Seismic rock properties and their significance for the interpretation of seismic amplitude variation with angle (AVA), offshore Liberia and Sierra Leone

David Went[1]*, Jon Rogers[1] and Felicia Winter[1] demonstrate that lithology has a very strong impact on the amplitude variation with offset or angle (AVO/AVA) response and that shale and brine sand responses need to be identified with confidence before any prognosis of a hydrocarbon signature is made.

Abstract

Well and seismic data from the Leonian and Liberian basins confirm the presence of a working petroleum system, with syn and post-rift Cretaceous intervals containing excellent source rocks, reservoir sands and sealing shales. Rock property studies conducted on well log data indicate that lithology (sand versus shale) has a strong impact on amplitude variations with offset or angle (AVO/AVA). Elastic seismic inversions confirm the observations made from well logs. The key learning is that shale and brine sand responses need to be clearly identified before any prognosis of an AVO anomaly resulting from the presence of hydrocarbons is made.

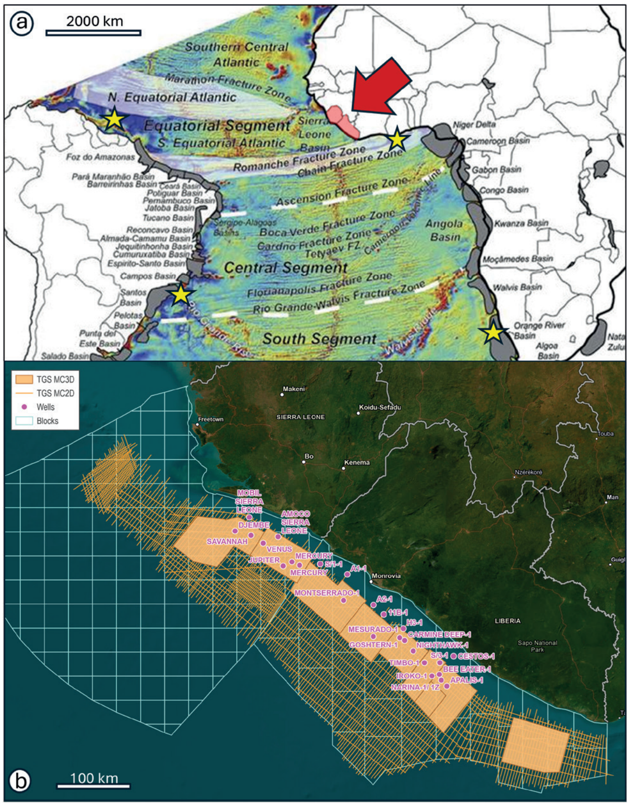

Figure 1 a) Location and geological setting of Sierra Leone and Liberia in the transform margin of the Atlantic Ocean. Examples of recently established major petroleum provinces in Guyana, Brazil, Ghana and Namibia are marked with yellow stars (Granot and Dyment, 2015); b) seismic and well data coverage offshore Sierra Leone and Liberia.

Introduction

The deep waters of the Atlantic margin have proven to be a good place to explore for hydrocarbons in recent years with large commercial discoveries having been made, for example, in Brazil, Guyana, Ghana and Namibia (Figure 1a). Most discoveries have been made in siliciclastic plays in stratigraphic traps (e.g. Daily et al 2013, Hedley et al 2022). In these plays, there is typically a heavy reliance on seismic interpretation to define traps and on amplitude analysis, including amplitude variation with offset or angle (AVO/AVA), to suggest hydrocarbon presence. Well data typically plays an important part in calibrating seismic responses. However, in newly emerging plays it is commonly scarce, so it is important to maximize the learnings from the existing well data to improve subsurface interpretation and increase the chances of commercial success.

