



# Correlation and Calibration of 4D Seismic Vintages for Effective Postproduction Intervention

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## Authors' contributions

This work was carried out in collaboration among all authors. Author BTO designed the research, participated in the interpretation and proof read the final draft. Author MTO participated in literature review and author MIO proof read the final draft. All authors read and approved the final manuscript.

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## ABSTRACT

Poor or low data quality usually has an adverse effect on the quantitative usage of (4D) seismic data for accurate analysis. Repeatability of 4D Seismic or time-lapse survey is considered as a vital tool for effective, potent, and impressive monitoring of productivity of reservoirs. Inconsistencies and disagreement of 'time-lapse' data will greatly affect the accuracy and outcome of research when comparing two or more seismic surveys having low repeatability. Correlation is a statistic procedure that measures the linear relation between all points of two variables. Error due to acquisition and processing must be checked for before interpretation in order to minimize exploration failure and the number of dry holes drilled. The seismic data available for this study comprises of 779 crosslines and 494 inlines. The 4D seismic data consisting of the base Seismic shot in 1998 before production and the monitor Seismic shot in 2010 at different stages of hydrocarbon production were cross correlated to ascertain repeatability between the two vintages. A global average matching process was applied while phase and time shift were estimated using the Russell-Liang technique. Two pass full shaping filters were applied for the phase matching. Maximum and minimum 'cross-correlation' are 0.85 (85%) and 0.60 (60%) respectively. Statistics of the 'cross-correlation' shift show standard deviation (0.3), variance (0.12), and root mean square (0.78). For high percentage repeatability and maximum correlations, the requested correlation

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threshold is 0.7 but 1 and 0.99 were obtained for the first and the second matching respectively. Conclusively, the overall results show that there is high repeatability between the 4D seismic data used and the data can be employed conveniently for accurate 'time-lapse' (future) production monitoring and investigation on the field.

*Keywords: 4D Seismic; repeatability; statistics; correlation; hydrocarbon exploration.*

## 1. INTRODUCTION

### 1.1 Research Background

Exploration and exploitation of crude oil and gas globally have continued to come under severe strain with attendant negative effects on both the economy and the environment. There is a need for utilization of new trends and ideas in hydrocarbon exploration and proper adjustment of hydrocarbon strategies for the discovery of more oil and gas fields to guarantee energy security worldwide [1]. Analyzing the 4D data correctly will aid in improving oil and gas asset management. Apart from well logs and core data, seismic data is one of the important tools used mostly for essential and accurate investigation in the exploration industry [2]. Different dimensions of seismic data include those acquired before production during exploration geophysics used mainly for pre-production investigation. This includes a 'one dimensional' seismic survey (1D) also known as well shot, check-shot survey, or vertical seismic profile for determination of sonic velocities used for time-to-depth conversion of other nearby seismic data. 1D has good horizontal resolution but lacks good lateral resolution. Two-dimensional (2D) seismic survey have imaging deficiencies but it is used for obtaining a regional overview in an area. Three-dimensional seismic survey (3D) assists mainly in sampling the subsurface volume instead of the area and it is used for more detailed mapping to get a higher and better degree of lateral and horizontal resolution and clearer image of the subsurface geology ahead of the 2D seismic survey. The non-convection 'four-dimensional' seismic survey ('time-lapse') is the precise repetition of a particular 1D, 2D or 3D seismic survey at two or even more different calendar times or vintages of hydrocarbon production on the same producing field. Time is the fourth dimension, and this is not a geologic time rather the seasonal time as arranged in months and years [3]. The first survey (Base survey) was acquired before production while the repeated survey Monitor survey was acquired at any stage of production on the same field. 4D seismic being a reservoir surveillance tool is employed for

mapping and investigate fluid movement interfaces in producing hydrocarbon reservoirs [4,5,6,7]. The difference between a repeated or monitor survey and a baseline survey can be analyzed and interpreted to determine reservoir changes resulting from production [8].

4D Seismic is very important in observing and monitoring changes in a reservoir that cannot be detected and mapped with the conventional 1D, 2D and 3D data. 'Time-lapse' seismic methods can help in locating and detecting bypassed/undrained reserves thereby increasing future hydrocarbon reserves (supply) and recovery. It also images fluid flow especially in those volumetric regions that were not captured by the wells [9]. 4D seismic can be used to track production when monitoring hydrocarbon reservoirs and in the monitoring of underground storage of carbon dioxide (CO<sub>2</sub>) gas as well as monitoring geohazards [10]. During time-lapse (4D) seismic measurements, the geological setting is assumed unchanged because the time interval measured between the base and monitor surveys is negligible in comparison with the geological time scale [11,12].

During acquisition and processing of 4D surveys, precautions are taken to increase repeatability or reduce non-repeatable noise between the vintages, [13], 4D method relies on seismic differences and the differences must be from field production and not from seismic acquisition and processing differences, or from variations of noise from the field [7]. Repeatability depends on acquisition geometry, processing uniformity, the complexity of overburden, and 'signal-to noise' ratio [7].

