AEGC
Australasian Exploration Geoscience Conference
Brisbane 2023

Data integration to quantify structural risk and GRV uncertainties over the western flank of the Cooper Basin.

Alessandro Mannini
Beach Energy
alessandro.mannini@beachenergy.com.au

Jon Cocker
Beach Energy
jon.cockeri@beachenergy.com.au

Diogo Cunha
Beach Energy
diogo.cunha@beachenergy.com.au

SUMMARY

Beach Energy has successfully discovered and produced hydrocarbons from the Western Flank of the Cooper Basin since 2002. Beach Energy's entire acreage is covered by good quality Pre-Stack Time Migrated Seismic Data (PreSTM). Multiple drilling campaigns executed over the years have confirmed that structure and migration are the most significant risks to finding additional hydrocarbons in the area. Since an assessment of the pre-drill gross rock volume (GRV) is crucial to inform future exploration campaigns, extensive efforts were made to fully understand the GRV distribution using a stochastic approach and the risks associated with the presence of four-way closures. Once the depth conversion project is completed, exploit the value of the latest stochastic technology and the benefits of a Pre-Stack Depth Migration (PreSDM) reprocessing. The risks (probability of a structure being present), uncertainties (GRV distribution) and reservoir depth estimation were validated by the post-drilling results of 13 exploration and appraisal wells. Drilling results confirmed that the chosen approach is more precise and accurate than previous attempts to quantify risks and uncertainties using the same input data.

Keywords: Depth Imaging, Depth Uncertainty, GRV distribution and post-drilling validation.

INTRODUCTION

The Cooper-Eromanga Basin is Australia's most prolific onshore oil and gas basin and continues to yield oil and gas discoveries.

The Cooper Basin covers an area of approximately 127,000 sqkm and extends across the northeast of South Australia and southwest of Queensland. The Eromanga Basin covers an area of roughly 1,000,000 sqkm and extends over South Australia, Northern Territory, Queensland and New South Wales (Figure 1).

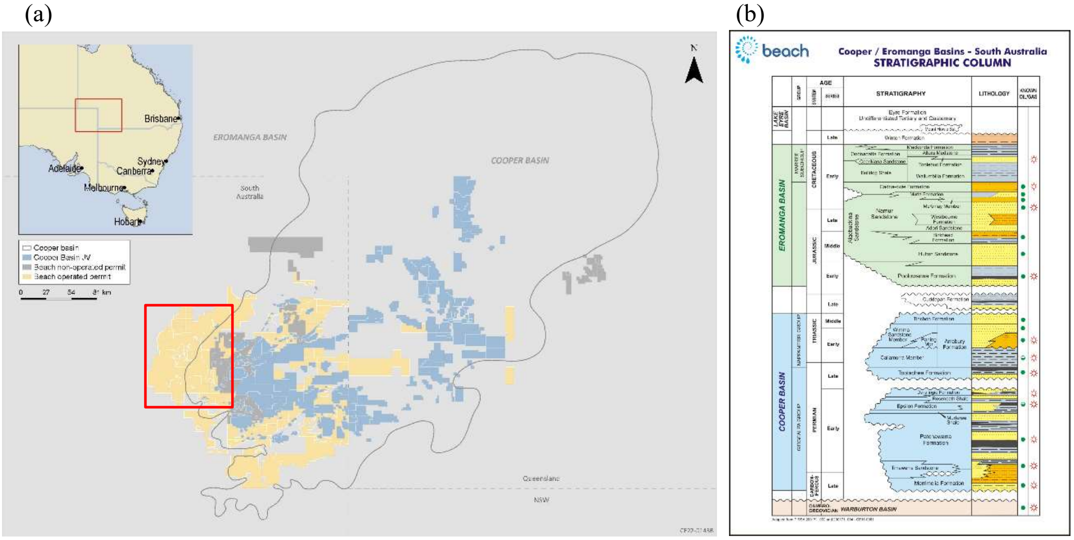


Figure 1. (a) Location map of the Cooper-Eromanga Basin, Beach Energy permits and the Western Flank sector, where this study was performed. (b) Cooper-Eromanga Stratigraphic Column.

Beach Energy has established a world-class operated oil business on the Western Flank of the Cooper-Eromanga Basin and has grown to become Australia's largest onshore oil producer. This area is covered by several vintages of 3D seismic data acquired from 2004 to 2016, covering a total of approximately 3000sqkm, with varying data qualities. The currently available land seismic data are overall of good quality. However, geophysical challenges exist because of the complex surface geology of the area and, in particular, the extensive presence of dunes, lakes and flat regions where salt pans can be developed.

