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REVIEW ARTICLE

THE SUBSURFACE STRUCTURES IN KOCR FIELD IN THE NIGER DELTA, NIGERIA, USING 3D SEISMIC TIMELAPSE DATA

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ABSTRACT

The subsurface structures in KOCR Field, in the Coastal Swamp Niger Delta, Nigeria, are here presented, using seismic 3D timelapse. The KOCR Field lies on latitudes 4°50'58''-4°55'19''N and longitudes 6°18'41''-6°26'41''E with aerial extent of 840km^2. The base (1997) and the monitor (2009) seismic surveys resulted in a 4D response difference. The Base and Monitor data have a root-mean-square repeatability ratio (RRR) of 0.38 implying a very good repeatability when considering the acquisition, processing and environmental noises. Data processing and interpretation were carried out using Petrel software. The average thickness of the reservoir is about 69m at the depth of 3932m. Reservoir pressure decline rate of 0.062psi/day resulted in production decline rate of 1192.21bbl/day. Structural interpretation of seismic data reveals a highly-faulted field. Fault and horizon interpretation shows closures that are collapsed crestal structures. All the interpreted faults are normal synthetic and antithetic faults which are common in the Niger Delta basin. The lengths, dips and orientations of the faults and horizons, in the base and monitor stacks, are equal indicative of no faults reactivation that could have resulted from hydrocarbon production. The results of this work can be used in reservoir, field and environmental management in the area of study.

KEYWORDS

seismic, timelapse, faults, structures, Niger Delta, Nigeria

1. Introduction

In Time-lapse seismic, the difference between two seismic vintages acquired at different time intervals under same acquisition conditions gives information on the variation of geophysical properties due to the hydrocarbon production. Reservoirs producing oil or gas are subjected to pore pressure depletion. This creates changes in the stress and strain fields of the rock material both inside and outside the reservoir. In addition to leakage of hydrocarbons, hazards are associated with wells crossing reactivated faults. Reactivated faults can also have close relationship with earthquakes. In this research, seismic timelapse and well-log data are used in an attempt to establish subsurface structures in KOCR Field, Nigeria. The results of the work can be applied in the hydrocarbon exploitation scheme to minimize the damages associated with production, and also to ascertain reactivation of faults in the area study.

2. Timelapse Seismic Data Quality

A time-lapse or four-dimensional (4D) seismic survey compares two or more seismic surveys acquired at different stages of hydrocarbon production (Vedani et al., 2009). The success of time-lapse reservoir monitoring depends on removing the non-repeatable effects such as configurations, seasonal changes, atmospheric temperatures, tides, elastic properties of the overburden, compaction, multiples, and rock heterogeneities (Vedanti et al., 2009; Kragh and Christie, 2002; Spetzler and Kvam, 2006; Varela et al., 2006). Obstructions, weather patterns, cost constraints, and maritime traffic can also influence the survey orientation. Having considered the above sources of error in repeatability, the acquisition system itself, positioning accuracy, receiver sensitivity/calibration, and source calibration must also be looked into. In interpreting time lapse seismic data, one commonly used method to quantify the repeatability is Normalized Root Mean Square (NRMS) analysis. The percentage NRMS difference of the two traces (a_t-b_t) from two different surveys within a given time window t_1-t_2 is computed using the formula (Kragh and Christie, 2002):

$$NRMS = 200\frac{RMS\,(a-b)}{RMS\,(a)+RMS\,(b)} \tag{1}$$

where NRMS is measured in percent, and the RMS operator is defined as:

$$NMS\,(a_t) = \sqrt{\frac{\sum_{t_1}^{t_2}(a_t)^2}{N}} \tag{2}$$

where N is the number of samples in the time interval t_1-t_2. Typical NRMS values are acquisition shot in different directions: 0.6 - 1.2 (or 60% - 120%), parallel surveys and legacy processing: 0.4 - 1.0, dedicated survey and processing: 0.1 - 0.4, and a lower number is a better survey (Eiken et al., 2003; Staples et al., 2006; Osdal et al., 2006; Furre et al., 2006). The NRMS-values for some of the early 4D studies were 60-80% (Landro,

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1999a; Landro, 1999b). The more recent NRMS-values are between 10% and 30% for marine 4D studies (Osdal et al., 2006; Furre et al., 2006; Goto et al., 2004). Land data has higher NRMS-values and are often higher due to acquisition challenges and seasonal changes within the near surface layers.