When two or more surveys are compared, alteration in reservoir attributes that are suggestive of the reservoir's fluid content may disclose that is if the seismic measurements are exact and the position/station of seismic sources and receivers are precise [14]. Parts of causative of error in seismic survey can be attributed to those conditions that will not allow for complete and accurate reshoot. These include those factors that exceed human restrain and control like 'tides, buildings, currents, topography,

weather, water tables, surface obstacles, wells, high-tension electrical installations, newly placed constructions, the presence of pipelines and others in producing field areas [7].

Previous evidence and proof may have been removed or may not be easy to locate, therefore, new benchmarks must be installed [7]. However, it is not feasible to get a faultless repeatability in field in respect of Time-Lapse seismic surveys because of the problems of preserving the exact survey details and some other factors involving the comparison of different vintages [15]. These survey factors according to [15] include 'survey azimuth, random noise attenuation, Spatial regularization, navigation data quality, multiple attenuation, variable fold of coverage, swell noise attenuation, water velocity variations, different source wavelets, coherent noise attenuation, and others' [15]. Because of these factors, 'time-lapse' seismic processing was mandatory to improve repeatability and reduce the artificial differences between 4D seismic data to avoid interpretation errors leading to drilling of dry holes [16]. Cross-correlation (sliding dot product or sliding inner-product) arises when two processed signals at or between two different time series are compatible/ matched to produce or exhibit a third signal in linear correlation to unravel some hidden sequences. Correlation coefficient ranges from 1 to -1, therefore, accuracy of data sets rely on the proximity of cross-correlation value to one (1). In this study, the cross correlation involving base and monitor seismic survey was aimed at establishing the similarity between two or more seismic surveys on the field. A correlation coefficient outcome gives the nearness of the survey used. Having a low coefficient shows that some differences occurred between the base and monitor surveys. Any changes and differences are expected amidst the reservoir section or the production area. Other areas aside the production zones will have to be calibrated and modified to fit the 4D surveys. Calibration is performed for amplitude or time/phase change to ensure that any changes found after inversion of the data volumes are due to output or production effects rather than acquisition or processing effects [17,18]. Changes in the reservoir are likely to impact the overburden and underburden materials, and this must be investigated.

Autocorrelation involves two identical traces with a maximum crosscorrelation of one (1.0) and where there is no similarity in the cross-correlated traces, then the normalized

crosscorrelation coefficient is less than one (1.0). When there is no correlation between the two surveys, it is indicated by zero (0) and it is either due to a processing defect/fault or hydrocarbon extraction/production-related spurious changes in the reservoir. By specifically analyzing variations in time-lapse seismic data for clarifying shifts in fluid saturation, the analysis of time-lapse seismic data has advanced from qualitative now to quantitative analysis [15,19].

The 4D seismic data include two or more vintages shot at different times on the same producing field. The extracted difference 4D volume should be close to zero, except where reservoir changes have occurred. Again, there is a need to ascertain accuracy in the correlation of the 4D seismic data to avoid spurious results that are due to acquisition and processing which could destroy the overall or outcome of the 4D seismic study and interpretation. The 4D seismic volumes' repeatability is very vital for the enhancement of overall hydrocarbon recovery.

## 1.2 Brief Geological Settings of the Study Area

The research area ('Royal' field) is situated in the eastern part of Niger Delta, southwestern Nigeria as shown in Fig. 1. The 'Royal' field has undergone active hydrocarbon production for over a decade.

The formation of the Niger Delta basin was initiated in the early Tertiary time [21]. The tertiary Niger Delta is a petroleum producing province consisting of three major lithostratigraphic units (Fig. 2). These are lower Akata (marine shale), middle Agbada (deltaic sedimentation), and uppermost Benin Formations (continental channel sand). The field has undergone active hydrocarbon production for over a decade.

## 2. METHODOLOGY

The inline, crossline and well locations are shown on the study area's base map in Fig. 3 below.

4D seismic data comprising of two different post-stacked 3D seismic volumes (base and monitor) in SEG-Y format were used for this study. The seismic data comprise of 779 crosslines and 494 inlines. The base (initial) seismic was shot in 1998 before production and the monitor ('time-

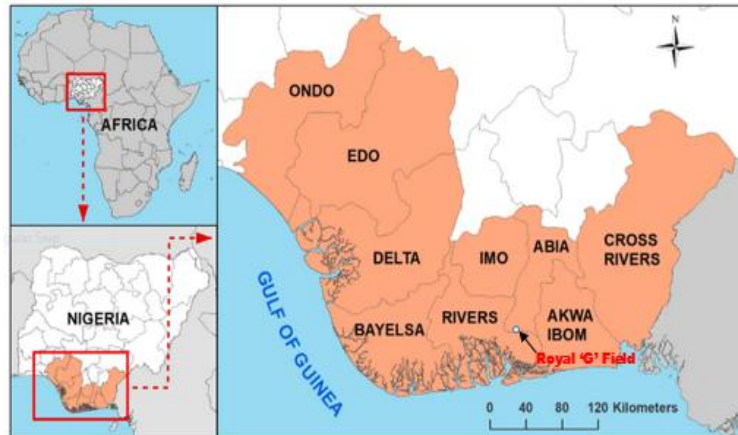


Fig. 1. The 'Royal' field in Niger Delta modified after [20]

