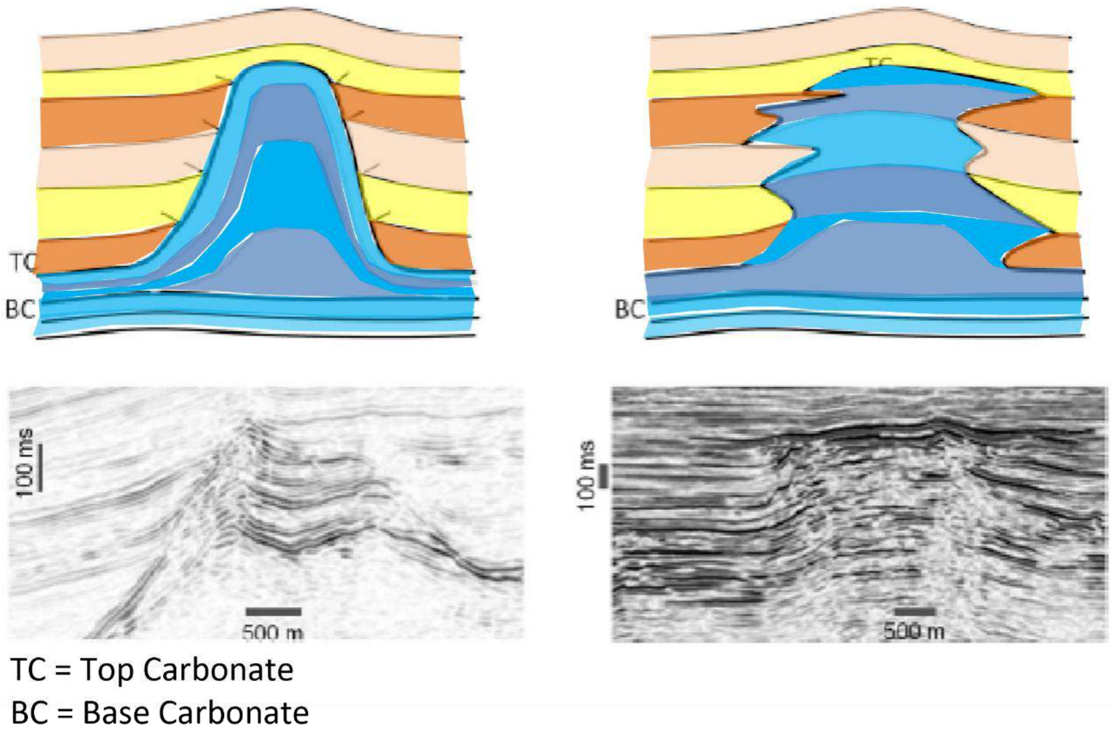

Figure 2. The occurrence of naturally dipping configurations on the carbonate platforms and delta clinoforms, resolved through micro-faunal dating, sequence stratigraphy and seismic imaging (Burgess et al, 2013).

