Improved 4D data quality offshore Angola in a mature 4D multi monitor context

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Summary

Development of the Greater Plutonio field complex in Angola Block 18 has been supported by 4D since the first monitor survey was acquired in 2009. Existing 4D data over the field had been considered to be of high quality. Here we develop a processing flow including ΔSΔR (the sum of the mis-positioning of the sources and receivers from baseline to monitor survey) thresholding and parallel pairwise binning with transfer operators to further improve the quality of the 4D products, while optimizing the 4D quality for all six possible time steps between the baseline and three monitor surveys.

Introduction

The Greater Plutonio development lies in Block 18, offshore Angola. It consists of 5 fields, each with 3 to 5 reservoir sections which sit in water depths of 1200 to 1500 m. It has been on production since Q4/2007. Oil is processed and exported via an FPSO.

The development is actively supported by 4D narrow azimuth towed streamer seismic data. The acquisition program to date has consisted of a baseline survey acquired in 2000 with subsequent monitor surveys acquired in 2009, 2011 and 2013. The favorable rock properties and geometry of the fields result in considerable value being gained from the 4D products. The key technologies adopted to date in extracting value from the 4D data have been steerable streamers and sources, TTI anisotropic velocity model building and imaging, and multi-vintage parallel 4D processing (Jackson and Riviere, 2013). A typical example of the 4D data quality seen at Greater Plutonio is shown in Figure 1.

4D data from the processing associated with Monitor 1 and 2 had been considered to be of high quality with low NRMS levels and interpretable 4D difference products. A desire to further improve the 4D data quality was none the less driven by a need to ensure that the influence of 4D data can be sustained beyond the early field development phase. Achieving this would provide data of sufficient quality to support base management decisions as the field matures and development well programs are completed.

4D data quality challenges

Despite the high quality of the 4D data at Greater Plutonio there remain 4D data quality issues. Crossline migration artifacts are observed throughout the 4D images. The artifacts increase in amplitude with the amplitude of the subsurface reflection. Therefore, they coincide with the bright events around the reservoir. The severity of these events in the data increases towards the longer offsets to the point where the far angle products are not interpretable. When extracting map-based 4D attributes, the migration artifacts present in the data can, in places, result in energy on the attribute maps which could be interpreted as real 4D signal. Figure 1 demonstrates this clearly.

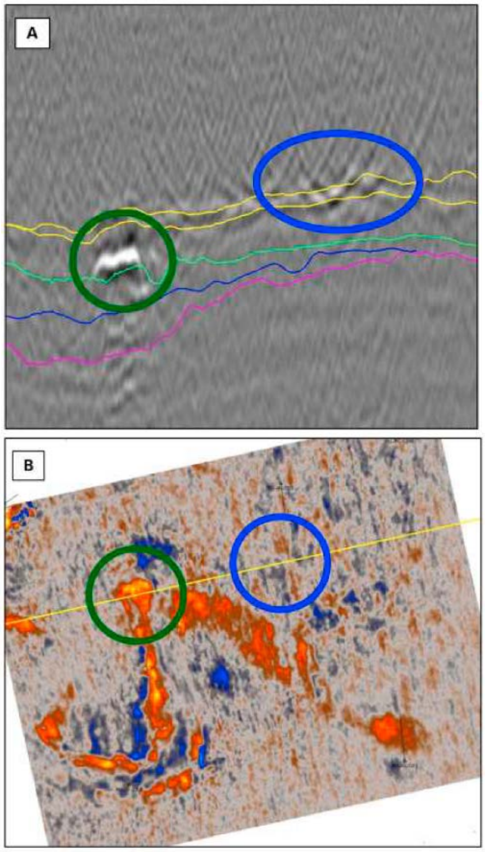

Figure 1: Cross line (A) shows strong 4D signal (green circle) as well as migration artifact noise (blue circle). The noise is of comparable amplitude to the 4D signal. (B) shows a 4D map with strong 4D signal visible (green circle). The map also contains the 4D migration artifacts which can be seen to be aligned with the acquisition direction (blue circle).

Early data inspection had led to observations that the 4D migration artifacts were coincident with either the edges of

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sail lines or possibly the outer cables of sail lines. The origin of the migration artifacts were extensively investigated considering established 4D processing techniques to equalize amplitude, timing and phase error between the baseline and the 2009 survey. Refining these corrections did not give significant uplift compared with previous processing products.