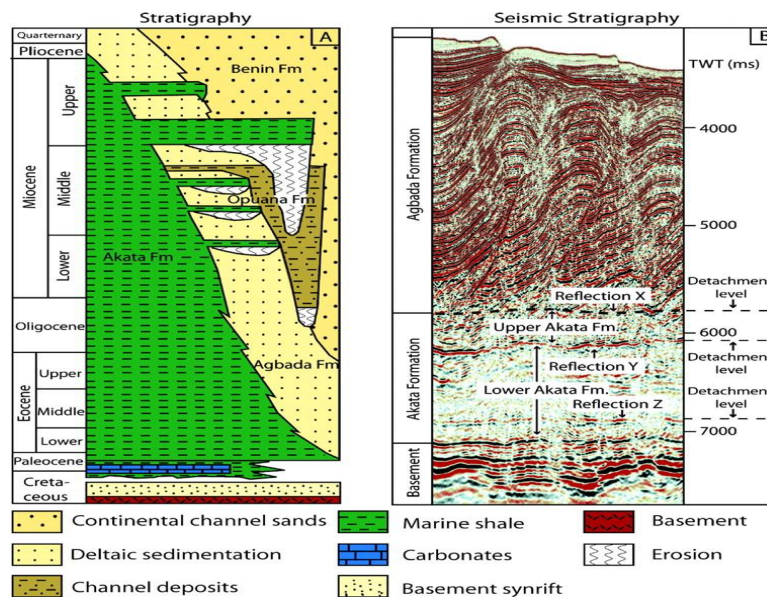


Fig. 2. Stratigraphic column of the Niger Delta [21]

lapse') seismic was shot in 2010 after a period of production. The two seismic data were loaded together simultaneously on pro4D window using Hampson Russel pro4D guide. Horizons were picked using Petrel software and were imported into the pro4D. 4D base volume was set as a reference for data calibration. The difference volume from monitor volume minus the base data was extracted. Since the base data is deducted from itself, the initial difference volume has no or zero amplitude. If there is no or only a poor correlation between base and monitor results, there will be no repeatability, and a calibration method/process will be used. Regrinding and comparing the processing output

geometry of one seismic survey to the other are part of the calibration process. The two or more 3D data sets were reprocessed so that the inline and crossline were having the same number e.g Base and monitor Seismic survey at crossline 1229 (Figs 4 and 5). The Russell-Liang technique was used to calculate, estimate and appraise the phase and time shift step by applying 'a first order constant phase correction and a constant bulk time shift'. All of the traces were subjected to a global average matching procedure with just one phase step and one time shift. The shaping filter, also known as a match filtering, was created and applied to the Monitor survey. By measuring a convolutional shaping

filter based on a design window, this method was used to fit the static time shift, phase, amplitude, and frequency content between the surveys. The Wiener-Levinson filtering algorithm is used in this shaping filter step. Crosscorrelation shallow statics (warp) step employed a time shift to align mispositioned events [20]. Time shift was calculated 'trace-by-trace'. Information within, below and above the reservoir matched the Time Variant Shifts. To obtain the amplitude differences, time deficiencies were reduced and data sets were deducted from one another. An amplitude shift test was performed to ensure that the seismic data above the reservoir zone was identical.

The covariance of the two variables was first calculated. The standard deviation of each variable was determined. The correlation coefficient is calculated by multiplying the covariance by the product of the standard deviations of the two variables. The standard deviation is a calculation of how much data deviates from its mean. The covariance of two variables measure how they shift together, but it has unbounded magnitude making it hard to analyse. The normalized version of the statistic can be calculated by dividing covariance by the product of the two standard deviations.

### 3. RESULTS AND DISCUSSION

The base seismic (Fig. 4) is the first seismic survey shot before development began on the site, as seen in the 4D seismic datasets at crossline 1229. Fig. 5 shows the monitor seismic

and this is the second seismic survey shot after a period of production and hydrocarbon extraction. The difference seismic, which is the difference between the base and monitor seismic surveys [8], is depicted in Fig. 6. If there is high repeatability between the base and monitor seismic surveys, the necessary 4D or 'time-lapse' information can be successfully interpreted using 4D difference seismic for enhanced hydrocarbon recovery.

#### 3.1 Crosscorrelation

The predictive map slice indicating the crosscorrelation between the two datasets performed at 0 ms, 1200 ms, and 1300 ms time window are displayed in Figs 7, 8, and 9 respectively. The 'reservoir focused' areas, as well as a few milliseconds above and below the zone, were included in the time window. When the base and monitor surveys were 'cross-correlated', the production-related effects causing time or phase changes were visible [16]. This allows any sort of required calibration to be handled to compensate for changes outside of the reservoir and production areas (the circled areas). The map of the maximum crosscorrelation slices shows these two datasets have a maximum correlation of 0.85 (85%) without any pre-inversion processing. These also show that within the field sector, the lowest correlation is about 0.60. (60%). The patchy zones /areas coloured green and yellow showed a lower correlation between the two vintages, while the bluish to the purple colour indicated a higher correlation.