The seismic resolution is generally inadequate to properly inform exploration, appraisal and development campaigns since vertical relief of four-way closures can vary between 2 to 20m. Fortunately, a few hundred multi-target wells have been drilled to date, and therefore a quite large sample population is available for analytical analysis.

To address the limitations of the available seismic vintages, a subset of the existing seismic 3D volumes was reprocessed to improve structural definition by accounting for the lateral velocity changes and removing the short and mid-wavelength undulations. The depth estimation precision was improved by using a Kirchhoff depth migration algorithm for the first time over the Beach Energy assets, incorporating the velocity anisotropy derived from 27 wells.

Historically, discoveries over the Western Flank of the Cooper-Eromanga Basin have been of two types: four-way structural closures at the McKinlay Member and Namur Sandstone level, and stratigraphic traps in the Birkhead Formation. Although the overall exploration success rate over the Western Flank of the Cooper Eromanga Basin is relatively high, accurate STOIIP predictions have been challenging due to conscious biases and data limitations. In addition, and for similar reasons, depth predictions to further appraise exploration discoveries have been challenging and less accurate than expected.

Early in 2020, Beach Energy embarked on a multi-well exploration program to test the remaining prospectivity at the McKinlay-Namur level. As expected, post-drilling analysis using all the available well data identified Gross Rock Volumes (GRV) as pivotal for accurate STOIIP estimations and, subsequently, integral to and remaining properly rank the available exploration portfolio. In more detail, without a correct distribution of GRV, we run the risk that our P10-P90 range is either optimistic or pessimistic, affecting project economics. Single deterministic depth conversion cannot accommodate the uncertainties with the seismic and well data resolution in multi-deterministic depth conversions might be, at best meaningless and, at worst, misleading without a proper understanding of the distribution they should sample. Therefore, it was decided to assess GRV distributions using stochastic methods. Geostatistics and stochastic methods applied to depth conversion produce reliable and repetable GRV ranges, and they also provide the best depth prediction considering uncertainties in seismic interpretation and velocities. In addition to the above, it is possible to interrogate the equiprobable depth realisations for the probability of a structure being present, connectivity of different structures or compartiments, average reservoir thickness and more. The methodology and results of both seismic processing and stochastic depth conversion for GRV estimation are summarised in the following paragraphs.

Seismic Reprocessing

Three 3D seismic volumes acquired between 2007 and 2010 and respectively named Modiolus, Neritus and Calpurnus 3D, totalling 650 sqkm were reprocessed to test the feasibility of the PreSDM reprocessing workflow over the entire Western Flank. Seismic data was merged into a single seismic dataset called NMC, and subsequently processed using Time and Depth migration algorithms. The main objective of the reprocessing project was to build the best possible near-surface velocity model to ensure the most accurate prediction of low-relief structures. The critical processing steps were as following:

1. Statics: tomographic, delay time and a near-surface model, built using uphole data, were tested and compared. The tomographic solution produced a significant uplift in modelling shallow dunes compared to the other two solutions and was chosen to apply in production.

2. Noise attenuation: required many passes of noise attenuation in multiple domains to improve the S/N ratio of the data. This was done on a 20m x 20m bin grid.

3. 5D regularisation: acquisition source and receiver line intervals are 280m x 280m. Source and receiver line infills were performed to create smaller COV (Common Offset Vector) tiles of 280m x 280m to increase nominal fold and improve both time and depth imaging.

4. Depth tomography update and PreSDM: several iterations of depth tomography update were performed to improve the depth velocity model resolution and hence improve the accuracy of the low relief structures.

The data quality of the final PreSTM full stack volume met the project's primary objective, with high-quality first break picks resulting in a high-resolution near-surface velocity model. The final PreSTM full stack generally had better long-wavelength statics than the legacy PreSTM full stack, which is crucial in predicting low relief structures in the area of interest.

Multiple passes of 3D noise attenuation were applied in the cross-spread domain to improve the S/N ratio of the data. Source and receiver line infills were performed in 5D regularisation and interpolation to create smaller COV tiles of 280 m x 280 m. This step increases the nominal fold and improves time and depth imaging resolution. On the COV sort gathers, some evidence of multiple energy existed in the deeper section. However, no attempt was made to remove the multiples as it is below the area of interest. In addition to the above, the PreSDM full stack significantly improved the geological structure's accuracy. Though time processing was of high quality, the problem caused by horizontal velocity changes could not be fixed with time processing. The PreSDM processing showed the advantage over time processing in dealing with this problem. Overall, through the PreSDM full stack smoothed and simplified small structures compared with the time-processing result (Figure 2).