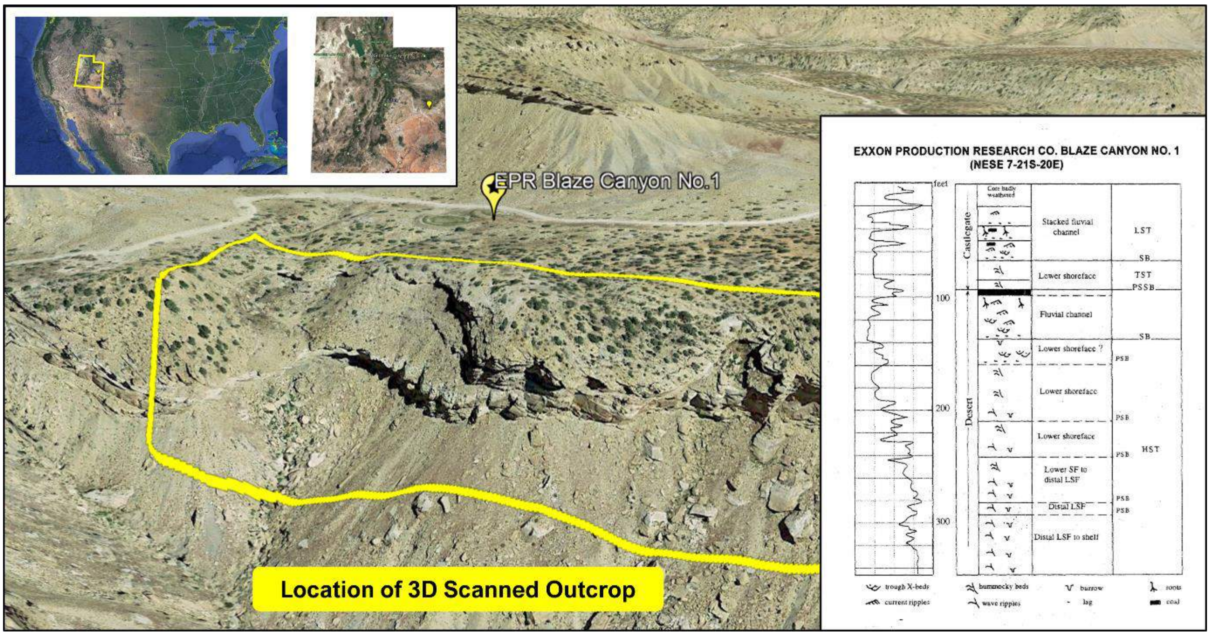

Figure 3. A research well, EPR Blaze Canyon No. 1, was drilled about 350m northwest of the cliff face in the 90s by Exxon Production Research group and published in Van Wagoner (1995) along with numerous sedimentary logs and stratigraphic analysis surrounding the Book Cliffs area. The well was also cored and an array of formation evaluation logs were recorded to allow petrophysical evaluations.

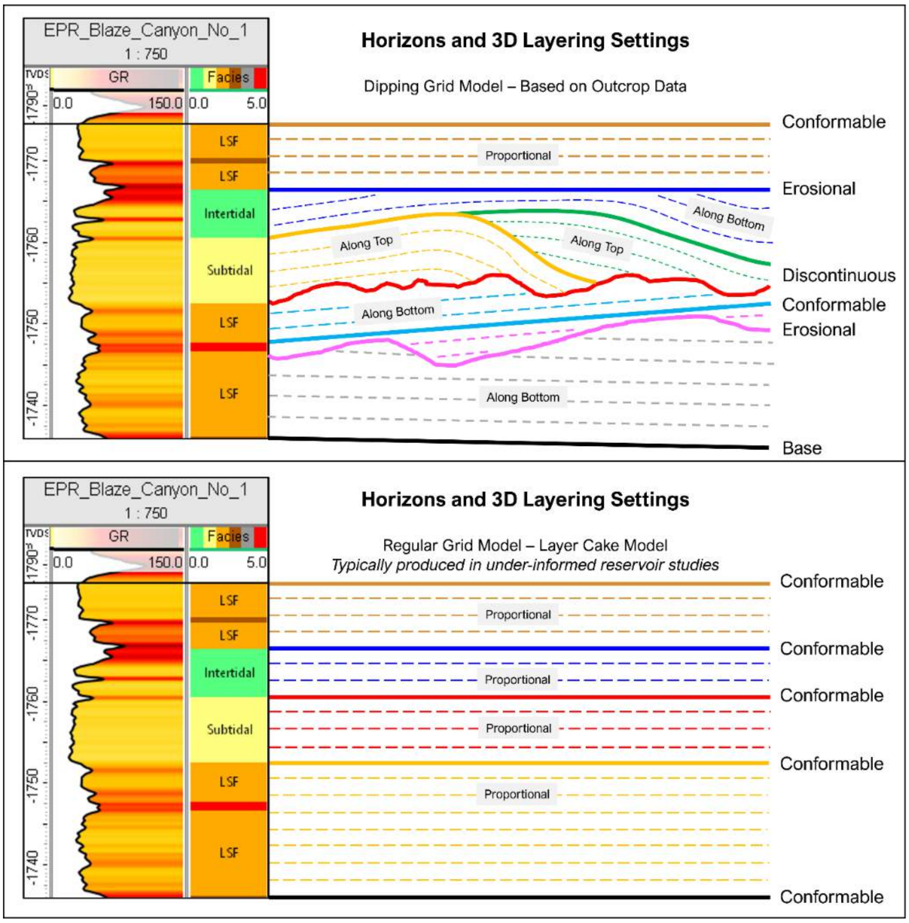

Figure 4. 3D layering settings used as comparative study in this work to create the dipping grid model and the regular grid model.