The purpose of this article is to show the results of a rock property study and seismic inversion workflow conducted on the offshore West African Leonian and Liberian Basins (Figure 1b). Seismic rock properties determined from well logs provide an important link to interpretation of seismic responses in the subsurface (Castagna et al 1993). Rock properties determined from well logs in the Leonian and Liberian basins highlight that lithology has a very strong impact on the amplitude variation with offset or angle (AVO/AVA) response and a key learning is that shale and brine sand responses need to be identified with confidence before any prognosis of a hydrocarbon signature is made. Armed with this understanding, material exploration opportunities may be identified, each of which has the potential to transform this region from a frontier system to a commercial hydrocarbon province.

Geological setting and exploration history

The Leonian, Liberian and Harper Basins occur offshore Sierra Leone and Liberia, form part of the transform margin of West

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Africa (McGregor et al 2003) and are the conjugate margin to the Guyana-Amazon basins in South America (Figure 1a). Atlantic rifting of these segments mainly occurred in the Aptian-Albian and syn-rift sequences have been penetrated by wells in both Leonian and Liberian basins (Brownfield and Charpentier 2006). However, it is the overlying late Cretaceous interval which has been the main focus of more recent exploration drilling, with thick post rift sequences proven to contain excellent source rocks, reservoir sands and sealing shales (Winter et al 2020). Minor non-commercial discoveries have been made that confirm a working petroleum system but frustratingly, many dry wells have also been drilled. The targeted traps are typically stratigraphic and rely on pinch out on the continental slope. Prognosing which traps contain oil typically relies heavily on AVA analysis and the identification of a suitable AVA (AVO) anomaly. Understanding the AVA behaviour and what constitutes a suitable anomaly is therefore critical to successful exploration.

Database and method

The well and seismic database used in this study is shown in Figure 1b. Fourteen wells from the deep-water Liberian Basin and nine wells from the Leonian basin were analysed petrophysically to establish lithology, porosity, fluid type and saturation. Seismic rock property curves, acoustic impedance, Vp/Vs and EEIχ27 were generated from P-Sonic, S-sonic and density logs. An example of the petrophysical output is displayed in Figure 2a.

The relationships of seismic rock properties to this petrophysical interpretation of lithology, porosity and fluid type/saturation was established by using multi-well cross-plots and by generating forward models of intercept and gradient from the log data using Shuey's equation (Shuey 1985; Figures 2b and c). Gassman fluid substitution was performed to determine the magnitude of hydrocarbon effects (Smith et al 2003). Models for 38 API oil with low (200scf/bbl), medium (800scf/bbl) and high (1200scf/bbl) gas-oil ratio were constructed. The predicted velocity and density data for oils of these types use the pressure and temperature data from the wells and the equations in Batzle and Wang (1992).

Seismic data was inverted for relative extended elastic impedance (rEEI) using the method described in Went et al (2023) and well logs were used to verify the fidelity of the inversions. The method generates intercept impedance (AI) and gradient impedance (GI) from band limited impedance inversions of the near and far angle stacks. AI and GI are combined to generate an attribute rEEI at a cross plot rotation angle (chi) of 27°, an optimal angle to highlight changes in siliciclastic lithology and fluid (cf. Whitcombe et al 2004).

Petrophysical results and seismic inversion

The depth-related rock property trends for the well data used in this study are summarised in Figure 3. Acoustic impedance increases with depth below sea bed (TVDBSB) as a natural response to increased burial. At any given depth sands may show