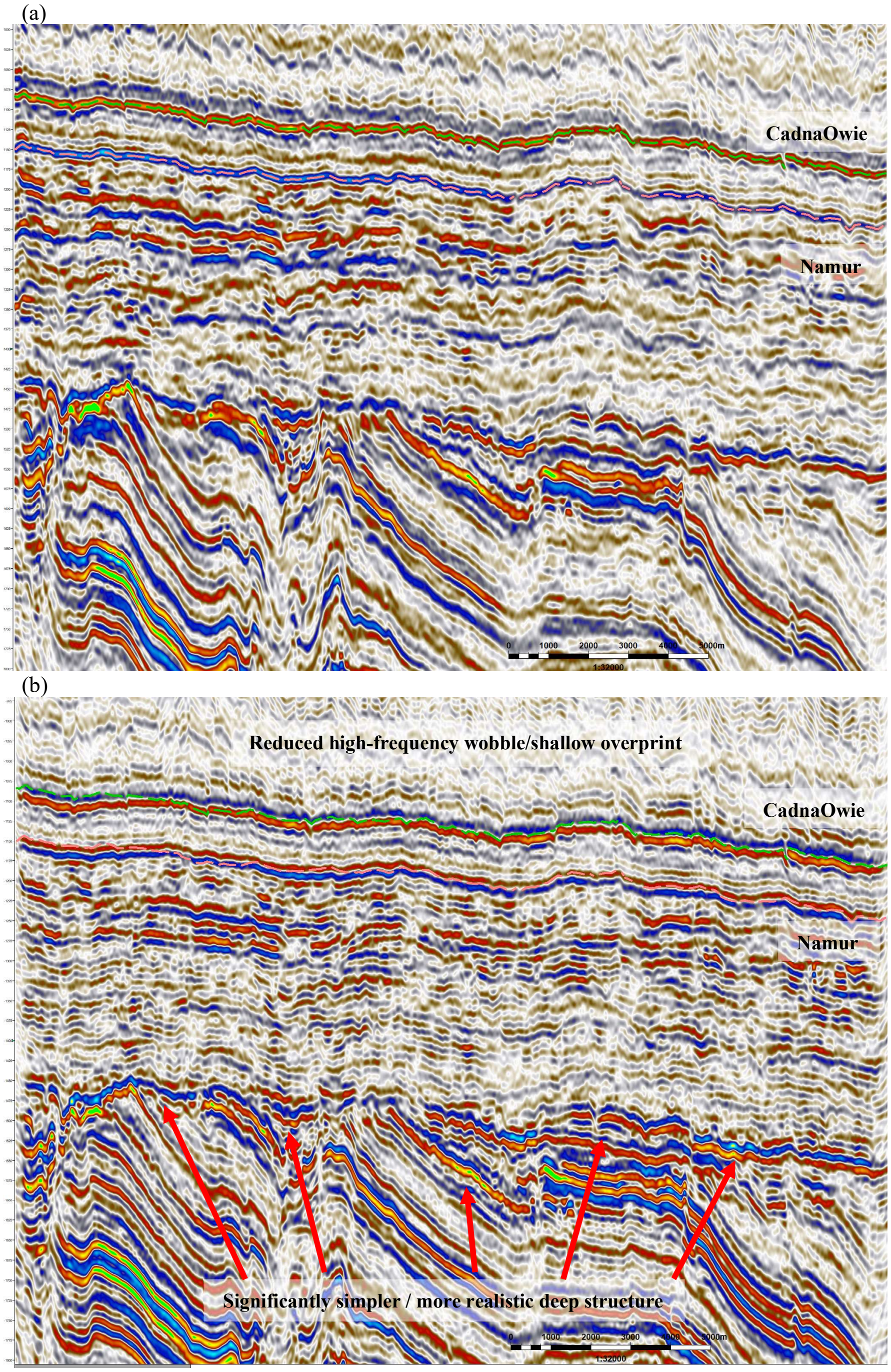


Figure 2 (a) The legacy seismic (WF Merge PreSTM) time section with the Namur Sandstone seismic event is highlighted. (b) NMC PreSDM seismic section in time with the Namur Sandstone seismic event highlighted

General Workflow

Once the newly reprocessed seismic datasets were available, the focus shifted to the stochastic assessment of GRV for prospect ranking. Different elements of the workflow used in the present study comprise: i) Uncertainty Quantification, ii) Geostatistical Depth Conversion of Seismic event (Namur), iii) Geostatistical surface generation of sub-seismic surfaces, iv) Prospect identification, v) GRV and structure probability calculation. An initial evaluation of the above elements was carried out over the entire Western Flank using the available time-migrated seismic data (Figure 3). Once this project phase was completed, employing more than 300 wells, additional investigations were carried out only in the area of the new reprocessed data (Figure 3).