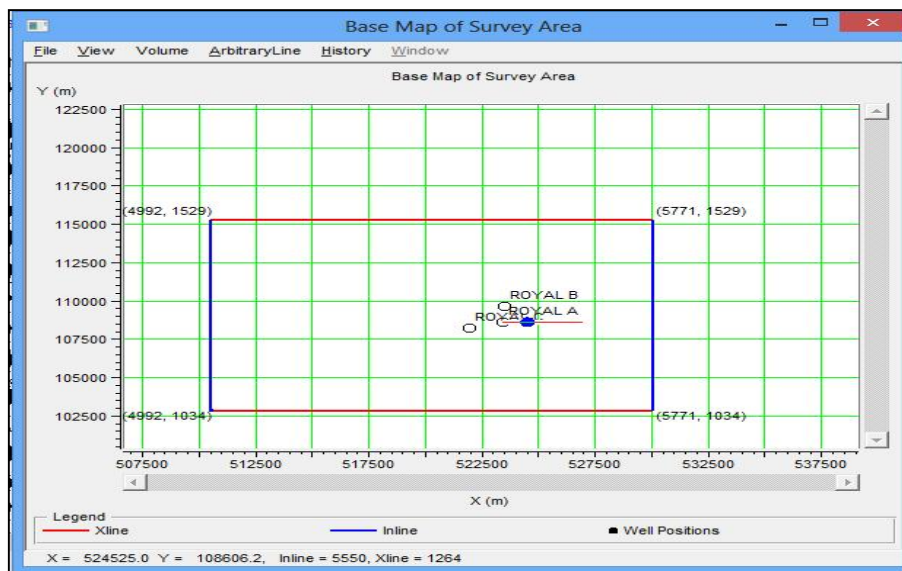


Fig. 3. Base map of the study area



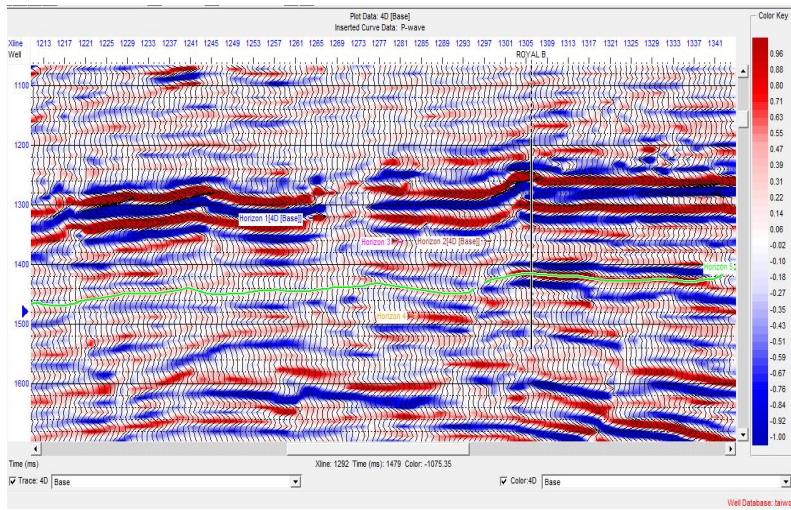


Fig. 4. 3D Base Seismic survey at crossline 1229

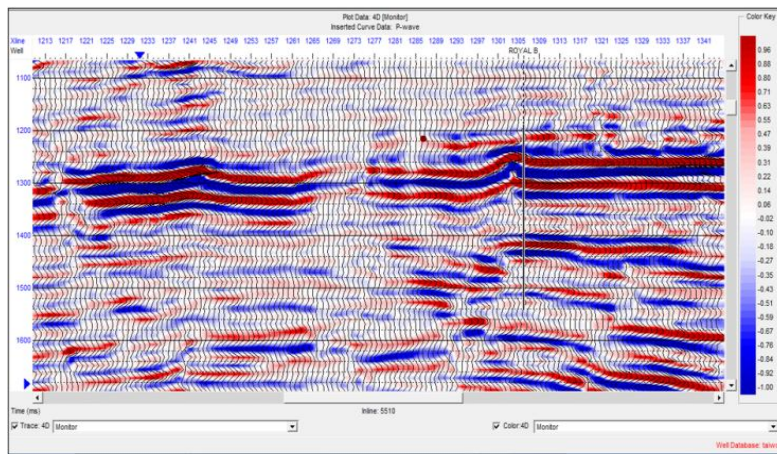


Fig. 5. The 3D Monitor Seismic survey at crossline 1229

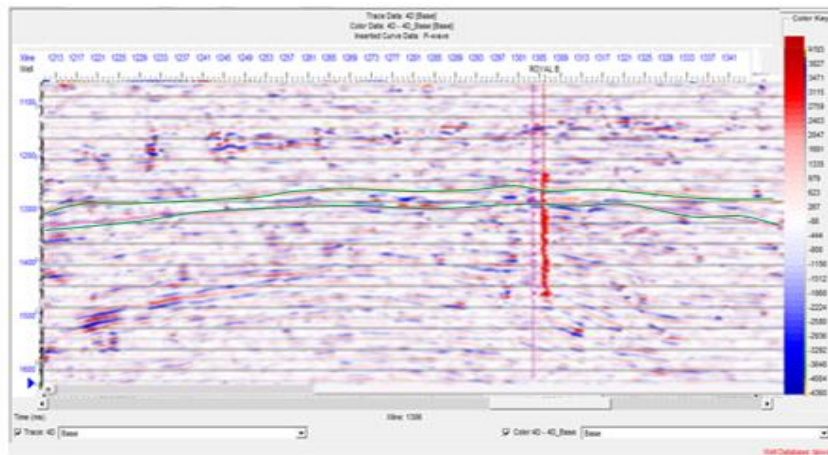


Fig. 6. The 3D Difference Seismic survey at crossline 1229

Creating amplitude slices from the monitor – base difference volume can be used to describe the aerial extent of the production-affected areas. The difference in amplitude near the wells, on the other hand, is often greater than 50% of the original signal level. The significant difference in reflectivity between the two surveys is due to production effects during the time/period between the two surveys.

The lower correlations within the field are mainly around well locations (circled area), so no re-processing is needed. The low correlation areas were attributable to production-related actions/effects, and they were retained for the