Further investigation focused on the strong correlation between the 4D migration artifact nadirs with the higher ΔSΔR values between the surveys. The highest ΔSΔR value for paired traces between the base line and monitor survey occurred when the monitor trace in a pair of 4D traces had come from a monitor sail line other than the "pre-plotted" repeated monitor sail line, typically instead being paired with a trace from the outer cable of the next sail line over, so that neither the source location or the associated receiver location were well repeated.

Solutions to 4D data quality challenges

As the processing flow developed following the acquisition of the third monitor survey, the following updates were implemented:
1) Trace rejection based upon 4D source and receiver repeatability (ΔSΔR clipping).
2) Pairwise parallel processing approach.
These changes were implemented during the processing of the third monitor survey at Greater Plutonio, acquired in 2013.

1) Trace rejection based on ΔSΔR clipping.
Crossline migration artifacts in legacy Greater Plutonio 4D datasets were observed to correlate with higher values of ΔSΔR. By removing traces with high ΔSΔR it was thought that the migration artifacts would be suppressed (Helgerud et al., 2011). Initial testing successfully improved the 4D data quality. But how much data should be discarded or clipped out? With too little clipping, although data quality improved somewhat, the uplift was not maximized, whereas when clipping was too severe the 4D products were seen to not be optimized. A sweet-spot needed to be established.

Two approaches were tested to determine how to vary the ΔSΔR clip limit with offset: A 'conservative clip' was parameterized to remove no more than 15% of traces for a given offset (resulting in an offset varying ΔSΔR clip limit) but limited to a minimum ΔSΔR clip value of 200 m. The alternative 'harsh clip' imposed a ΔSΔR clip limit of 200 m across all offsets. Neither was observed to harm the already established and understood 4D signal content, as such the 'harsh clip' was applied in the production processing. The impact in terms of the percentages of traces removed from the dataset is presented in Figure 2, whilst Figure 3 shows that the nadirs of the migration artifacts are coincident with where the clipping method has removed traces.

Clip thresholds tighter than 200 m were also tested but these created gaps in the offset planes that were too large for fold equalization interpolation algorithms to recover and as such these inadequately interpolated traces resulted in new 4D artifacts being generated.

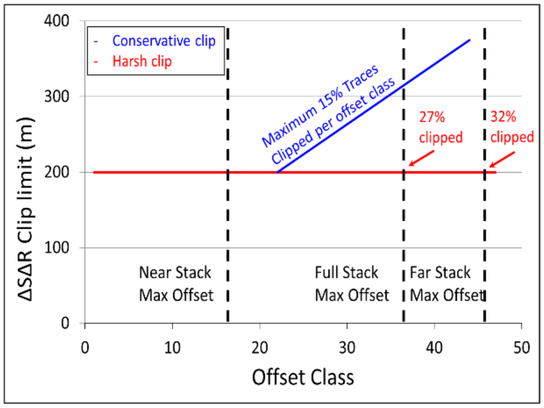

Figure 2: Offset dependence of the 'conservative' and 'harsh' clip methods.
The percentages marked represent the number of traces removed from the corresponding offset classes. The empty bins introduced by clipping traces were later filled by interpolation. The vertical lines represent the maximum offset class present in each angle stack used in 4D interpretation. The two clipping approaches are equivalent for the near stack.

2) Pairwise parallel binning.
Clipping out all traces with ΔSΔR > 200 m increases the amount of interpolation required during a conventional 4D processing flow. This is already the case when we consider just one base line dataset and one monitor survey. The situation becomes even more challenging for multi monitor surveys. This processing followed acquisition of the third monitor survey. Processing that had followed the second acquisition phase (i.e. used base line and monitor 1 and 2) had adopted a 4D multi-vintage binning criteria, where all three surveys were simultaneously binned. Simultaneous 4D multi-vintage binning selects the best traces for an offset bin that can be populated by all vintages; therefore, a hole in any one vintage will be propagated into all vintages. While this approach satisfies all surveys simultaneously it does not produce optimized 4D products for any of the individual time steps, for example the 4D between the base line and the first monitor is compromised by the inclusion

of monitor 2 in the binning criteria. When the ΔSΔR clip threshold of 200 m is considered for all six time steps (2000 to 2009, 2000 to 2011, 2000 to 2013, 2009 to 2011, 2009 to 2013 and 2011 to 2013), then over 40% of the bins within the survey would be left empty. In places entire sail lines would be discarded.