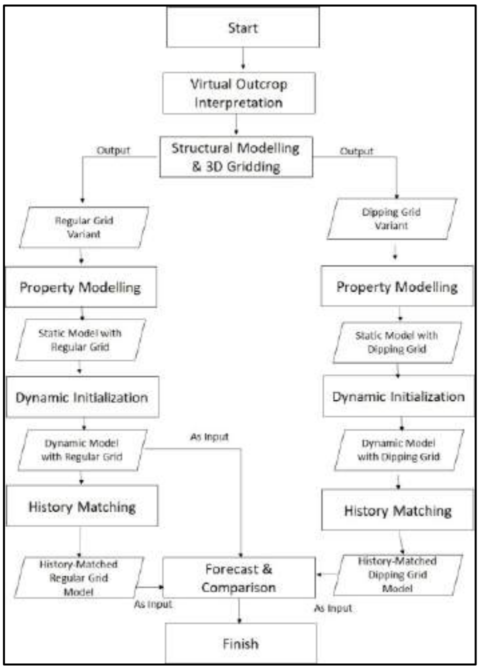

Figure 5. Complete workflow of the study.

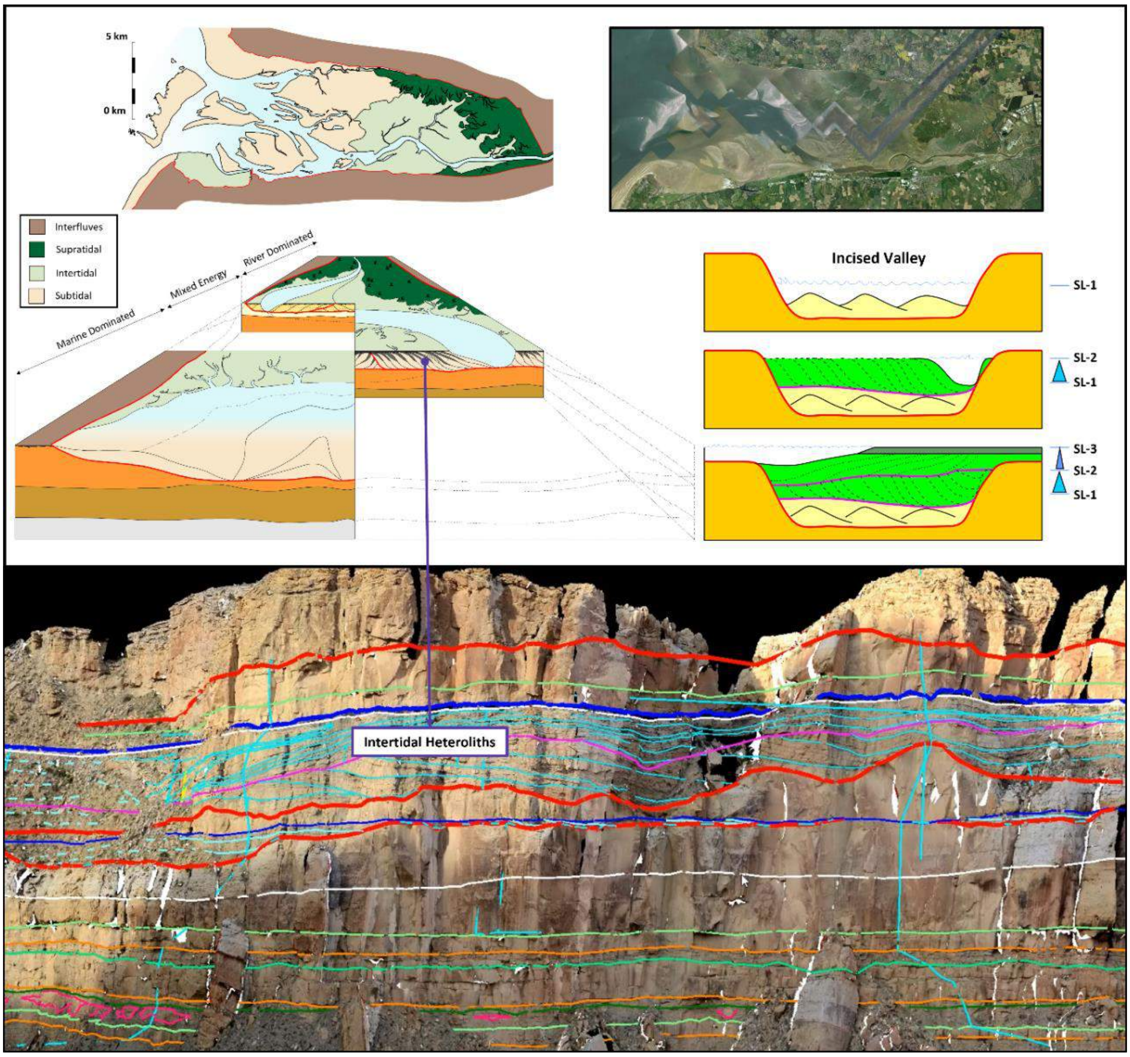

Figure 6. The interpreted 3D outcrop model and conceptual depositional system based on modern analogue