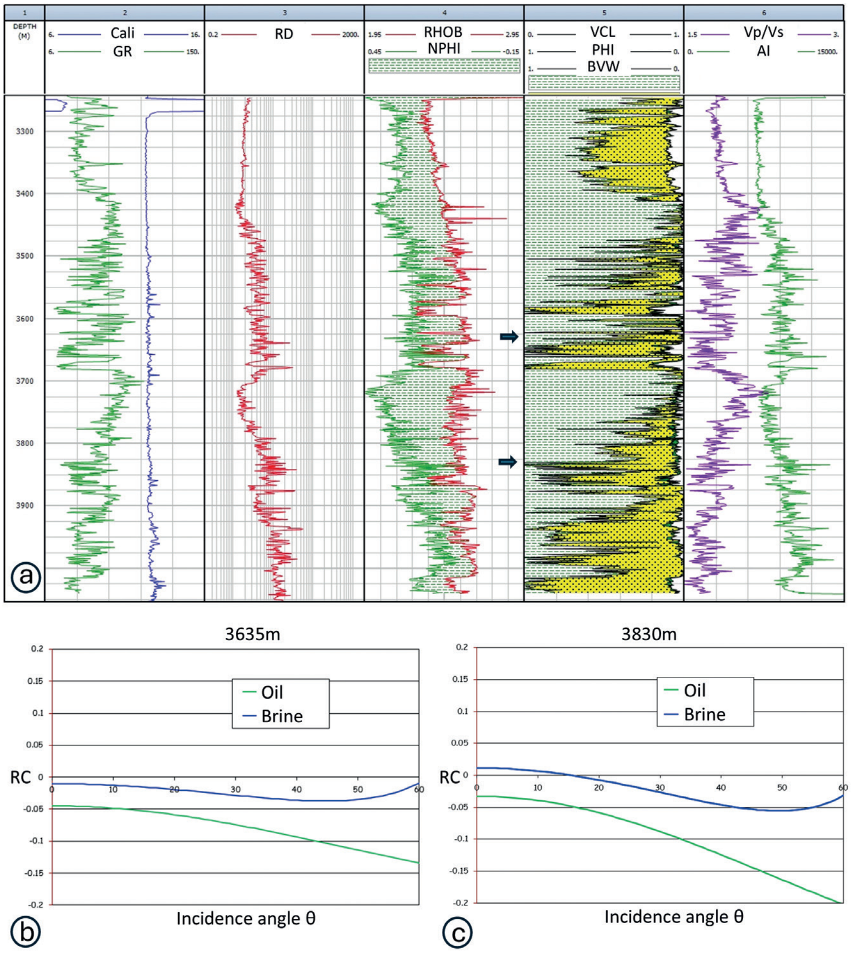

Figure 2 a) Example petrophysical analysis (CPI) of a deep-water offshore well. Note the close correlation of the Vp/Vs curve to the gamma ray curve and volume of shale. Acoustic impedance in sandstone is locally higher or lower than adjacent shale; b and c) angle-dependent forward reflectivity models for the shale over sand interfaces arrowed in the CPI.

