Research Article

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A combination of genetic inversion and seismic frequency attributes to delineate reservoir targets in offshore northern Orange Basin, South Africa<https://doi.org/10.1515/geo-2020-0200>

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Abstract: The reported occurrence of Albian- and Cenomanian-aged braided fluvio-deltaic channels in the Orange Basin, South Africa, opens a window of exploration activities to characterize these channels as they are renowned to form some of the world's giant oil field. In this study, a seismic acoustic impedance inversion and seismic attributes (instantaneous frequency and iso-frequency) analysis is used to investigate potential Albian and Cenomanian fluvio-deltaic channels in offshore, northern Orange Basin. Reservoirs were mapped using a well and 3D seismic volume (8-bit) after initial dip-steering coherency filtering had been performed on the seismic volume to remove incoherent noise and improve data resolution. Model-based acoustic impedance inversion was applied on the seismic volume to delineate fluvio-deltaic channels in addition to using the RMS (root mean square) amplitude attribute. Iso-frequency using the cosine correlative transform (CCT) method was equally applied to delineate these channels. Instantaneous frequency attribute was analyzed for potential hydrocarbon-charged sediments. This was achieved by utilizing thirty-three seismic traces as an input in the Hilbert transform window, after which trace envelope and instantaneous phase were transformed into instantaneous frequency. Acoustic impedance inversion results reveal the presence of two channels within the Cenomanian sequence, which shows high porosity (~40%) along its geometry. The CCT method shows that the 8 Hz frequency window resolved the presence of a channel within the Albian sequence. A meandering channel within the Albian sequence was equally delineated by the RMS, while the application of instantaneous frequency (IF) attribute indicates the presence of hydrocarbon-charged sediments of

Cenomanian age in proximity to a listric normal fault because of the attenuation of frequency observed close to the fault. This study demonstrates a case study of the application of seismic impedance inversion and seismic attributes for the delineation of potential reservoirs and hydrocarbon-charged sediments in a basin.

Keywords: acoustic impedance inversion, seismic attributes, reservoirs, Orange basin

1 Introduction

Reservoir characterization studies in the Orange basin have focused more on utilizing geochemistry and petrography to appraise and predict the quality of reservoirs in the basin. Previous studies [1–3] had suggested the poor development of qualitative reservoirs due to severe precipitation of quartz and clay cements, especially in the proximal part of the Orange Basin. Evidently, the Ibhubesi gas field discovered in the southern section of the Orange basin has been declared as a tight gas reservoir [4], which suggests the presence of highly compacted reservoirs, occasioned by the severe cementation of diagenetic cements. The aforementioned studies are more localized to specific reservoirs based on drilling campaigns and not an absolute indication of the quality of reservoirs in the basin. This underscores a need for further exploration to characterize potential reservoirs for further drilling campaign in the basin. The occurrence of fluvio-deltaic channels of Albian and Cenomanian age has been reported in the Orange Basin [5]; therefore, the delineation of these channels is critical to future exploration drive in the basin.

The application of Seismic attributes and genetic inversion [6–11] is suggested to investigate potential reservoirs in this basin. Different authors [6,10–13] have documented the successful application of seismic attributes and seismic impedance inversion in characterizing reservoirs and hydrocarbon-bearing reservoirs. In these cases, seismic impedance inversion and seismic attributes are tested independently or combined to delineate hydrocarbon bearing reservoirs. However, the combination of

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these methods is more reliable to reduce possible uncertainties associated with the identification of depositional and structural features.

The main objective of this study is to use these methods (seismic impedance inversion and seismic attributes) to investigate the occurrence of fluvio-deltaic channels and hydrocarbon saturated reservoirs within the Albian and Cenomanian sequence in the northern Orange Basin. This study applies a genetic inversion [7] for acoustic impedance inversion, performs instantaneous frequency attributes (IF) analysis of the seismic data, decomposes frequency at different bandwidths (iso-frequency) from the seismic data, and performs a root mean square (RMS) of the seismic data waveform.