'time-lapse' evaluation's adjustments. Corresponding cross-correlation slices in Figs 10, 11, and 12 for corresponding 0 ms, 1200 ms, and 1300 ms time show bulk time shift of zero respectively. To this extent, the time shift information shows that there is a high degree of repeatability between the two data sets, as spurious differences and effects related to seismic acquisition and processing must have been greatly reduced. For the datasets, a histogram depicting the time shift and its corresponding percentage is shown in Fig. 13 further buttress that there are good correlation and repeatability between the dataset and they required no further calibration.

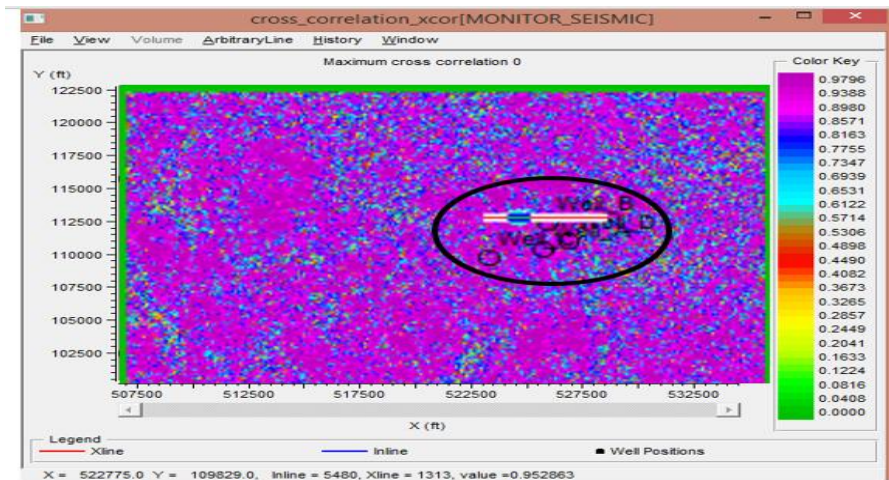


Fig. 7. Predictive Map slice of the crosscorrelation percentages for Base and Monitor Survey at 0 ms time window