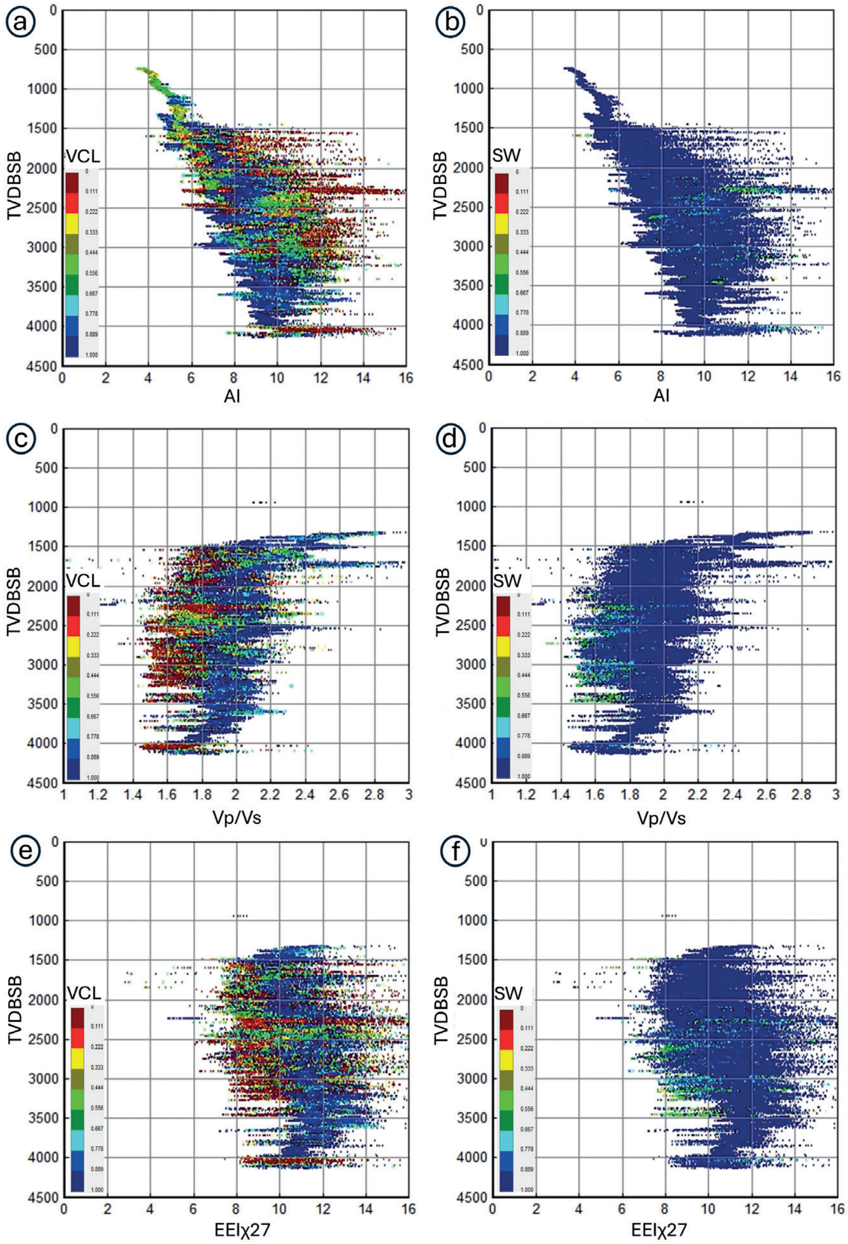

Figure 3 Depth of burial-related seismic rock property trends colour-coded by lithology and fluid type; a) acoustic impedance (AI) versus TVDBSB coded by volume of clay (VCL); b) acoustic impedance (AI) versus TVDBSB coded by water saturation (Sw); c) Vp/Vs versus TVDBSB coded by volume of clay (VCL); d) Vp/Vs versus TVDBSB coded by water saturation (Sw); e) extended elastic impedance (EEIχ27) versus TVDBSB coded by volume of clay (VCL); f) extended elastic impedance (EEIχ27) versus TVDBSB coded by water saturation (Sw). At a given depth lithology and fluid are better discriminated by Vp/Vs or EEI χ27 than acoustic impedance.

lower, similar or, more commonly, higher impedance than shales (Figure 3a). Hydrocarbon-bearing sandstones are not typically anomalous in terms of their acoustic impedance when compared to shales and brine sands at an equivalent depth (Figure 3b), and hence, are unlikely to form bright spots on the stack. Background Vp/Vs typically reduces from around 2 to 1.8 between 1500 m and 4000 m below sea bed. It is, however, lower in sandstones (reducing from 1.8 to 1.6) and higher for shales (reducing from 2.1 to 1.9) over this interval (Figure 3c). Hydrocarbon-bearing sandstones, at any one depth, tend to exhibit Vp/Vs values at the low end of the sandstone spectrum (Figure 3d), suggesting this would be a better attribute than acoustic impedance for identifying hydrocarbons directly. Extended elastic impedance at χ27 (EEI χ27) increases with burial depth, with porous sandstones typically showing lower values than shales at any given depth (Figure 3e). Porous hydrocarbon-bearing sandstones typically show among the lowest EEIχ27 values at any given depth (Figure 3f). Hence, EEIχ27 is considered to be the optimal attribute for identifying fluid type directly from the seismic data. The above burial-related trends are broadly comparable to those in other normally compacting sedimentary basins (e.g. Mur and Vernik 2022).