of Dee Estuary in Liverpool, UK.

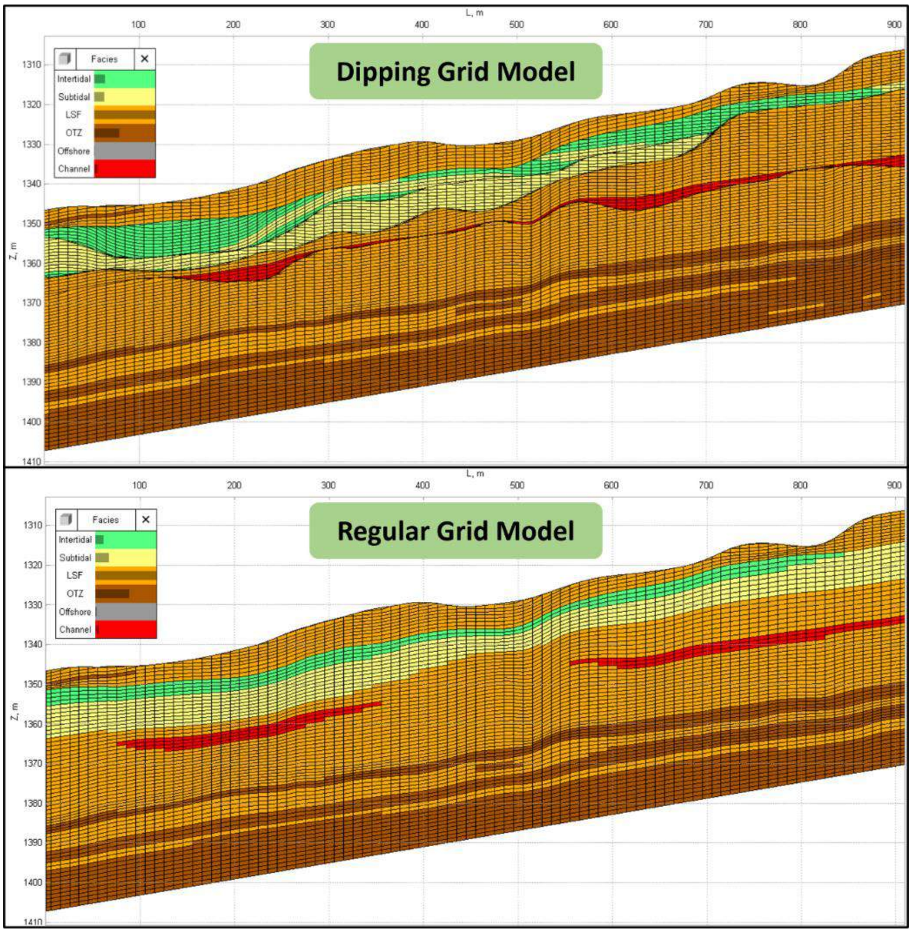

Figure 7. The dipping and the regular grid variants capturing more or less the similar heterogeneity in terms of facies and petrophysical properties.