Many literatures have reported interesting seismic timelapse studies in the oil prolific area of the Niger Delta Basin, Nigeria. Furthermost, these studies majored on timelapse feasibility studies and reservoir monitoring and management (Osayande and Ogborugbo, 2009; Aniwetalu et al., 2017; Ogbamikhumi et al., 2017; Uko and Otugo, 2016; Uko et al., 2018). Moreover, literatures in public domain are very scarce on seismic timelapse, in Nigeria, with the main objective of determining effect of hydrocarbon production on subsurface structures and faults reactivation. Researchers focus their attention mostly on the local geological studies aimed primarily at founding hydrocarbons (Doust and Omatsola, 1990; Ekweozor and Daukoru, 1994).

There are the technology, business and geohazard drives that may motivate a research on the effect of hydrocarbon production on surface, subsurface structures and faults reactivation using seismic Timelapse. Firstly, some of the major business consequences of timelapse reservoir compaction and surface subsidence. Some group researchers state that reservoir compaction improves production performance (Veeken et al., 1994; Bruno, 2002; Setarri, 2002). This is possible because compaction causes reduction in porosity and permeability which effect production. A group researcher also states that porosity loss affects the computation of oil and gas reserves (Pourciau et al., 2005).

Secondly, from technology viewpoint, reservoir compaction and surface subsidence resulting from time-lapse monitoring have important potential applications in reservoir characterization and monitoring. By calculation time-lapse time shift, the magnitude and patterns of subsidence are good indications of reservoir shape, size and depth, besides being affected by reservoir rock and fluid properties and production history. Using subsidence from time-lapse time shift, subsidence pattern may also be a good indication of permeability anisotropy (Roste et al., 2005). Subsidence pattern may be an indication of bypassed oil (Vedanti et al., 2009). Time-lapse Time shift R-factor can also be used together with 4D seismic for reservoir monitoring. The R-factor is defined as the ratio between travel time changes and the path length changes (Hatchell et al., 2005). The geomechanically mechanism and the seismic response of reservoir compaction have implications on reservoir characterization and monitoring (Hatchell and Bourne, 2005a). Time-lapse seismic data are used to chart changes in velocity and thickness during production, and in the overburden.

Moreover, and thirdly, timelapse reservoir monitoring can also be used to investigate environmental geohazards in the area of the study. Reservoir compaction and surface subsidence may cause oil-well to collapse and drilling platform to sink, which are very costly to repair (Allen and Mayuga, 1969). Subsidence also affects pipelines, roads and other structures (White and Tremblay, 1995; Zoback and Zinke, 2002; Chin and Nagel, 2004; Barkved et al., 2003). Subsidence causes coastal flooding (Geertsma, 1973b; Reed and Cahoon, 1993). Reservoir compaction can lead to reactivation of faults, casing failure and borehole breakout (Barkved et al., 2003; Morton et al., 2006; Mildren et al., 2002; Reynolds et al., 2003). Zoback and Zinke reported microearthquakes at the Valhall Field. Reactivated faults correlate with tremors (Segall, 1989; Segall, 1992).