The P-velocity – density and Vp – Vs relationships are similar in both basins. The relationships are displayed in Figure 4 and show characteristics broadly comparable to those established globally (e.g. Gardner et al 1974, Greenberg and Castagna 1993, Went 2021). These trends are instrumental in determining offset-dependent reflectivity behaviour (Figure 2c and d). They also relate to porosity, which mostly decreases systematically with depth of burial (Figure 4c) (Ehrenberg and Nadeau 2005).

Intercept and gradient values determined from forward models of angle-dependent reflectivity from between 1800 and 3000 m below seabed in multiple wells are summarised in the well-data intercept – gradient cross plot in Figure 5a. This plot demonstrates

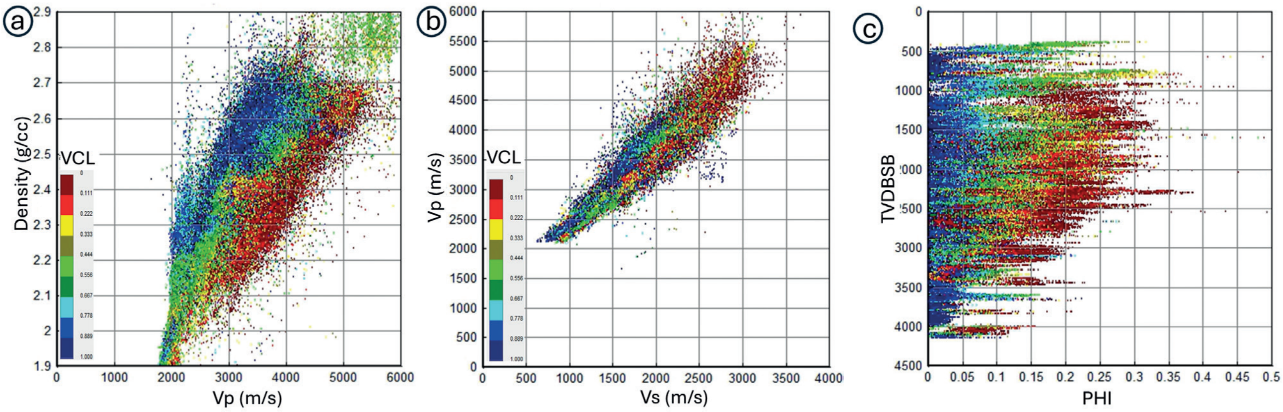

Figure 4 a) P-velocity (Vp) versus density colour-coded by volume of clay (VCL); b) Shear velocity (Vs) versus P-velocity (Vp) colour-coded by volume of clay (VCL); c) porosity (phi) versus burial depth (TVDBSB) colour-coded by volume of clay (VCL).

the control of both lithology and fluid on the intercept-gradient relationships. The modelled shale on shale interfaces generate an intercept-gradient trend that goes through the origin and which is oriented at a rotation angle (χ) of approximately 27°. This is the background trend. The modelled shale over brine sand interfaces show intercept gradient relationships that define a trend that does not go through the origin. The trend lies roughly parallel to the shale-shale (background) trend but which is offset to either the SW of the plot (shale over sand) or to the NE of the plot (sand over shale). This is the brine sand trend. Hydrocarbon presence lowers EEIχ27 and shifts the data points further to the SW of the plot (shale over sand). The compressibility of the hydrocarbon phase determines the magnitude of the modelled hydrocarbon effect. A light oil (38 API) with a low GOR shows a small departure from the brine trend. Increasing gas content results in greater separation of the hydrocarbon-bearing sands from the brine case and thereby increases the likelihood of direct detection from seismic (Figure 5a).