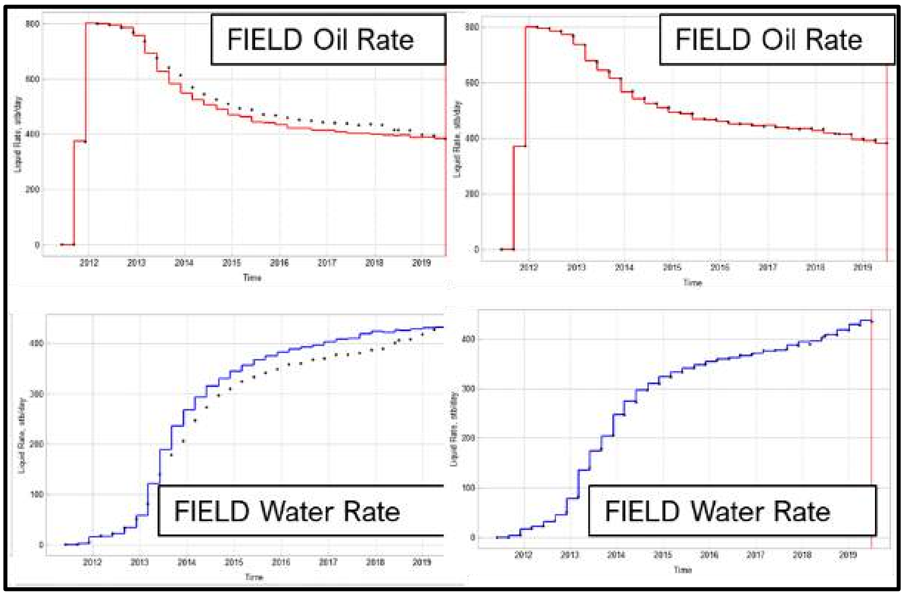

Figure 8. Similar level of matching on field level between regular grid (Left) and dipping grid models (Right).