3. THE GEOLOGY OF THE STUDY AREA AND THE NIGER DELTA

The study area, KOCR Field, lies on latitudes 4°50'58''-4°55'19''N and longitudes 6°18'41''-6°26'41''E (Figure 1). The KOCR Field is located in the Coastal Swamp Depobelt Niger Delta of aerial extent of about 840km^2 (Oboh-Ikuenobe, 1995). The KOCR Field is made of lithofacies that are rich in palynodebris, black debris, wood fragments and amorphous organic matter. The KOCR reservoir, characterized by numerous predominantly E trending growth faults, is of the Middle Miocene and of the Agbada Formation (Oboh, 1993; Davies et al., 2019). The Late Tertiary Niger deltaic sequence is divided into three units, the Benin Formation, Agbada Formation and Ataka Formation existing in descending order (Figure 2). Akata Formation is mainly composed of marine shales with locally dark grey sandy and silty beds. It is the lowest unit of the Niger Delta complex (Figure 2). Its thickness varies from 576m to about 6060m. The age of the formation ranges from the Oligocene to Recent (Doust and Omatsola, 1992; Reyment, 1965; Murat, 1972; Weber and Daukoru, 1975; Kogbe, 1976).

Agbada Formation is formation was laid down under transitional environment, Figure 2. It is made up primarily of alternating fluviomarine sandstones and marine shales. It ranges in age from Eocene in the north to Pliocene in the south. The sandy parts of the formation constitute the main hydrocarbon reservoirs of the delta oil-fields and the shales constitute seals to the reservoirs. It has a variable thickness of about 4500m. The formation, which occurs throughout the Niger Delta probably, has outcrops at the extreme flanks of the delta where it has been called Ameki formation (Doust and Omatsola, 1992; Reyment, 1965; Murat, 1972; Weber and Daukoru, 1975; Kogbe, 1976). Benin Formation consists of coarse-grained gravely sandstones with minor intercalation of shales. It is a continental deposit of Miocene to Recent in age (Figure 2). It has very little hydrocarbon accumulation and has a thickness in excess of 1820m. The typical outcrops of Benin formation can be seen around Benin, Onitsha and Owerri (Doust and Omatsola, 1992; Reyment, 1965; Murat, 1972; Weber and Daukoru, 1975; Kogbe, 1976).

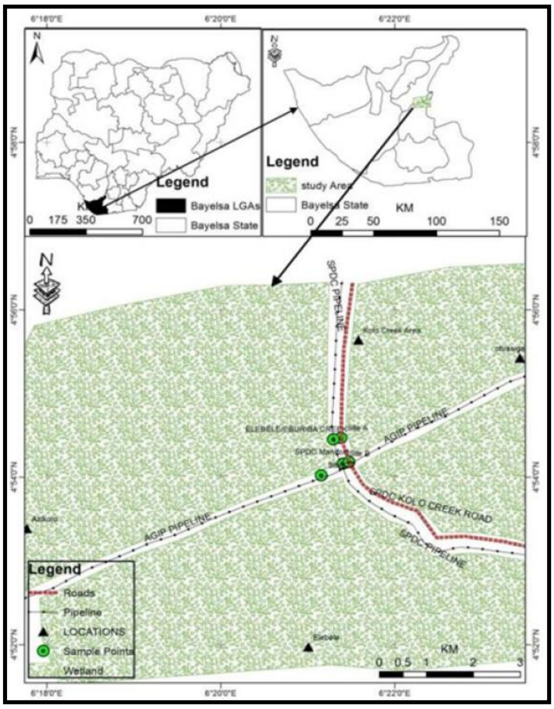


Figure 1: Map of Nigeria showing the Study Area, KOCR Field

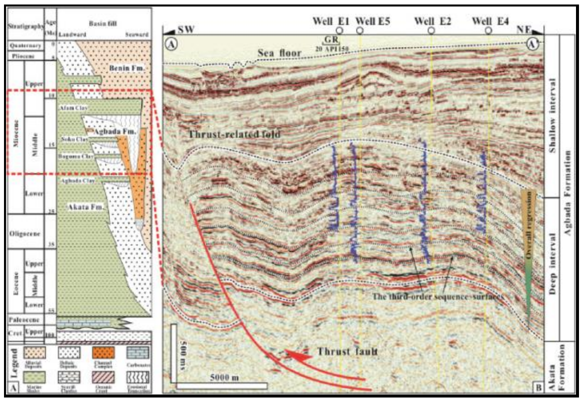


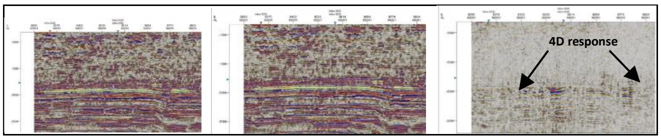
Figure 2: Schematic Representation of stratigraphic column showing the three (3) Formations of the Niger Delta (Doust and Omatsola, 1990).