Seismic inversions for relative extended elastic impedance (rEEI) have been performed on selected 2D lines and 3D data sets to test for the detectability of lithology and fluid changes. Figure 5b shows an AI-GI cross plot from the Liberia basin over a brine well with oil shows. The cross plot is colour coded by EEIχ27 and mimics the well data cross plot. The challenge is to identify the shale, brine sand and hydrocarbon sand trends. The rEEI χ27 attribute clearly represents a look across the intercept-gradient cross plot perpendicular to the background trend (in the direction of the arrow in Figure 5b). Hence, seismic sections of rEEIχ27, or map form displays extracted from horizons, allow for the geometry of different types of anomaly to be observed. These displays may define anomalies related to geomorphological features, such as submarine channels, or anomalies which conform with depth-structure. As such they can be useful additional aids to estimating the rEEIχ27 thresholds for shale, brine sand and hydrocarbon sand. Figure 6 shows an rEEIχ27 inversion from a strike line in the Liberia basin. The section is dominated by red colours which point to low contrasts (mid-point values) in rEEIχ27, typical of the background trend or shale on shale reflectivity. The yellow and blue-dominated horizons (somewhat lower and higher values of rEEIχ27) are anomalous relative to the background trend and form a coherent interval in the lower part of the section. Calibration to the well confirms this is a sand-prone interval and that these responses relate to the brine sand trend. It may therefore be used to map the reservoir fairway in the seismic volume. The traces of hydrocarbon present in this well do not correlate with any changes in the elastic response; hence there is no calibrated hydrocarbon signal in this section.

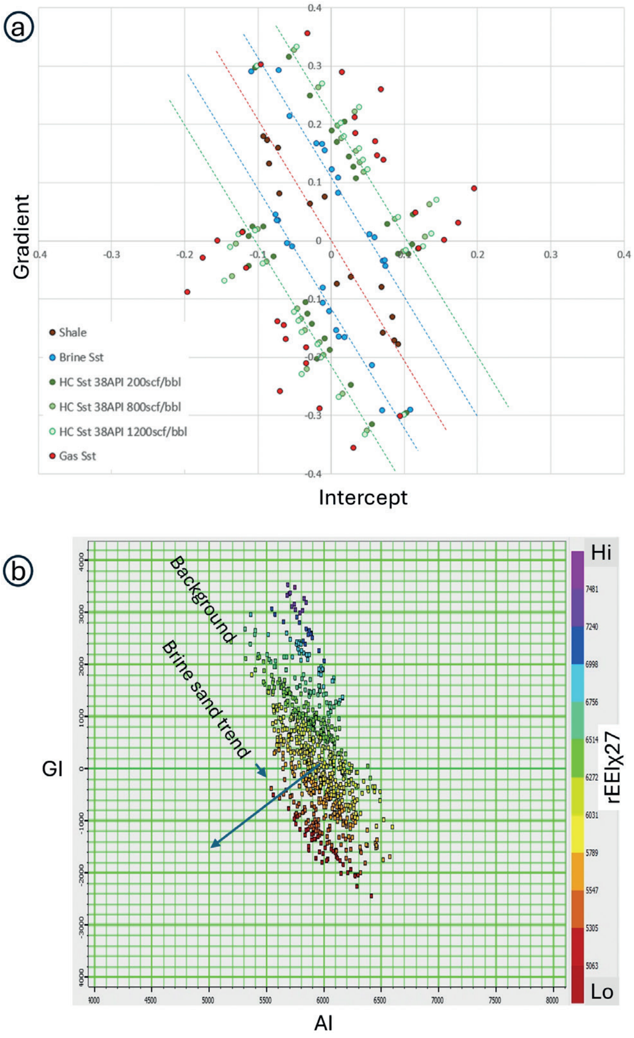

Figure 5 Intercept versus gradient cross plots: a) from well data in the Liberia basin, b) from seismic data over dry hole with shows in the Liberia basin. The well data cross plot shows the shale, brine sand and hydrocarbon sand trends. The anomaly present in the seismic data cross plot is a brine sand anomaly distinctly different to background shale trend.