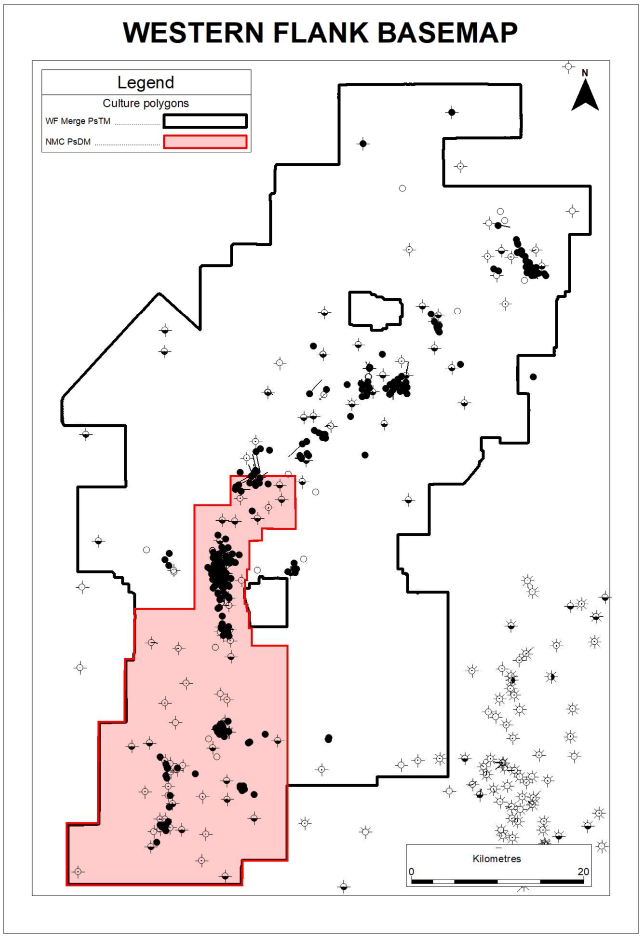


Figure 3. Basemap with the wells presents seismic data outlines over the area of interest.

Uncertainty Quantification

The most challenging part of the workflow was to quantify the uncertainty in different domains to properly assess the uncertainty associated with the Depth prediction of a given seismic event. Four types of uncertainties were defined at the beginning of the analysis: i) Time uncertainty, ii) Velocity uncertainty, iii) Depth uncertainty, and iv) McKinlay Member to Namur Sandstone Isopach uncertainty. The time uncertainty quantifies the uncertainty associated with the seismic interpretation of a given seismic event (Figure 4). Velocity uncertainty quantifies the uncertainty associated with the velocity trend used for the Depth estimation. Depth uncertainty quantifies the uncertainty associated with the interpretation of McKinlay Member and Namur Sandstone using the available well logs. Time-depth relationships of 214 wells were used to obtain the statistics of Time and Velocity uncertainty. The extensive analysis resulted in a final estimation of 1.61 ms and 6 m/s, respectively. The Depth uncertainty or the standard deviation of the difference between the most likely formation top and the deepest or shallowest alternative interpretation was assessed using all the 319 available wells over the AOI and was estimated in ~1m. Finally, McKinlay Member to Namur Sandstone isopach uncertainty was calculated simply by kriging all the 319 available well data. Mean, Standard Deviation, Maximum, and Minimum envelop maps were generated and used during the Stochastic Depth Conversion. All the above-described uncertainties were combined using an experimental variogram with a range of 3000m (Figure 5).

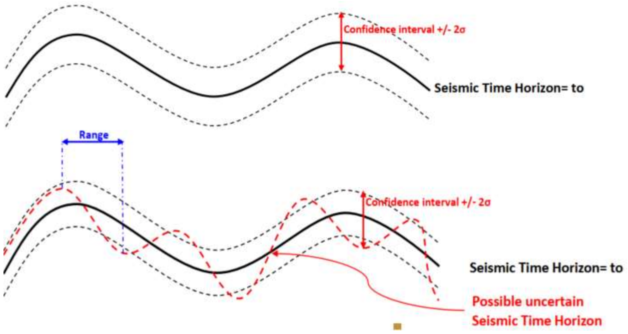


Figure 4 Illustration of uncertainty linked to possible local fluctuations of the time and velocity

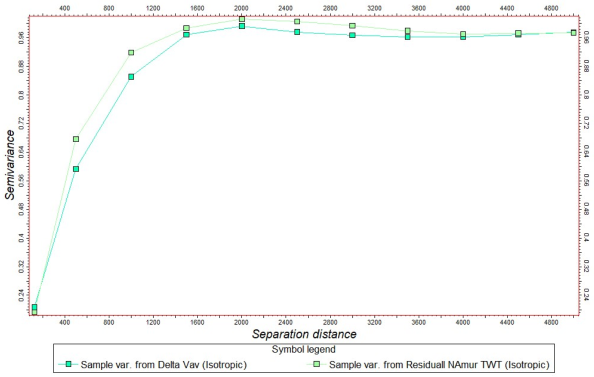


Figure 5 Variogram analysis to derive the range of the maximum uncertainty

Geostatistical Depth Conversion of Seismic Event (Namur)