The genetic inversion process involves the use of a non-linear inversion algorithm output operator to transform the seismic data into the desired log-response equivalence by estimating a minimal difference between the computed synthetic and the recorded seismic trace [14]. However, seismic attributes can be analyzed directly from the seismic data as they are components of seismic data that can be computed or implied from the seismic data, which are often sensitive to geological features and can define a particular reservoir property [15]. These concepts are applied within an exploration block in the northern Orange Basin, South Africa (Figure 1), after an initial noise filtering of the 3D

seismic cube had been performed for a quality check. This process eliminates passive frequency through a Ricker frequency filter and improves the poststack seismic data quality. The application of these concepts reveals some interesting findings in this study.

2 Geology of the study area

The Orange Basin is situated along the passive South Atlantic continental margin that straddles the borders of Namibia and South Africa [16]. The architecture of the basin is defined by the Walvis Ridge in the north and Agulhas-Columbine arch in the South (Figure 2a). Margin evolution was initiated by extensional forces that started in the early Mesozoic [17,18] and culminated in rifting and drifting apart of the South American and African continents, in the late Jurassic and early Cretaceous.

Major tectonic phases that characterize the Orange Basin are classified into pre-, syn and post-rifts [18]. The pre-rift basement rocks are overlain by a succession of pre-Barremian syn-rift basic lavas within the central rift sequence, and coarse continental clastic, fluvial, and lacustrine sediments, along with volcanic deposits within the marginal rift basin [Figure 2b; 19]. These are in turn overlain by a Barremian to post-rift succession of

Figure 1: Location map of 3D seismic survey position, various 2D lines acquired and well AF-1 used within it (a), the coverage of Orange Basin with three wells drilled so far in block 1, while the red arrows point to the Orange river system in the North and Olifants river system in the South respectively (modified from Hartwig [5]) (b).

Figure 2: Location map of Orange Basin, South Africa (a) and the generalized stratigraphy of Orange Basin the study area (b) modified from Broad *et al.* [19].

alternating fluvial red beds and marine sandy rocks that are deposited as a result of transgression and regression of sea level [20].

The Albian sediments that overly the Aptian sediments consist of thick-bedded bioturbated mudstones and massive planar cross-bedded sandstones [21]. Deepest marine conditions was experienced in the basin in the early late-Cretaceous depositing mainly siliciclastic sediments [22]. However, by the end of Cenozoic, sedimentation rates had reduced and deposits composed mainly of a mix of carbonates, siliciclastics, and authigenic sediments [22].

In addition, the sedimentary evolution in the Basin was affected by major slumping events in the late Cretaceous-

early Cenozoic, which reshaped the basin morphology because of massive erosion and sediments bypassing that characterized these periods [23]. The major reservoirs in this basin are the Barremian Aeolian sandstones of the commercial Kudu gas field [24]. This is in addition to the lower Cretaceous (Albian) and upper Cretaceous (Cenomanian) marine sandstones (including sand-rich distributary channels), which are the main reservoirs in the South Africa section of the Basin [5]. As shown in Figure 2b, the sedimentary deposits in the Albian and Cenomanian period are of deltaic and coastal plain origin, and their sedimentary environment ranges from fluvial in the South to deltaic/shallow marine in the North of the Basin [2].

3 Methods and materials

3.1 Seismic data acquisition and processing

The 3D seismic data were acquired in 2009 under a joint proprietary between the Petroleum South Africa and Cairn India with the aim of investigating a sniffer anomaly [25]. The survey covers an area of 750 sq km exploration Block in the northern Orange Basin, South Africa. The survey utilized a shot and receiver group interval of 25 and 12.5 m, respectively, a sampling rate of 2 ms, and a maximum recording length of 7 s. The dominant frequency ranges between 100 and 125 Hz, while a low-cut off frequency of 3 Hz was applied. The processing technique involves an automatic gain recovery to account for amplitude loss followed by the deconvolution process at the operator length of 200 ms, while a 3D Dip moveout correction was applied using a maximum dip of 40 ms/trace.