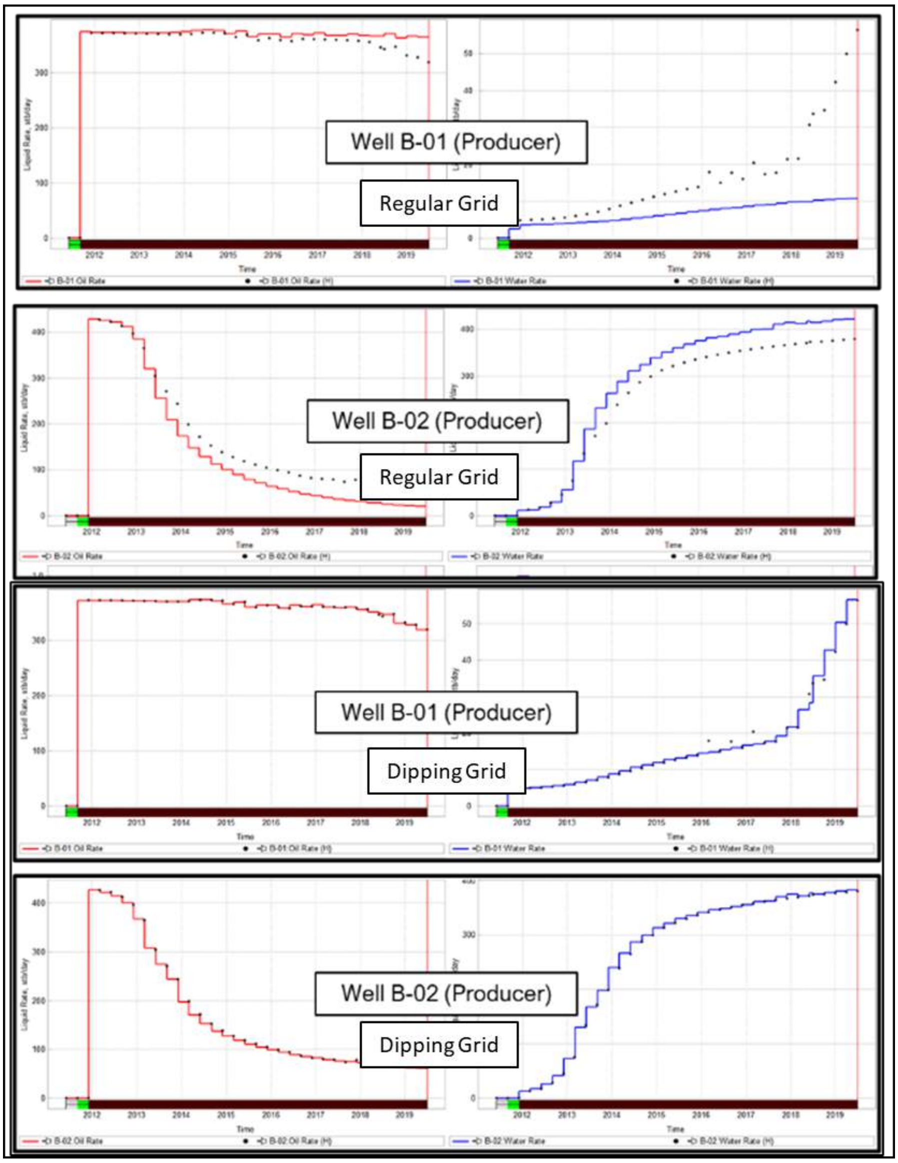

Figure 9. Contrasting level of matching on well-to-well level between regular grid and dipping grid models.

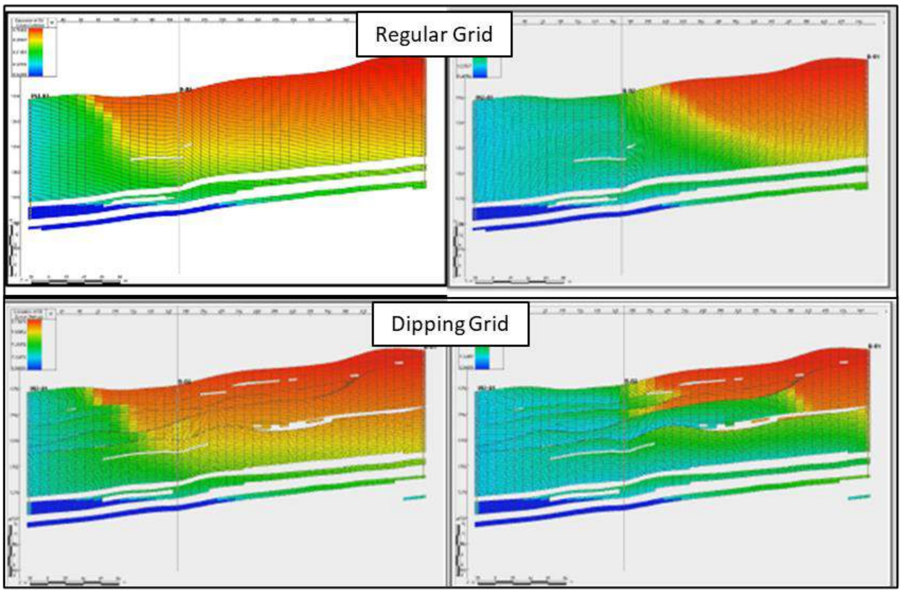

Figure 10. Sweeping profile for both models. Showing different flow uniformity on the well-to-well production profile.