Once the uncertainty estimation of the various inputs was completed, the geostatistical depth conversion started. Consistently with the previous phase of the project, the input data required were: i) TWT surface, ii) Average velocity surface, and iii) Formation Top for each well. The Geostatistical depth conversion was performed as a simple one-layer depth conversion; therefore, only the Namur Sandstone interpreted seismic surface was used. The Cooper-Eromoanga Basin has, in general, a benign velocity field, essentially a function of the compactional trend. To adequately capture such a compaction trend, a high correlation linear relationship between the time and average well velocity was used (Figure 6).

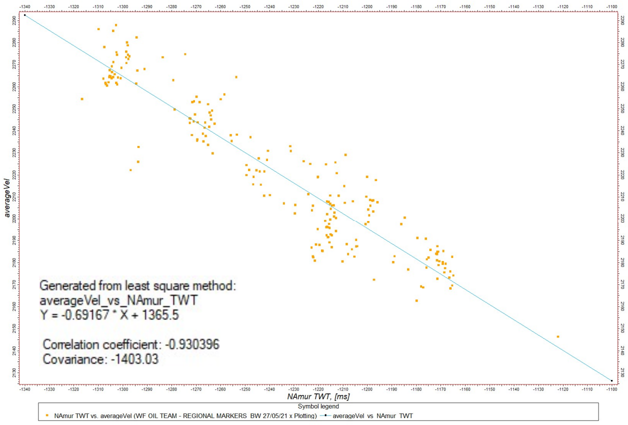


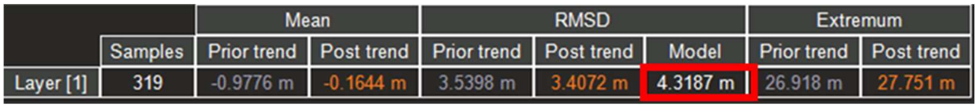
Figure 6 Crossplot of the Namur Sandstone Formation Top in time (x) versus average velocity.

The initial testing and parameterisation were completed using the Pre-STM merged Seismic data volume (Figure 3), and its associated seismic interpretation. Once the PreSDM reprocessed data of the NMC subset became available, they were incorporated into the analysis and compared against the previous assessment. Both wells average and seismic velocities were used to depth convert the NMC dataset (Table 1 for data comparison).

Level		Twt	Depth	Velocity
Namur Sandstone WF Merge PreSTM	Input	Time Surface	Formation Top	Average Velocity From Well-Trended Surface
	Uncertainty	2ms	1m	6m/s
	Variogram Range	3000m	N/A	3000m
Namur Sandstone NMC PreSDM (method 1)	Input	Time Surface	Formation Top	Average Velocity From Well-Trended Surface
	Uncertainty	2ms	1m	6m/s
	Variogram Range	3000m	N/A	3000m
Namur Sandstone NMC PreSDM (method 2)	Input	Time Surface	Formation Top	Average Velocity From Seismic Velocities Surface
	Uncertainty	2ms	1m	6m/s
	Variogram Range	3000m	N/A	3000m

Table 1 Summary of the input parameters for the Geostatistical depth conversion for each seismic volume.

In simple terms, the stochastic depth conversion, carried out using the Seisquare Software platform, can be summarised in two steps: a depth residual minimisation process to assess the best depth surface and modelling of the depth uncertainty using the available well data associated with such surface. For each of the three cases summarised in Table 1 a best-estimated depth map and its associated depth uncertainty were calculated at Namur level. Results of depth conversion were summarised in a Statistical table (Figure 6), one per each case. Comparing the Post Trend RMSD with the Model RMSD, the reliability of the previously assessed uncertainty ranges could be understood. Once the uncertainty ranges were validated using this method, they were used to generate thousands of equiprobable depth surfaces for GRV assessment. As well as, the Geostatistical generation of sub-seismic surfaces for the project's next phase This step was necessary since it is impossible to resolve the McKinlay member from the Namur Sandstone seismically. Still, at the same time, the top McKinlay Member is a critical surface to understand the Trap geometry and the position in the space of any potential spill point.