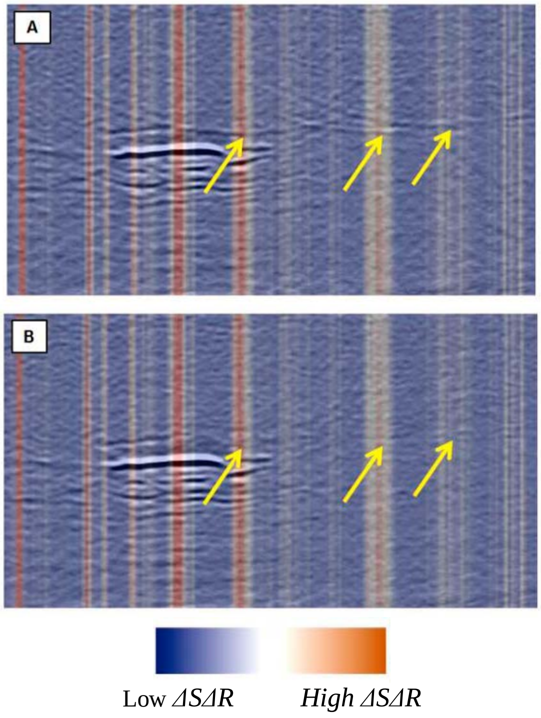

Figure 3: The seismic data in (A) is full offset stack 4D without a ΔSΔR clip limit. Clear migration artifacts are visible. The seismic data in (B) is full offset stack 4D with the application of a 200 m ΔSΔR clip limit. The migration artifacts have been removed. The color overlay is the same on both sections. It represents the fold of coverage change within each bin before/after the application of the ΔSΔR clipping. Red being high amounts of clipping, blue lower amounts. Nadirs of migration artifacts coincide with the areas where traces were removed due to their higher ΔSΔR values. This QC plot gives confidence that the data excluded by the 200 m ΔSΔR clip limit is the cause of the migration artifacts in the data and that the method does not impact the 4D signal content

To minimize the number of empty bins resulting from imposing a ΔSΔR clip threshold and optimize the 4D for each time step, a pairwise parallel processing flow was adopted. This also allowed for separate smaller polygons to be picked around the FPSO for each pairwise pair.

The approach is a modified version of the method described by Brain et al. (2013). Here the baseline survey has been co-processed individually with each monitor (rather than the monitor being co-processed with the other monitor surveys, as per Brain's paper), resulting in three pairs of data:

- 2000_{2013} & 2013_{2000}: baseline data 4D binned with the 2013 monitor data.
- 2000_{2011} & 2011_{2000}: baseline data 4D binned with the 2011 monitor data.
- 2000_{2009} & 2009_{2000}: baseline data 4D binned with the 2009 monitor data.

The subscript refers to the dataset that the volume was binned with.

The method makes use of the application of transfer functions to allow for four datasets (baseline and three monitors) to be delivered to the interpretation team, rather than the six datasets which are migrated.

Transfer functions are used to transfer the binning differences between the three realizations of the 2000 dataset into the 2009 and 2013 datasets. The transfer function represents the differences due to the binning for each of the 4D pairs. Using these allows us to return to four datasets, one for each vintage, rather than the six datasets from the pairwise binning described above.

The transfer functions are generated by subtracting the migrated offsets of the 2000_{2011} data and 2000_{2013} data respectively from the 2000_{2009} data. The relevant transfer functions are then added to the 2011_{2000} and 2013_{2000} datasets.

Results

The impact of the new products has been significant. 4D maps and sections are much cleaner (Figure 4 and 5), new 4D signal is visible as a result of being able to use smaller FPSO polygons in the pairwise parallel approach (Figure 4) and more 4D signal is visible above the noise floor (Figure 5).

Conclusions

In addition to new 4D deliverables, the processing following the acquisition of the third monitor survey at Greater Plutonio attempted to improve the 4D data quality by removing spurious migration artifacts in the data. These artifacts were associated with poorly repeated monitor traces. The artifacts have been greatly suppressed by adopting a 200 m limit on the acceptable ΔSΔR for any trace pair in the dataset. Adopting this approach increased the amount of interpolation that was required to fill empty bins in the dataset. To mitigate this, a pairwise parallel processing approach was adopted. This approach reduced the amount of interpolation required and removed the

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requirement to copy holes between multiple surveys. In addition, bespoke FPSO polygons could be picked for each pairwise pair. This allowed the use of much smaller FPSO polygons, resulting in new 4D signal being observable closer to the FPSO obstruction.