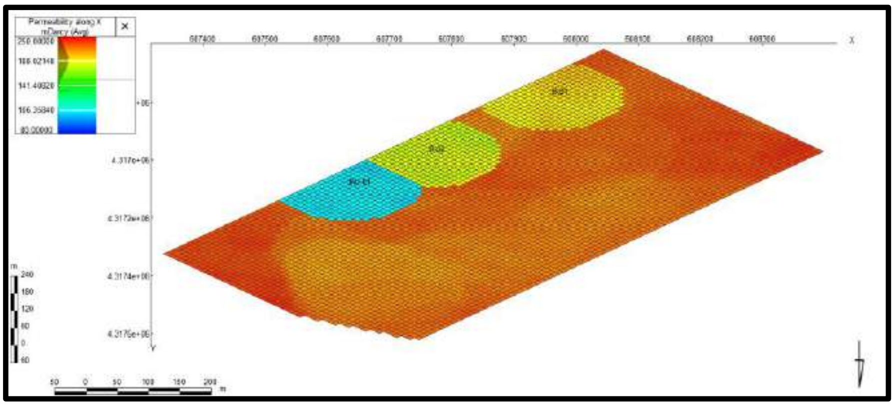

Figure 11. Near well permeability multiplier applied to regular grid model to mimic the water-fingering phenomenon observed on the dipping grid model.

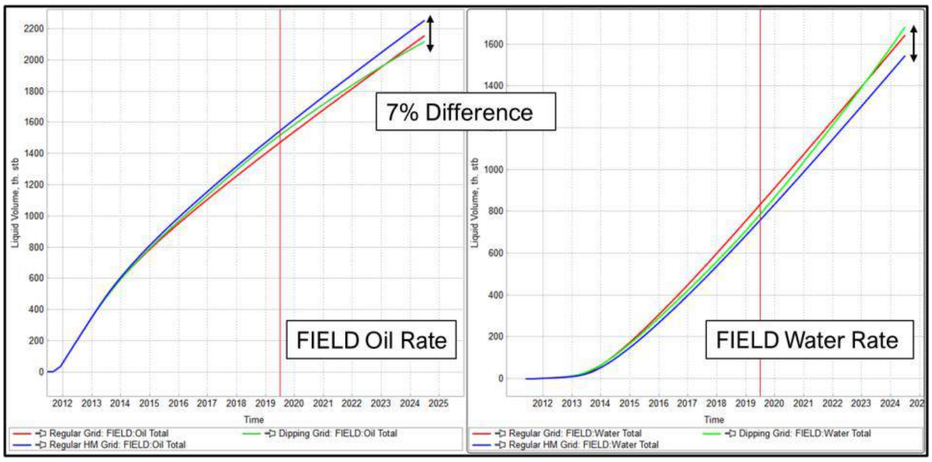

Figure 12. Forecast result comparison for first forecast scenario.

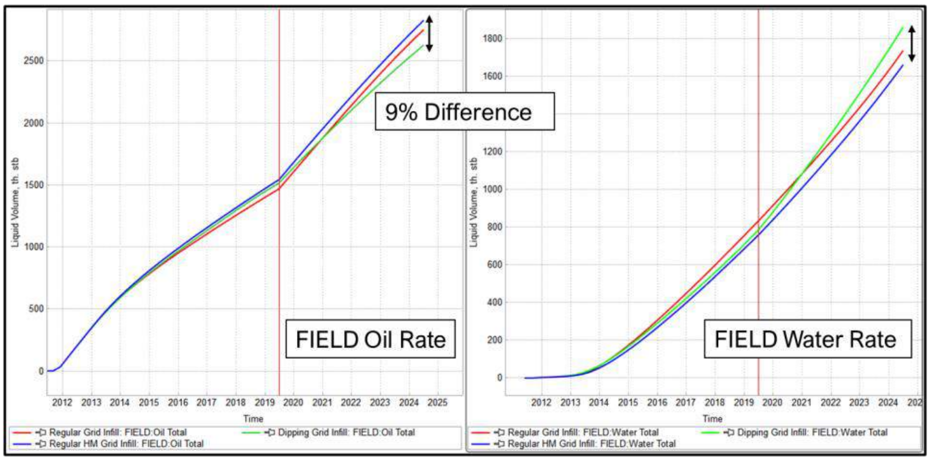

Figure 13. Forecast result comparison for infill case scenario.