3.2 Quality control and seismic-well tie

The seismic cube was subjected to dip-steering coherency filtering to remove incoherent noises and enhance resolution of seismic and geological features (Figure 3a and b). A time-depth relationship between the 3D seismic volume (8-bit) seismic data and the well was built by utilizing formation tops and checkshot data to generate a synthetic seismogram (Figures 4 and 5). This workflow process was

completed by first generating velocity log from sonic log using the following formula:

$$\text{Velocity} = 1/\text{Sonic}.$$

Thereafter, the velocity log was used to generate an acoustic impedance log by multiplying the obtained values with formation density log values [26]. In addition, a reflection coefficient log was generated with a synthetic seismogram to calibrate the results with the 3D seismic data at the well position (Figures 4 and 5).

3.3 Genetic inversion

Acoustic impedance inversion (forward model based inversion) enables the description of internal rock properties such as lithology, porosity, and fluid types. The theoretical principle of genetic inversion process is based on acoustic waves reflecting off subsurface rock interfaces at different amplitudes based on the density and velocity contrast of these interfaces. Based on this, an earth model centered on the arrival time and amplitude of acoustic waves can be generated by utilizing the poststack seismic data to produce an estimate of the earth's acoustic impedance.

In this study, genetic inversion algorithm combines neural network and generic algorithm to determine single nonlinear operator, which produces a best fit between poststack seismic data and logs data of control wells was applied on the 3D seismic data to generate 3D acoustic impedance cube [7]. Seismic acoustic impedance stochastic

Figure 3: Seismic data at 968 ms before frequency filtering to remove incoherency and enhance the mapping of geological features (a). Seismic data at 968 ms after frequency filtering to enhance the mapping of geological features (b).

Figure 4: The different log signatures of well AF-1 showing the positions of target sequence of Albian and Cenomanian age (a). A seismic cross-section showing Albian and Cenomanian sequence investigated for potential reservoirs (b).

Figure 5: The synthetic log generated from well AF-1 tied to the seismic section to position formation tops to its actual position for mapping. Inset is the dominant frequency of the seismic data.

inversion as performed here involves the use of high-frequency acoustic impedance log generated from the process mentioned earlier (under quality control section) to train 3D seismic cube to generate a 3D acoustic impedance cube. The process uses a nonlinear multi trace operator to convert seismic cube to a corresponding log property [7]. The observations made from the acoustic impedance inversion were calibrated with the density log estimated-porosity model because of the relationship between these two rock properties. Subsequently, the mapping of the

Albian and Cenomanian sequences were done from the respective formation tops positions to identify main reservoir targets within these sequences, and time slice sections within these periods (Albian and Cenomanian) were investigated.

3.4 Iso-frequency (frequency decomposition)

Iso-frequency (frequency decomposition) is applied in reservoir characterization studies to extract high-resolution stratal slices of seismic data frequency for the identification of potential hydrocarbon reservoirs in the subsurface. The suitability of a particular frequency bandwidth to image potential reservoirs is commonly dependent on reservoir thickness and geometry. For instance, in imaging thin reservoir beds, higher frequency is more appropriate, while lower frequency is suitable for thicker beds [27]. The frequency subsets could range from low to high, i.e., 15, 29, and 44 Hz [27].

The iso-frequency attribute applied in this study utilizes the correlation cosine transform (CCT) method: a mathematical equation for the discrete Fourier transform model (DFT). Each bin in the DFT output is an equivalent of a particular frequency where the

Frequency of a K^{th} bin = $k \times (\text{sampling rate}/N)$, where N is the number of samples or cycles. In this study, N is 1.5.

3.5 Instantaneous frequency

The instantaneous frequency seismic attribute as pioneered by [28] used the Hilbert transform to convert seismic trace $x(f)$ to a more complex seismic trace $z(f)$. The transformation process involves the rotation of phases of real seismic trace $x(f)$ and imaginary $y(f)$ seismic traces. These represent cosine and sine of spectral amplitudes, respectively. The negative and positive frequency components of the cosine are rotated by $+90$ and -90 , respectively, to complete the Hilbert transformation process [29]. The application of this method in reservoir characterization is impeccable in isolating sweetness (hydrocarbon charged reservoirs) because of frequency attenuation associated with gas compressibility [30]. In this study, a default value of 33 was used as an input in the Hilbert filter window, which represents the amount of seismic trace, which its amplitude (trace envelope) and instantaneous phases are transformed into instantaneous frequencies.