		Mean		RMSD			Extremum	
	Samples	Prior trend	Post trend	Prior trend	Post trend	Model	Prior trend	Post trend
Layer [1]	319	-0.9776 m	-0.1644 m	3.5398 m	3.4072 m	4.3187 m	26.918 m	27.751 m

Figure 6. Statistic table with the summary parameters resulting from our input data and associated uncertainty. Mean – represents the average depth residual; RMSD - standard deviation of depth residuals; Extremum – represents the maxim values expected for the depth residual (used to identify abnormal points); Prior trend – the result of the input data; Post trend – result after the trend that minimised the depth residual is derived; Model - Modeled standard deviation corresponds to the confidence range around the estimated depth trend, derived from time uncertainty values and residual interval velocity uncertainty values (i.e. without reference to measured well depth).

Geostatistical surface generation of sub-seismic surfaces

The McKinlay Member depth simulations were generated by combining the Namur Sandstone surfaces with the McKinlay Member to Namur Sandstone Isopach and their associated uncertainty. The Stochastic workflow randomly varied the mean isopach values using the standard deviation bounded by the maximum and minimum values while honouring the McKinlay Member Formation tops (Figure 7). Namur Sandstone and McKinlay Member Best Depth Estimation maps were used for the Pre-drilling depth prognosis.

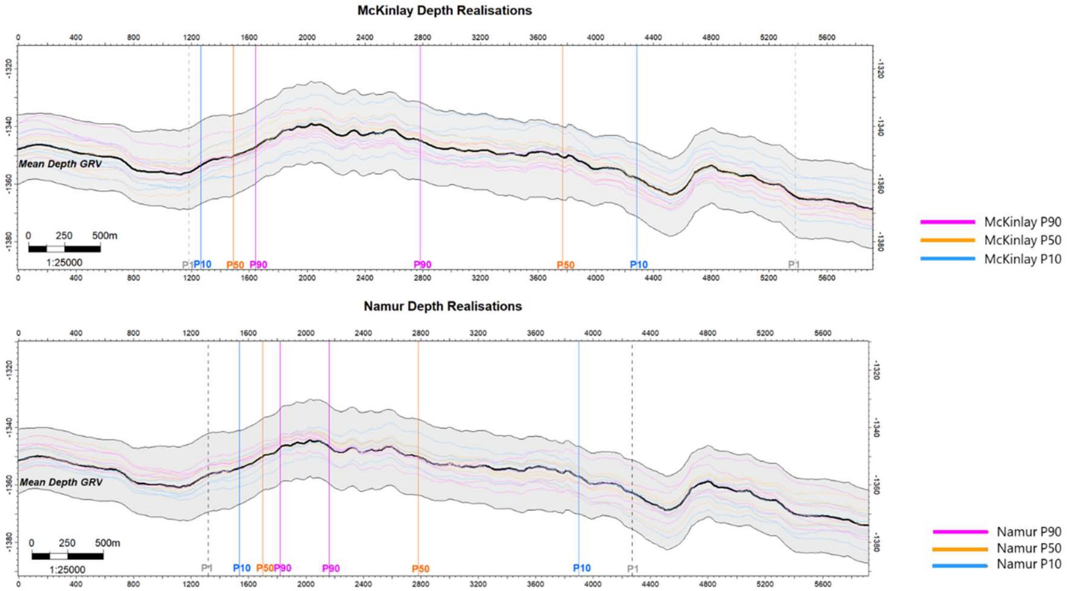


Figure 7 Example of the Namur Sandstone realisations vs Mckinlay Member realisations

Prospect identification

Once the best-estimated depth map for McKinlay Member and Namur Sandstone were available, all structures not intersected by an existing well, with a minimum of 2 m of vertical relief and a minimum area of 0.05 sqkm were identified and plotted (Figure 8). The preliminary ranking was completed using a deterministic assessment of GRV over the best depth estimated maps per each prospect matching the previously described conditions. Then, the first 100 prospects were further investigated, analysing all the available depth realisations to produce proper GRV and column height distribution and maps of structure probability. This process was carried out for the area covered by the legacy PreSTM data and repeated over the PreSDM reprocessing area.