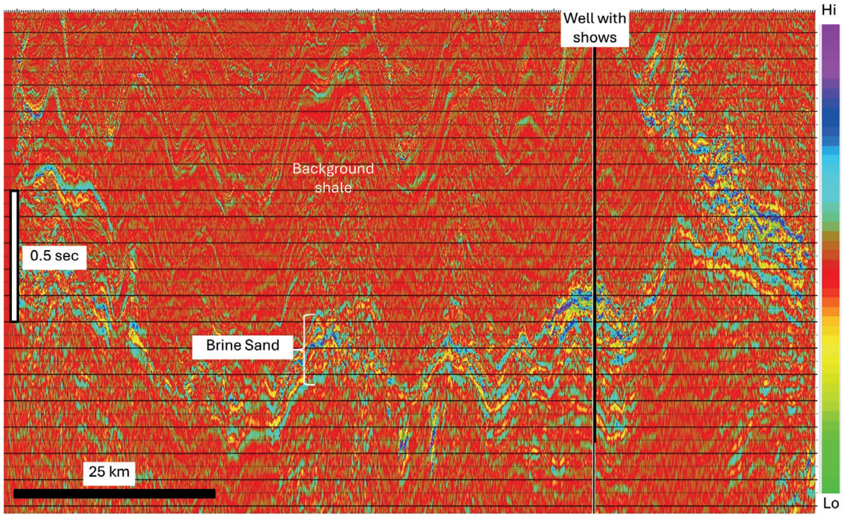

Figure 6 Seismic inversion for extended elastic impedance (rEEIχ27) in the Liberia Basin. The line shows a predominance of red, indicating low levels of impedance contrast, consistent with an interpretation of background shale. The lower part of the section shows strata coloured yellow and blue, indicative of a greater contrast in elastic impedance, interpreted as a predominantly brine-filled, sandstone-rich horizon, as confirmed by the well. The yellow blue responses in the top-right of the line highlight the presence of a younger sand fairway.