4 Results and discussion

4.1 Well logs and seismic data

The discrete facies log, Gamma ray log, sonic impedance log, reflection coefficient, synthetic log, density log, density porosity log, and the major unconformities of well AF-1 are shown, respectively, in tracks 2, 3, 4, 5, 6, 7, 8, and 9 of Figure 4a. The first track represents the depth track of the well in the subsurface. The facies logs with Gamma ray cut-off of less than 65 API for sandstones, between 65–90 API for siltstones, and greater than 90 API for shales were used in this study. The reservoirs encountered in this well are identified within the Cenomanian and the late Albian sequences, while a thinly laminated reservoir is also observed just below the Albian unconformity (Figure 4). The mapping of these sequences across the 3D volume was done from the position of the major unconformities at the well position as shown in Figures 4 and 5, which represents the formation tops. Horizon time slice intersection on the seismic volume was performed at the top of 14AT-1 and 14JT-1 sequences in which there are occurrence of potential Albian and Cenomanian reservoirs, respectively (Figures 4 and 5). Figure 5 shows the position of the formation tops (see the Z values) on the seismic volume after well-tie had been performed.

4.2 Validation of acoustic impedance and porosity relationship

The acoustic impedance log generated from a product of velocity and density logs during the process of the creation of a synthetic seismogram was used for the inversion process to generate the earth's acoustic impedance model from the 3D seismic data. Acoustic impedance typically increases with the depth as porosity decreases with the depth [31]; therefore, a relationship exists which makes it essential to calibrate observations made from one with the other. To validate this relationship, porosity derived from the density log is plotted against acoustic impedance log as shown in Figure 6 to determine the correlation coefficient. Because of the inverse relationship between acoustic impedance and porosity, a negative correlation coefficient is expected, and this is evident with the -0.837048 correlation coefficient value for the plot (Figure 6). This value suggests a less than perfect correlation between these variables; this is not unexpected because of various diagenetic events, which could include the degree of cementation, pressure dissolution, and reprecipitation. Reprecipitation and a higher degree of cementation could increase chemical compaction and consequently increase the acoustic impedance [14]. In addition, pressure dissolution could cause an anomalous increase in porosity at deeper depth without a direct corresponding increase in acoustic impedance.

Figure 6: Validation of acoustic impedance and porosity data relationship for well AF-1. The correlation coefficient is -0.83 .

4.3 Genetic inversion and RMS amplitude

The time slice of the acoustic impedance inversion extracted within the Cenomanian sequence at inline 2,340 indicates the presence of two parallel Cenomanian-aged channels at time slice 968 ms (Figure 7). The channels display a low-medium acoustic impedance signature along its geometry as shown in Figure 7. This suggests that the channels are not well consolidated or likely less cemented. The first channel (A) has an average width of 378 m, while the second channel is on average 285 m (B) in width (Figure 8). The channels are suggested to be paleo channels of the Orange River system, which in the present day is at close proximity to the study area as shown in Figure 1. The calibration of these observations with observations made on the porosity inversion indicates that these channels show high porosity along its geometry (Figure 8). These characteristics make these channels an ideal reservoir target, subject to their vertical thickness. Root-mean-square (RMS) amplitude attribute indicates medium-low amplitude signatures are dominant within the seismic data and reveals the presence of a medium amplitude, Albian-aged meandering channel at time slice 2,000 ms (Figure 9). The channel has a loop toward the tail-end of its geometry.