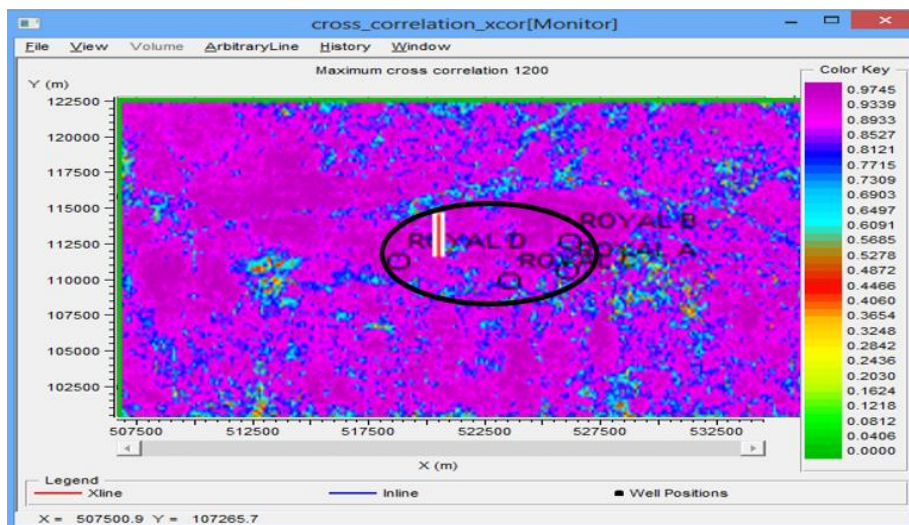
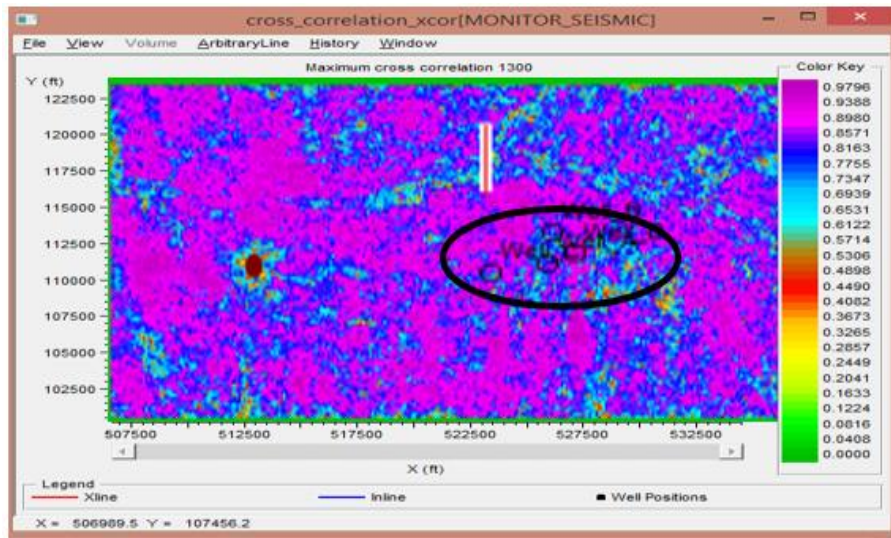
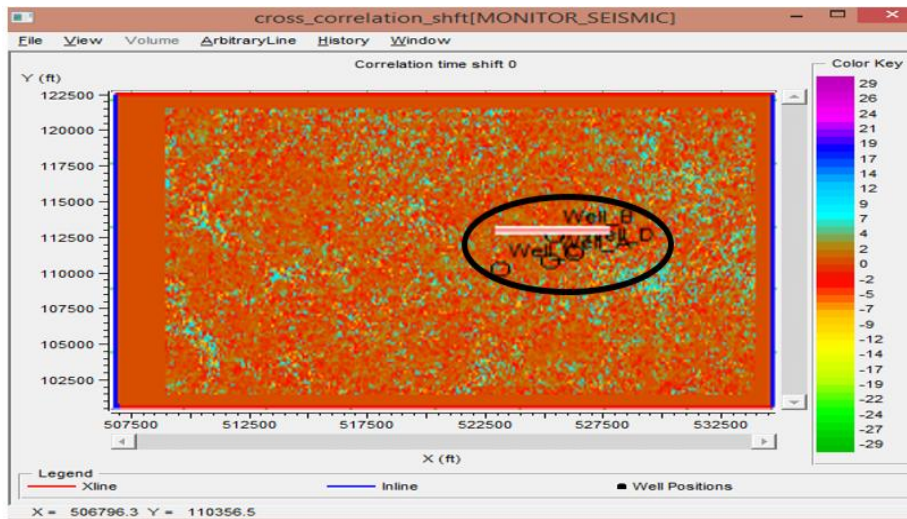


Fig. 8. Predictive Map slice showing the crosscorrelation percentages for Base and Monitor Survey at 1200 ms time window





**Fig. 9. Predictive Map slice of crosscorrelation percentages for Base and Monitor Survey at 1300 ms Time Window**



**Fig. 10. Predictive map of Correlation Time shift slice showing averagely low shifts and corresponding percentage for the datasets at corresponding 0 ms time window**

### 3.2 The Crosscorrelation Statistics

Results of statistics of the crosscorrelation shift for the 3D base and 3D monitor seismic volumes are displayed in Table 1. It shows low values for standard deviation (0.3), variance (0.12), and root mean square (0.78) within the dynamic range of 0 to 1 while putting the whole inline (779) and crossline (495) into consideration. The results revealed that the data clustered well near the mean. It shows that there is a good correlation between the two considered 4D Seismic volumes.

### 3.3 Volume Difference

The volume variance and difference analysis looked at how and where the two seismic volumes varied. This compared total volume. Due to compaction and pressure depletion, the majority (most) of the volume variations were found in the under-burden (circled area) of the reservoir. Figs 14 and 15 show the differences seen at the under-burden on different cross-sections through difference volume at inline 5520 and 5147.