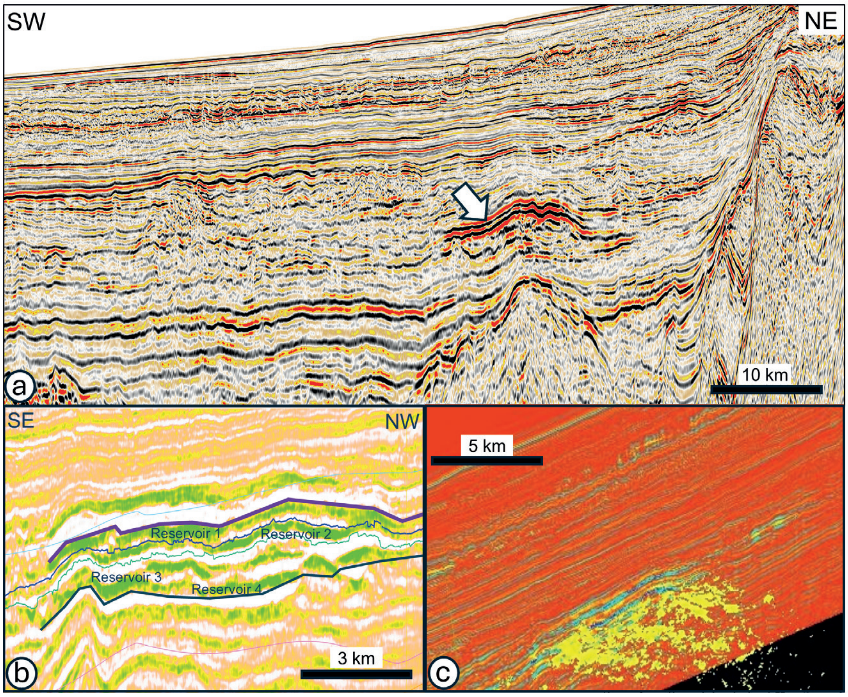

Figure 7 a) Oblique dip line showing rifted basement overlain by post-rift strata containing an antiformal structure, showing high seismic amplitudes (arrowed) that are interpreted as a mounded submarine fan sandstone complex; b) seismic inversion for rEEIχ27 co-rendered with the stack reveals low rEEI through four potential reservoirs within the sand complex; c) the rEEIχ27 anomalies broadly conform with the structure, suggesting a possible hydrocarbon response.

Application and discussion

The results above indicate that when appropriately evaluated, either through calibration to wells or through geological reasoning, the rEEIχ27 attribute displays can be used to determine the location of sand fairways and potentially hydrocarbon anomalies. On the right of Figure 6 an interval of younger strata shows moderately bright rEEIχ27, pinching out up-dip. The strength of the rEEI response is similar to that of the sand fairway penetrated by the well to the left. Hence, a brine sand interpretation is considered most likely. However, given the presence of oil in sands nearby, this younger sand fairway may also have been a path for hydrocarbon migration and local traps on this fairway may hold some oil which could be responsible for some of the slightly more anomalous rEEIχ27 values.

Figure 7a shows the full stack display of an oblique dip line from the Leonian basin. A prominent antiformal feature is interpreted as a sandstone-dominated submarine fan mound draped over a basement high. The stack amplitudes over this feature are strong. Seismic inversions for rEEIχ27 through this feature are illustrated in Figures 7b and c. In Figure 7b, stack reflectivity is combined with the rEEIχ27 attribute which highlights the presence of multiple stacked AVO anomalies. In Figure 7c the predominantly red colours are indicative of the background AVO trend, formed from shale on shale reflections. The less common discontinuous yellow layers are, by comparison, anomalous. Moderately low values of rEEIχ27 (weak yellow) are identified as brine sand anomalies whereas the stronger low values (strong yellow to green) present over the large sand mound show a broad conformance with structure and, collectively, may be considered a candidate fluid anomaly.

The premise of this article is that both brine sand and hydrocarbon sand can display as AVO anomalies. That is, changes in both lithology and fluid can shift the I-G trend away from the background. However, the cause of the shifts are somewhat different for lithology and fluid. The lithology control stems from the differences in the susceptibility of sand and shale to shear, which promotes a low Vp/Vs for sand and a high Vp/Vs for shale. The fluid effect, on the other hand, stems from the increased compressibility of sand in the presence of hydrocarbons (with little change in shear) which results in a lower AI and a lower Vp/Vs in hydrocarbon-filled sands compared to brine sand or shale. This is significant because it may be possible, in some cases, to detect these differing effects through comparison of AVO attributes that are known to be sensitive to fluid effects with those attributes that are not (Went 2025). In some basin plays the effect of lithology on AVO is negligible (e.g. Went et al 2025). In others, such as in this study area, the lithology effect is pronounced and should be clearly identified prior to making any prognosis of anomalies resulting from a lighter hydrocarbon fluid.

Conclusion

The Leonian and Liberian basins have well and seismic data which confirm the presence of a significant working petroleum system, with syn- and post-rift Cretaceous intervals containing excellent source rocks, reservoir sands and sealing shales. Traps are typically stratigraphic and prognosing which traps contain oil typically relies on analysis of amplitude variation with angle (AVA). Evaluation of seismic rock properties from well logs and seismic data in the Leonian and Liberian basins reveals a strong lithology control on AVA. Hence, the distinctive brine sand trend should be isolated from the background shale trend prior to prognosing an anomaly resulting from the presence of hydrocarbons.

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