4. MATERIALS AND METHODS

4.1 Data Quality

4.1.1 Seismic Data

Pre-stack time migrated full-offset 3D and 4D stacks were available. A key factor in the success of timelapse studies is to ensure that the base and monitor surveys are mainly introduced by production effects (Vedanti et al., 2009). All these sources of error was handled through normalized root mean square (NRMS) analysis. The NRMS of 0.38 has been achieved, in this study, implying very good repeatability when considering the quality of data and acquisition difference. The seismic timelapse difference between the base and monitor surveys was successfully extracted. The very fact of the difference from the monitor implies the existence of production-induced effect and acquisition, environmental and processing noises, hence the 4D or timelapse response signal (Figure 3).



(a) (b) (c)

Figure 3: (a) Time Slice of KOCR Base Inline/Crossline Survey; (b) Time Slice KOCR Monitor Inline/Crossline Survey; (c) Time Slice KOCR Difference Inline/Crossline Survey.

4.1.2 Well-Log Data

The available gamma ray (GR), density (RHOB), and sonic (DT) were in ASCII format. The logs were validated, checked and confirmed to be depth-matched. Borehole environmental corrections were applied to all the available logs. Logs with multiple runs were spliced. Log data in the field were rather incomplete because, some of the wells were not fully logged to total depth (TD) while some were found discontinuous. It was only KOCR-1 (Figure 4) out of 5 available wells that had complete suite of required logs. The sonic log was calibrated using the checkshot data. The calibration process is necessary in order to improve the quality of the sonic log because the sonic log is prone to washouts and other wellbore related errors.

4.2 Seismic-to-Well Ties

The calibrated sonic log is used along with the density log to generate an acoustic impedance (AI) log. The acoustic impedance log is calculated for each layer of rock. The next step involves generating the reflectivity coefficient (RC) log. The RC is calculated and generated using the AI log. The RC log generated is then convolved with a wavelet to generate a synthetic seismogram which is comparable with the seismic data. Synthetic seismograms were used to compare seismic reflection data to well log data. A comparison of the reflectivity or acoustic impedance responses derived from seismic and from wireline logs enabled matching of seismic events with geological markers Figure 5.

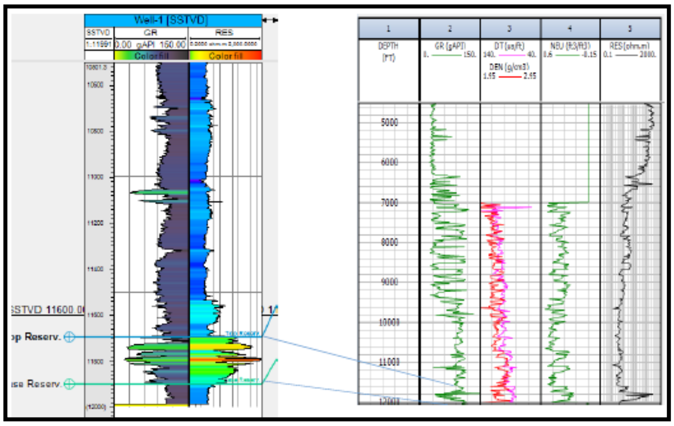
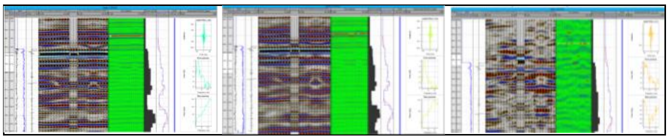


Figure 4: Composite Log of Well KOCR-1

The key horizons were correlated from nearby wells KOCR-001, KOCR-002, KOCR-003, KOCR-004, and KOCR-005. Well correlation involves lithologic description, picking top and base of sand-bodies, and then linking these properties from one well to another based on similarity in trends. Correlation of reservoir sands was achieved using the top and base of reservoir sands picked (Figure 6). The correlation process was possible based on similarity in the behaviour of the gamma ray log. In order to discriminate between sand and shale lithologies in the subsurface, the gamma-ray log is used.