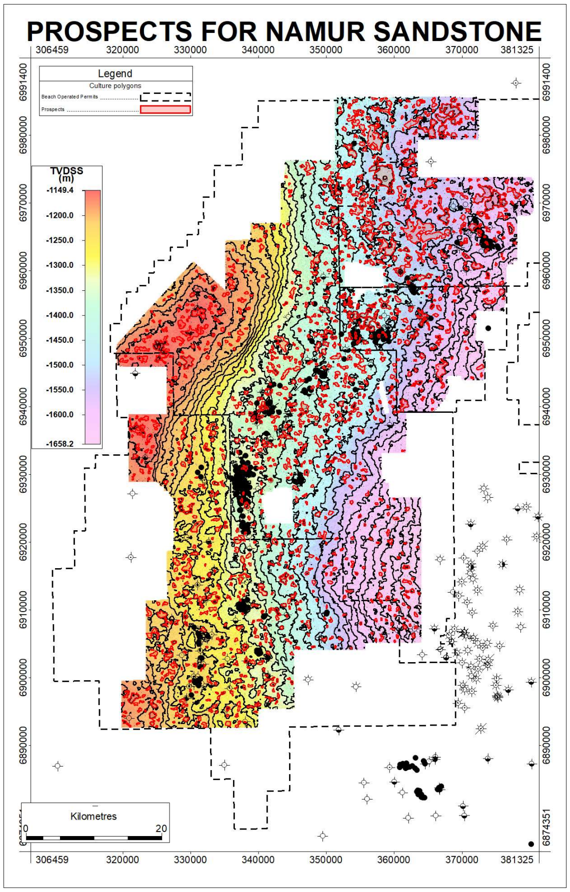


Figure 8 Example of the prospect distribution at the Namur level over the entire area using PreSTM legacy data.

GRV and structure probability calculation

Per each of the 100 prospects previously selected, an in-depth Stochastic analysis was carried out, which is summarised in Figure 9. Firstly, each depth realisation was scanned to identify the four-way structure spill point position. This information was then used in the GRV assessment per each realisation, and finally, a GRV distribution was built using all the available depth realisations. The Seisquare platform automatically calculates the following outputs: gross rock volume inside the closure (single value per realisation), area of the closure (single value per realisation), reservoir presence (map with the binary value of 1 or 0, with 1 meaning that at a given point the depth value is shallower than the calculated spill point) and column height (map with the column height value at any given location). Once the gross rock volume per realisation is computed, GRV distribution can be generated using all the available realisations. A Structural probability map can also be generated by simply dividing the number of realisations with a closure by the total number of depth realisations. Finally, an expected column height map can be generated merely by averaging each realisation's thickness value at any given location, Figure 10.

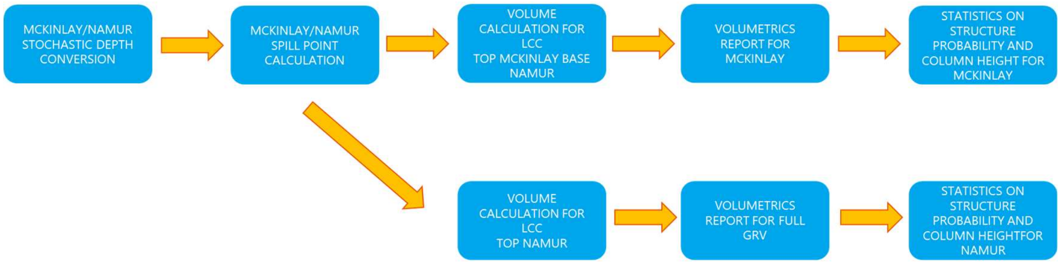


Figure 9 Standard workflow for prospect GRV, structure probability and column height.

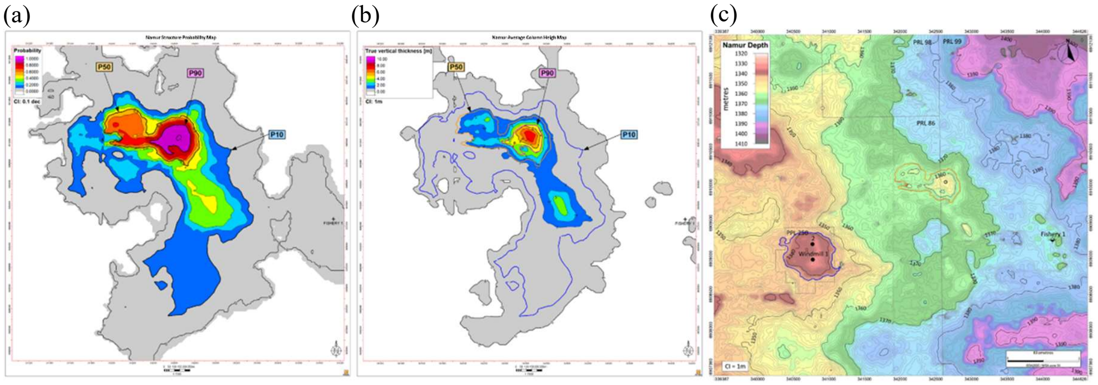


Figure 10 Example of a Structure probability map (a), expected column height (b) and the best depth estimation for the Namur (c).