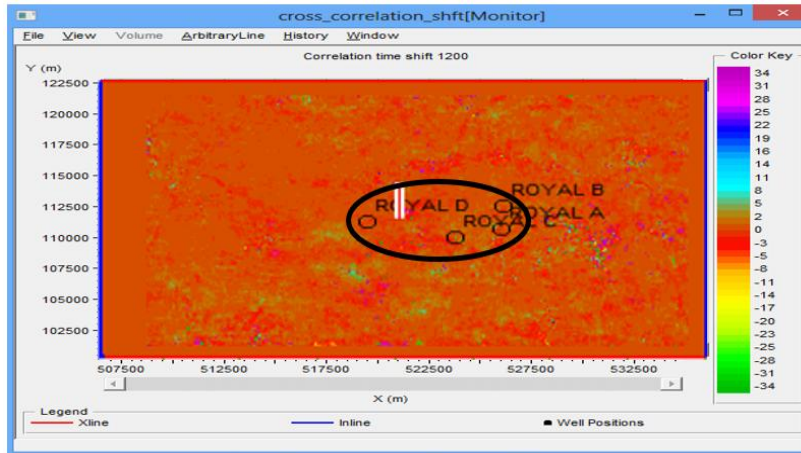


Fig. 11. Predictive map of Correlation Time shift slice showing averagely low shifts and corresponding percentage for the datasets at corresponding 1200 ms time window

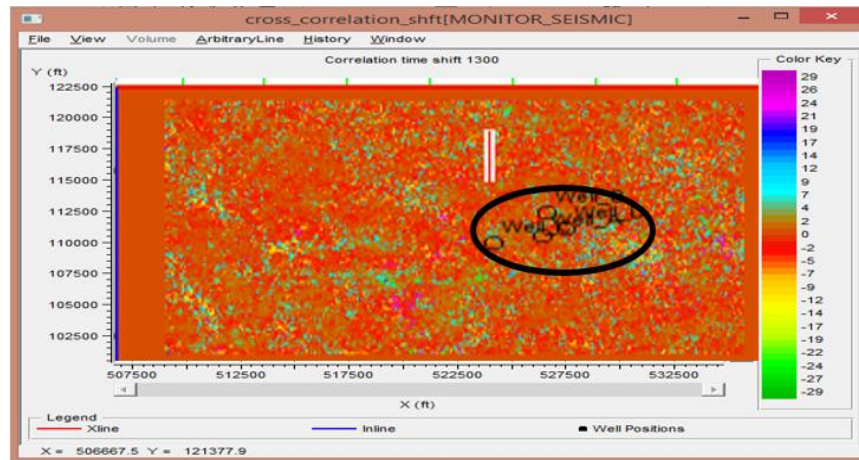


Fig. 12. Predictive map of Correlation Time shift slice showing averagely low shifts and corresponding percentage for the datasets at corresponding 1300ms time window

Table 1. The statistics of the cross correlation shift for the 3D Base and 3D Monitor Seismic volumes

Statistic	Values
Mean	0.698432
Standard Deviation	0.34668
Q1 (25%)	0.67134
Q2 (Median)	0.861813
Q3 (75%)	0.928358
Q (10%)	0
Q (90%)	0.957541
Variance	0.12
Sum	268851
Sum of the value squared	234038
RMS	0.77974
Number of valid values	384935
Dynamic Range	0 to 1
Inline Range	4992 to 5770 (779)
Crossline Range	1034 to 1528 (495)

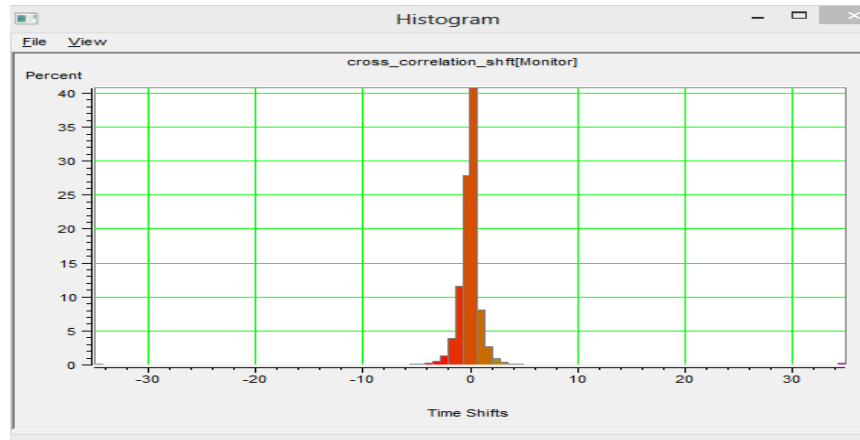


Fig. 13. The time shift and the corresponding percentage for the datasets shown on histogram

