Application of Quantitative Interpretation in De-risking Hydrocarbon Type: Implication for Shallow Water Exploration in EKEM Field, Niger Delta

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ABSTRACT

Hydrocarbon exploration and production in the Niger Delta has mainly been focused on the onshore, and deep-water plays, whilst the shallow water have in the past received relatively less attention. EKEM field has one of the largest oil reserves across the shallow water with five wells drilled penetrating ten hydrocarbon bearing reservoir and no production to date. Seismic reservoir characterization study is therefore required for an improved understanding of the reservoir fairway and most importantly fluid fill within prospective blocks in the field. Seismic amplitude analysis across key reservoirs levels suggests the likelihood of hydrocarbon accumulation within the key prospects, however an understanding of the hydrocarbon type across these prospective blocks away from well penetration is required. Rock physics feasibility study based on conditioned well logs was conducted and the results show that a distinction of oil and gas is possible using P-impedance and Vp/Vs ratio. Consequently, simultaneous inversion technique was deployed to derive these elastic properties from 3D seismic and well log data.

Keywords: Hydrocarbon, Inversion, Impedance, Prospect, Reservoir, Seismic

INTRODUCTION

EKEM field seats within the larger 'K Block' located offshore Nigeria, 5-20 km from the Eastern Niger delta coastline (Figure 1). The K Block extends over an area of some 900 km2 in a water depth of about 40 m. Fourteen wells have been drilled to date, all of which have encountered hydrocarbons, resulting in six discovered fields. None of the fields have been developed to date. The EKEM field is the largest oil field in the K Block and was discovered in the 70's. To date, five wells and two sidetracks (EKEM4ST1 and EKEM5ST1) have been drilled in the EKEM field. EKEM-001 was the discovery well, drilled in 1973, close to the axis of the main crestal collapse structure. EKEM- 002 (1975) and EKEM-003 (1982) were drilled as vertical appraisal wells on the western and southern flank, respectively. Deviated appraisal wells EKEM-004 and EKEM-004ST1 (eastern flank), and EKEM-005 and EKEM-005ST1 (north western flank) were drilled in 2004. The EKEM field has an expectation STOIIP of ca. 400 MMstb and GIIP of ca. 600 Bscf. The main hydrocarbon-bearing reservoirs are the B4000, D9000, E6000, E8800, E9900, F1000, F2200 and F3000 reservoirs. No fluids have been produced from the EKEM field to date, hence there is no historical reservoir performance information.

The many fault blocks and separate hydrocarbon- bearing reservoirs in EKEM continue to provide opportunity for Near Field Exploration (NFE) and appraisal opportunities requiring both Exploration and appraisal wells to be drilled to better quantify the uncertainties in volumes in-place and improve economic robustness of EKEM oil development. Seismic reservoir characterization study is therefore required for an improved understanding of the reservoir fairway and most importantly fluid typing within prospective blocks in the field.

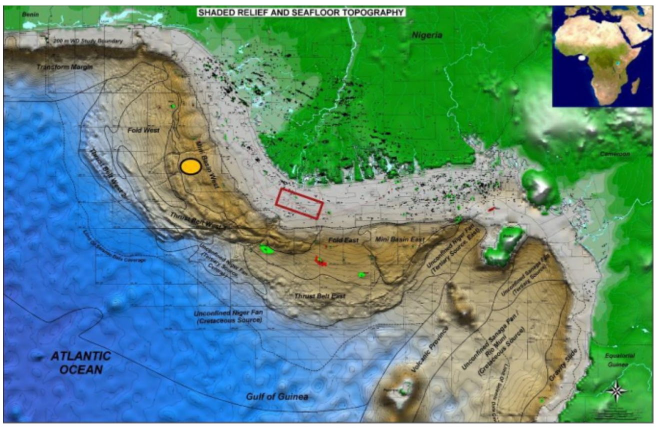

Figure 1: Niger delta map showing shaded relief and sea-floor topography. Study area shown in red box.

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GEOLOGICAL SETTING

Stratigraphy and Reservoir Geology

The reservoirs in the EKEM field form part of the paralic sequence of the Agbada formation, deposited during the late Miocene-early Pliocene ( ). The sequence studied during this project includes the reservoirs B2000 through G2000, spanning around 0.5 million years, from below a major flooding at (Me.1) at the base of reservoir E6000 to the following major flooding surface (Ge.1), located at the top of C7000 reservoir (Figure 2). Within the EKEM field, 8 parasequence sets could be identified from the top of the G2000 to the C7000 reservoir. These parasequence sets average 70 ft in thickness and are internally subdivided by flooding surfaces. Most of the parasequence sets start with a coarsening- upwards lower shoreface that rapidly progrades and evolves into massive sands that could represent stacked shoreface deposits and/or channels developed during the consecutive relative low sea level stage. Retrogradational patterns almost always coincide with the occurrence of thinning upwards heterolithic channel fill/lower shoreface deposits and a major flooding event at the top of the last unit.