Conventional fully parallel 4D processing requires all monitor surveys to be processed simultaneously each time an additional monitor is added. As well as improving data quality, the pairwise parallel approach opens up the possibility of simplifying future 4D processing flows with only the baseline and next monitor needing to be processed. It is continuous improvements in 4D seismic data like those presented here that will be the enabler to ensure that 4D seismic data remains a valuable tool as the Greater Plutonio fields mature. Its influence will shift from well planning to base management, but its importance will remain.

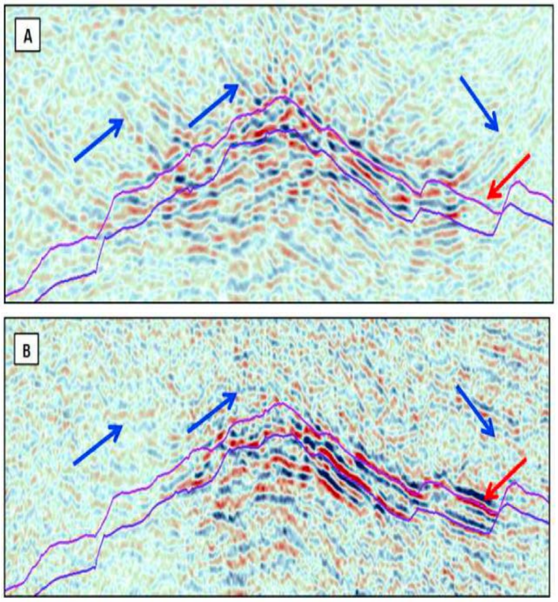

Figure 4: (A) and (B) show far stack 4D data using the same input data. (A) was processed through a conventional fully parallel 4D flow, whilst (B) was processed though a pairwise parallel flow with ΔSΔR clipping. (A) shows migration artifacts associated with poorly repeated traces. (B) shows coherent 4D data which is consistent with the structure and production from the field. The migration artifacts have been removed by trace clipping (marked with blue arrows). The new 4D signal seen in (B) (marked with the red arrow) comes from being able to use smaller FPSO polygons during a pairwise parallel processing flow.

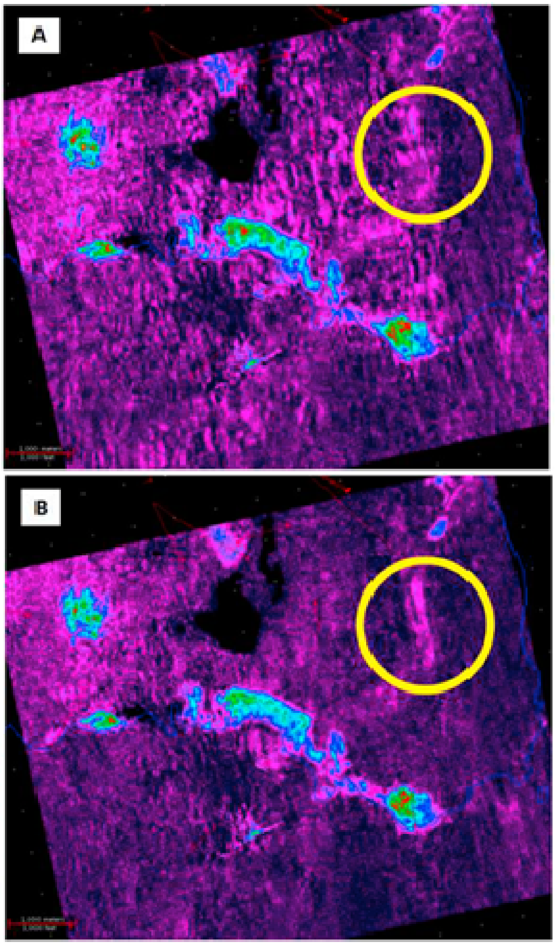

Figure 5: (A) and (B) show far stack 4D maps. The input is the same for both sections shown. (A) was processed through a conventional fully parallel 4D processing flow, whilst (B) was processed though a pairwise parallel processing flow with ΔSΔR clipping. (B) shows a 4D event circled in yellow that was hidden beneath the noise floor of migration artifacts in (A).

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EDITED REFERENCES

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