(a) (b) (c)

Figure 5: Seismic-to-Well tie for KOCR Wells: (a) Base; (b) Monitor; (c) Difference

4.3 Horizon and Fault Mapping

The steps used in seismic interpretation include well-to-seismic ties, fault mapping, and horizon mapping (Simmons and Backus, 1994; Goodway et al., 1997; Wapenaar et al., 1999; Zorasi et al., 2019). As a result of performing good well data conditioning, acoustic and definition of geological boundaries on the seismic data were achieved as well as highlighting some subtle subsurface structures.

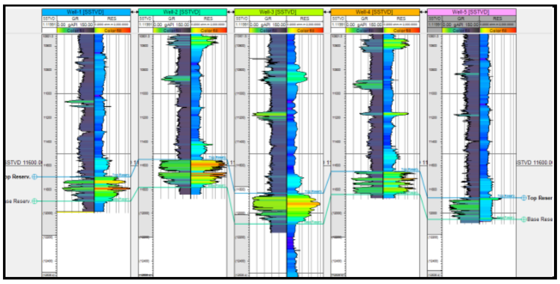


Figure 6: Composite Log of Well KOCR-1

5. RESULTS AND DISCUSSION

5.1 Production and Reservoir Pressure Reports

The Production and Reservoir Pressure Reports are presented in Figures 7 and 8.

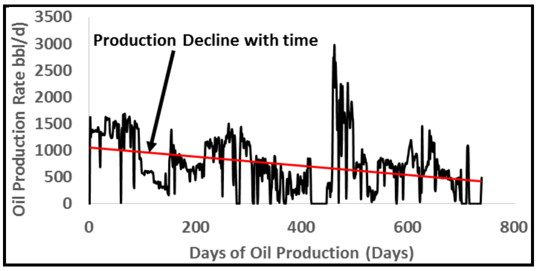


Figure 7: Reservoir Production Rate versus Days of Oil Production

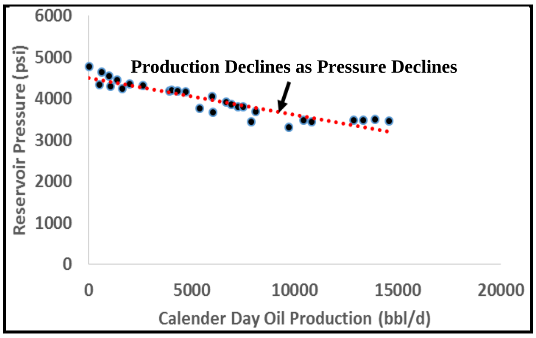


Figure 8: Effect of Reservoir Pressure Decline on production Rate

5.2 Faults and Horizons Interpretation

The results for the interpreted faults in COKR field are presented in Figure 9. All interpreted faults are normal synthetic and antithetic faults, and are regional, running from the top to bottom across the field. Hence, these faults play significant roles in trap formation at the upper, middle and lower sections of the field. The reservoir surfaces reveal that the reservoir structure is a collapsed crest. Structural interpretation of seismic data revealed that the field is highly faulted with synthetic and antithetic faults which are in line with faults trends identified in the Niger Delta. Reservoir is found at a depth of 3932m. The synthetic and antithetic faults act as good traps for the hydrocarbon accumulation in the study area.