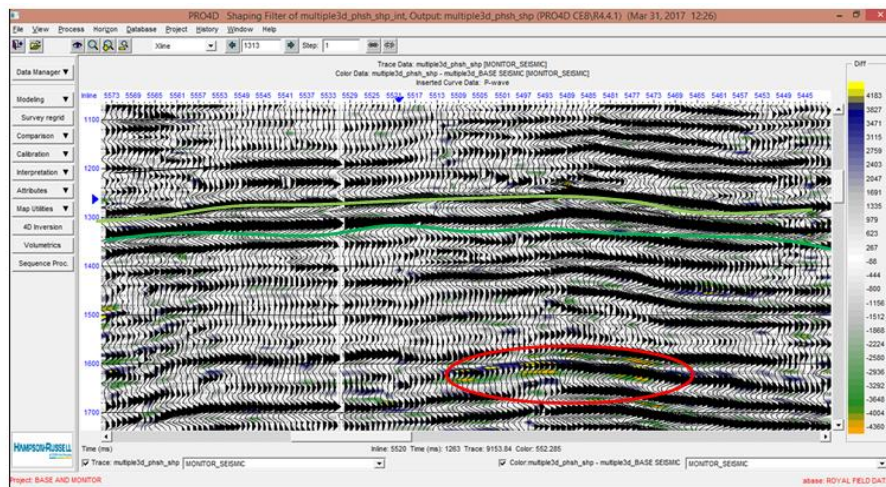


Fig. 14. The difference volume cross-section at inline 5520 for comparing Volume Difference

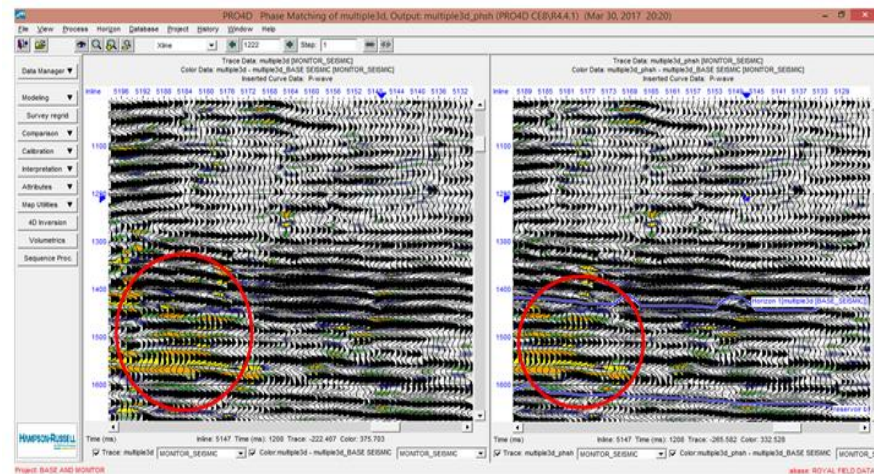


Fig. 15. The difference volume cross section at inline 5520 for comparing Volume Difference

**Table 2. Hampson russel window on phase matching statistics**

<b>First pass full matching statistics</b>	
Applying shaping filter	Multiple 3D-phsh
No of traces contributed to shaping filter	286170
Total traces-	385605
Requested correlation threshold	0.700
Maximum correlation found	1.000
<b>Second pass zero –phase matching statistics</b>	
Applying shaping filter	Multiple 3D-phsh
No of traces contributed to shaping filter	286170
Total traces-	385605
Requested correlation threshold	0.700
Maximum correlation found	0.999

### 3.4 Statistics of Phase Matching

The above correlation results in respect of the 4D seismic data volumes revealed that there is no need for further calibration of these data before full interpretation. However, to further confirm the percentage of repeatability between the base seismic and the monitor seismic data, two pass full shaping filter were applied for the phase matching (Table 2). For the first pass full matching, the statistics revealed that out of a total number of 385606 traces available, precisely 286170 traces contributed to the shaping filter. For the second pass zero-phase matching, the statistics show that out of the total number of 385605 traces available, precisely 286394 contributed to the shaping filter. The requested correlation threshold needed is 0.7 for high percentage repeatability while the maximum correlations found for the first and the second matching are 1 and 0.99 respectively. These are higher than the requested correlation threshold. Finally, the results supported that there is high repeatability between the 4D Seismic data used in the study area..

### 4. CONCLUSION

Error-free time-lapse data provides additional details in addition to that of 3D can efficiently reduce the uncertainty in the final reservoir models and thus have a positive effect on the economics of reservoir development. The calibration and correlation of 4D seismic volumes showed that within the field surroundings, the lowest and highest correlation is estimated to be about 0.60. (60%) and 0.85 (85%) respectively. The bulk time shift was zero. The requested correlation threshold was 0.7 but the maximum correlation thresholds found for phase matching were 0.999 and 1 showing that there were good correlation and high repeatability between the base and the monitor seismic dataset. The

majority (most) of the volume variations were visible and noticeable in the under-burden. This was caused by compaction that has taken place in the monitor survey due to hydrocarbon extraction. No spurious differences associated with acquisition and processing were present with the datasets. The datasets are adequate. It can be used conveniently to get the presence of seismic anomalies and the expected outcome of any interpretation done with it will be due mainly to 4D effects or production changes. This study attained the expected results because the quality of data was accurately detected and this can be employed in identification and extraction of information from the field dynamic reservoirs.

### COMPETING INTERESTS

Authors have declared that no competing interests exist.

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