CONCLUSIONS

Geostatistical modelling improved our understanding of GRV uncertainty, Structural Risk and PreDrill prediction. At the end of the 13 wells exploration and appraisal campaign, with wells drilled over the area covered by the legacy PreSTM data, the Geostatistical Depth estimation has delivered results aligned with Pre-Drilling forecasts, with 100% of wells inside the P1-P99 Depth range and 69% inside the P10-P90. Further assessment of the Geostatistical methodology was carried out inside the area selected for the PreSDM reprocessing test. The Geostatistical methods were also benchmarked inside such area against previously well-established simple deterministic depth prognosis (Figure 11). Overall the geostatistical methodology was more precise and accurate than a simple multi-deterministic approach. Furthermore, the methodology produces an even better pre-drilling prognosis when seismic data obtained as results of rigorous PreSDM processing are used.

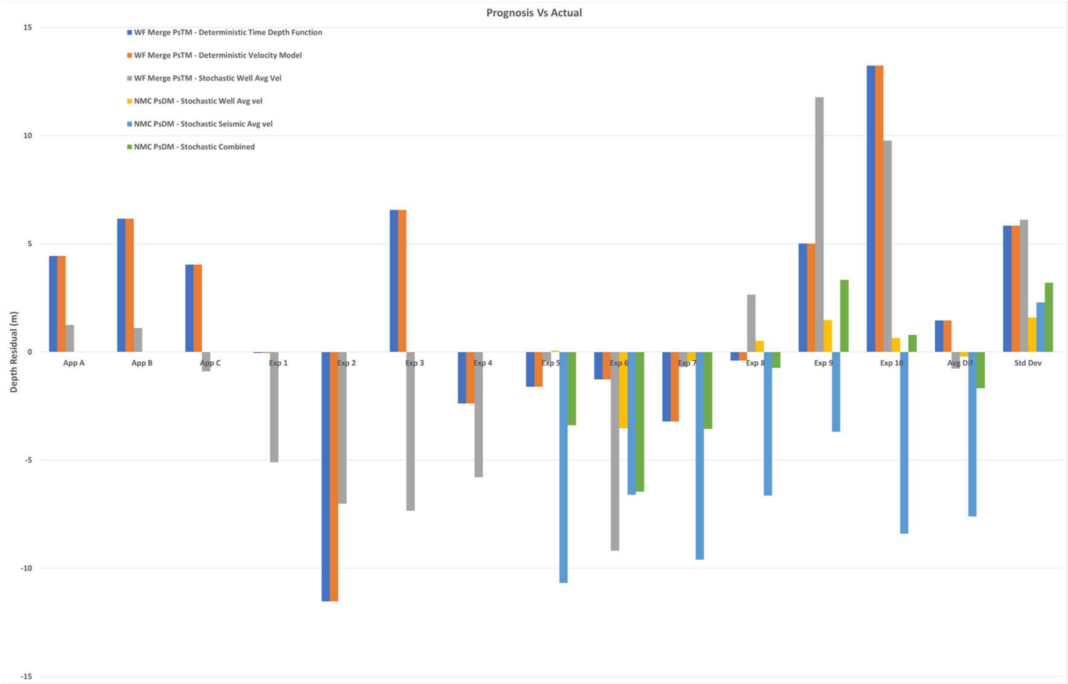


Figure 11. Prognosis comparison with the actual results for each methodology and well.

ACKNOWLEDGMENTS

I want to thank Beach Energy, Jon Cocker, Alessandro Mannini and the Western Flank E&A team for allowing me to implement this workflow and publish the results. Thanks to Seisquare, Laurent Souche, Mickael Collet and Walter Sifuentes for unconditional support and flexibility to quickly implement additional features to improve our results.

REFERENCES

Journel, A.G. and Huijbregts, C.J., 1978, Mining Geostatistics, Academic Press, London

More, H. and Halyorsen, K. B., 1989, The bayesian bridge between simple and universal kriging, Mathematical Geology 21

Chilès, J-P, Delfiner, P., 2012, Geostatistics: modelling spatial uncertainty, Second Edition. Wiley, New York

Huijbregts, C., Matheron, G., 1971, Universal kriging (an optimal method for estimating and contouring in trend surface analysis), McGerrigle JI (ed) 9th international symposium on techniques for decision-making in the mineral industry. Canadian Institute of Mining and Metallurgy, pp 159–169

Matheron, G., 1963b, Principles of geostatistics,. Econ Geol 58(8):1246–1266

De Finetti, B., 1974a, Bayesianism: Its unifying role for both the foundations and applications of statistics, International Statistical Review, 42, 117– 130

Gelman, A., Carlin, J. B., Stern, H. S., and Rubin, D. B., 2004, Bayesian data analysis, (2nd ed.), London, UK: Chapman & Hall.

Kaplan, D., and Depaoli, S., 2013, Bayesian statistical methods, T. D. Little (Ed.), Oxford handbook of quantitative methods (pp. 407– 437). Oxford, UK: Oxford University Press.

Kruschke, J. K., 2011b,. Doing Bayesian data analysis, Burlingon, MA: Academic Press