4.4 Frequency attributes

Instantaneous and iso-frequency attributes are applied to delineate potential reservoirs and likely hydrocarbon-bearing reservoirs in the study area. A bright spot (high amplitude) anomaly noticed on either side of the fault plane of a listric fault within the Cenomanian sequence suggests the likely presence of hydrocarbon-charged sediments possibly caused by the leakage of gas across the fault plane (Figure 10). Instantaneous frequency resolved the observation that the bright spot anomaly is due to hydrocarbon-charged sediments at the time slice of 758 ms because of the attenuation of frequency observed around the bright spot anomaly. Frequency attenuation in gas saturated sediments is due to the compressible nature of gas, which causes it to absorb higher seismic frequency. The hydrocarbon saturated sediments observed on either side of the fault suggests a potential leakage of gas across the fault may have caused the attenuation to occur on either side of the fault (Figure 11).

The iso-frequency attributes time slice extraction was performed to test the frequency bandwidth suitable for the seismic data to delineate the possible presence of potential reservoir channels. At time slice of 1,540 ms and frequency of 45 Hz bandwidth, the seismic data indicate the

Figure 7: Acoustic impedance inversion showing the two low-impedance channels parallel to each other within the Cenomanian sequence at time slice 968 ms.

Figure 8: Porosity inversion shows high porosity along the two parallel channels geometry at time slice 968 ms.

Figure 9: RMS amplitude section showing a low-amplitude meandering channel within the Albian sequence at time slice 2,000 ms. The channel displays a meander loop toward the termination of its geometry.

presence of sediments with high-frequency signatures (Figure 12a), which is ambiguous for the delineation of potential reservoirs as the frequency of most reservoirs in this area are of low frequencies. A further frequency

Figure 10: Seismic section showing a listric normal fault with an associated high amplitude (bright spot anomaly) at inline 758 ms within the Cenomanian sequence. Bright spot anomaly as observed here suggests gas leakage along the fault plane.

tuning was performed at various frequency bandwidths; however, at frequency of 8 Hz, an occurrence of a narrow, straight channel within the Albian sequence was delineated, which could be a potential reservoir target (Figure 12b).

Figure 11: Instantaneous frequency at inline 758 ms showing the listric normal fault and frequency attenuation around the bright spot (a). Time slice at 968 ms showing the listric normal fault (with bright spot anomaly) with frequency attenuation on both sides of the fault plane. Frequency attenuation here suggests gas-bearing sediments at the close proximity to the fault.

Figure 12: Iso-frequency time slice 1,540 ms taken at 45 Hz bandwidth (a). The figure shows an ambiguous variation in frequency signatures of the sediments. The frequency is not suitable to delineate possible buried channels in the study area. Iso-frequency time slice 1,540 ms taken at 8 Hz bandwidth (b). This figure shows the presence of a low-frequency, narrow channel within the Albian sequence. This suggests the reservoir target here is of low-frequency signature.

5 Conclusions

Model-based genetic inversion has been used to investigate potential hydrocarbon reservoirs within the Albian and Cenomanian sequences of the northern Orange Basin. The

utilization of coherency filtering attributes enhanced the quality of the data, reduced incoherency, and made acoustic impedance inversion successful. The comparison of observations made from the acoustic impedance inversion with the porosity attributes reduced the uncertainty that could be

associated with the identification of features made solely from acoustic impedance inversion. Based on this, two Cenomanian-aged fluvial channels were delineated. These two fluvial channels have low-medium impedance and high porosity along their geometry (Figures 7 and 8). RMS amplitude also indicates the presence of a low-medium amplitude meandering channel within the Albian sequence. The identification of a bright spot anomaly around a listric normal fault prompted its resolution by instantaneous frequency attribute. This shows that the frequency attenuation observed on either side of the fault plane is due to the presence of gas-bearing sediments in close proximity to the fault plane. The attenuation is stronger on either side of the fault plane due to the compressible nature of gas, which makes it to absorb more seismic frequency and thus confirms the presence of gas as the cause of the bright spot anomaly seen on the seismic section. The iso-frequency decomposition also revealed the presence of a low-frequency, narrow channel within the Albian sequence at 8 Hz. Finally, the presence of buried channels as seen within the Albian and Cenomanian sequences subject to the determination of their vertical thickness could be potential hydrocarbon reservoirs in this part of the basin.

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