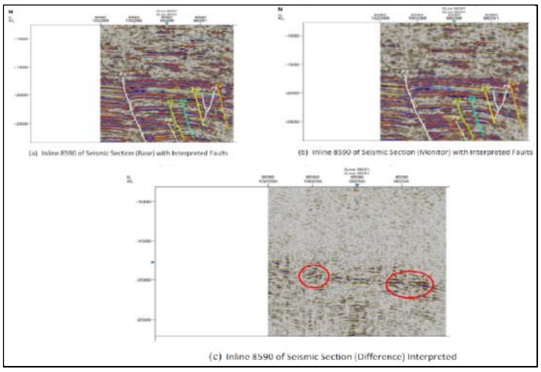


Figure 7: Base, Monitor and Difference Seismic Section for Inline 8590 Interpreted

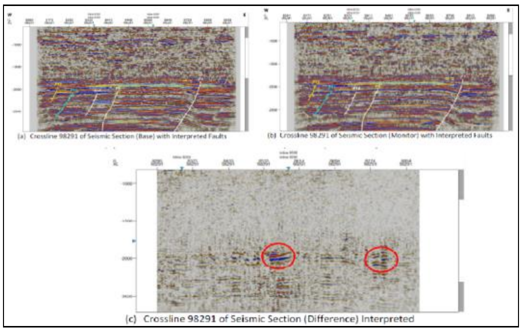


Figure 8: Base and Monitor Seismic Section for Crossline 98291 Interpreted

5.3 Fault Reactivation

Wide-ranging studies on induced-seismicity as a result of fluid withdrawal and subsurface fluid injection have been conducted by several researchers around the world (Evans, 1966; Mereu et al., 1986; Raleigh et al., 1976; Segal, 1985; Chan and Zoback, 2007; Kuecher et al., 2001; Pennington et al., 1986; Grasso and Wittlinger, 1990; Doser et al., 1991; Grasso, 1992; Mcgarr, 1991; Baranova et al., 1999; Davis et al., 1995). Most of these studies established that seismic events occur in the proximity of producing hydrocarbon reservoir, and increases after production or injection began. Some researchers reported that mechanical instability induced by fluid injection is related to the increase of pore pressure which allows slip on pre-existing faults by lowering the effective normal stress (Raleigh et al., 1976). Consequently, the reduction of pore pressure as a result of production should inhibit faulting. However, observations and studies of seismic events around different oil and gas fields around the world suggested that depletion will result in a change in stress around the reservoir that may encourage slip on faults outside of the reservoir (Mereu et al., 1986; Segall, 1985; Chan and Zoback, 2007; Kuecher et al., 2001; Pennington et al., 1986; Grasso and Wittlinger, 1990; Doser et al., 1991; Grasso, 1992; Mcgarr, 1991; Baranova et al., 1999; Davis et al., 1995).

Using poroelastic theory with an assumption of an ellipsoidal reservoir embedded in an elastic medium, Segall calculated stress changes surrounding a hydrocarbon reservoir induced by reduction of pore pressure inside the reservoir (Segall, 1985; Chan and Zoback, 2007; Kuecher et al., 2001). The stress changes can result in fault reactivation in the proximity of the reservoir leading to reverse faulting above and below the reservoir while normal faulting occurring near the edge of the reservoir. While the Segall solution analytically calculates stress changes and the potential of fault reactivation in the vicinity of the depleting reservoir, the impact of the compaction of an irregular shaped reservoir on a non-planar fault surface is best estimated using numerical modeling. In COKR Field, the fault lengths, dips and orientations are equal in both base and monitor seismic sections suggestive of no-fault reactivation from hydrocarbon production. Further studies are required to confirm this claim.

6. Conclusion

The following conclusions are made:

(i) Production decline of 1192.21bbl/day resulted from pressure decline of 95.50bar/year or 0.062psi/year.

(ii) Most of the data points were not repeatable as evidenced in the computed Normalized root mean square (NRMS) of 0.38 meaning that on 62.0% of Base and Monitor data points were coincident.

(iii) Structural interpretation of seismic data revealed that the field is highly faulted with synthetic and antithetic faults which are in line with faults trends identified in the Niger Delta. Fault and horizon interpretation revealed that closures found are collapsed creatal structures bounded by two major faults.

(iv) No fault reactivation resulted from the hydrocarbon production.

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