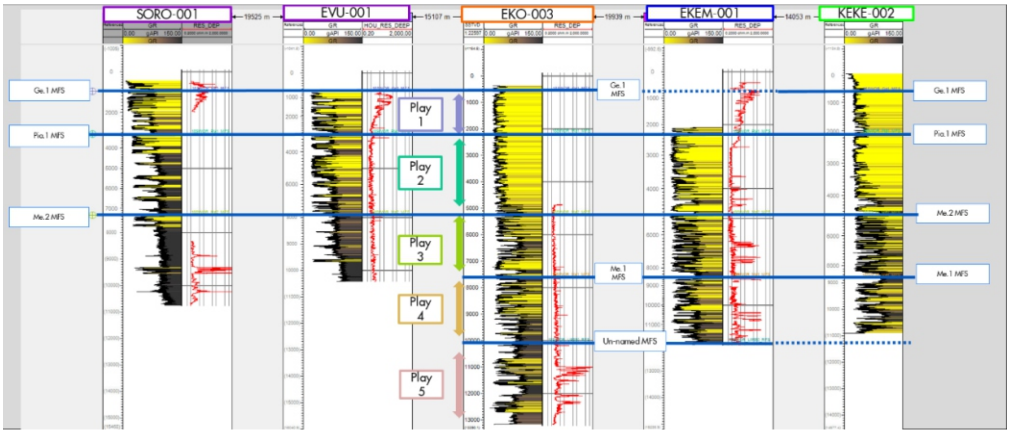

Figure 2: Stratigraphy flattened on each MFS top Marine flooding shales as continuous and correlateable seals across EKEM and neighboring fields within K-block.

Facies Interpretation

Facies have been interpreted on well logs, as no core data is yet available in EKEM. The facies interpretation is based on sequence stratigraphic principles and aims to distinguish flow units with different flow properties (e.g. kv/kh) from one another. The five facies classes used in the EKEM field are based on analogues from the Book Cliffs (Figure 3) and are itemized below:

- Shale is characterized by a continuously high gamma ray (GR) and a large separation between density and neutron logs. Shale is not part of net reservoir.
- Lower Shoreface have generally high GR, but less constant than in a shale facies, gradually changing to lower GR with more and more thin sand layers being interbedded in the shaly/silty background. The density-neutron separation is not constantly large but tapers upwards. LSF facies has a low vertical permeability but can be well connected laterally.
- Upper Shoreface (USF) has an overall low GR with a typical coarsening-upwards character. It can contain thin layers with higher GR. The density and neutron curves are overlying or slightly crossing over. USF facies is characterized by massive, laterally extensive sand bodies with a relatively high vertical permeability.
- Channel sand facies has a blocky, barrel- shaped GR character with no unique density-neutron character. Interbedded thin layers with higher GR (heterolithic facies) indicate an amalgamated channel complexes. Individual channel bodies may not be very extensive, but complexes of channels are laterally continuous over the extent of the field. Channel bodies cut into each other, thus ensuring a relatively high vertical

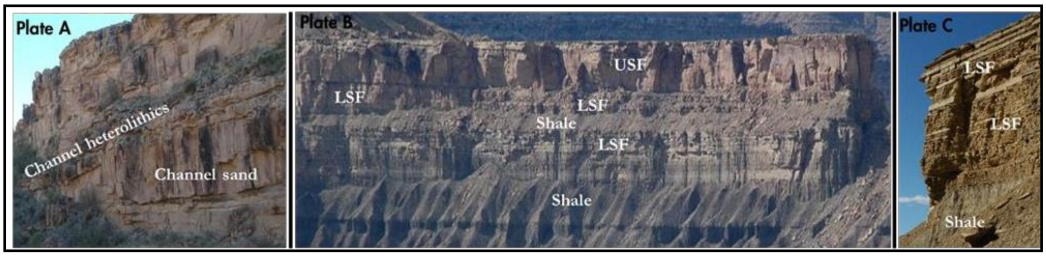

Figure 3: Outcrop analogues in Book Cliffs, Utah.

permeability.

- Channel heterolithics facies has a varying character, both high and low GR occur, but always in an overall ining upward pattern. The density and neutron curves do not or only occasionally cross over. Laterally accreting sands, tidal deposits and thin coastal plain deposits can all be part of the channel heterolithics facies. Vertical connectivity and vertical permeability are low. Figures 4 and 5 illustrates an ideal log character of the facies encountered with examples from EKEM well logs.

extensional faulting has given rise to a series of stacked reservoirs with various degrees of compartmentalization. The relationship between faults across the field indicates diachroneity in the structure development, with south dipping synthetic faults generally preceding antithetic faults, and migration of the crest location at depth. Growth faulting was found to be minimal within the crestal collapse, making the thickness of individual reservoirs and seals relatively constant across the field.

The faults have an arcuate geometry in map view, with

Facies			GR 0 150	CNL / FDC	Characteristics
Fluvial /Tidal Channel	Heterolithic				Serrated to smooth, thinning / fining-upward log profile.
	Sand Dominated				Sand dominated, some minor shales developed internally. Blocky log character. Density-neutron overlying.
Shoreface	Upper				Sand dominated, some minor shales, thickening / coarsening-upward log profile. Density-neutron overlying.
	Lower				Serrated thickening / coarsening-upward log profile. Heterolithic thin beds.
Shale					High GR, continuously wide separation in density-neutron. Evaluated as non-net in the petrophysical evaluation.

Figure 4: Definition of interpreted facies.

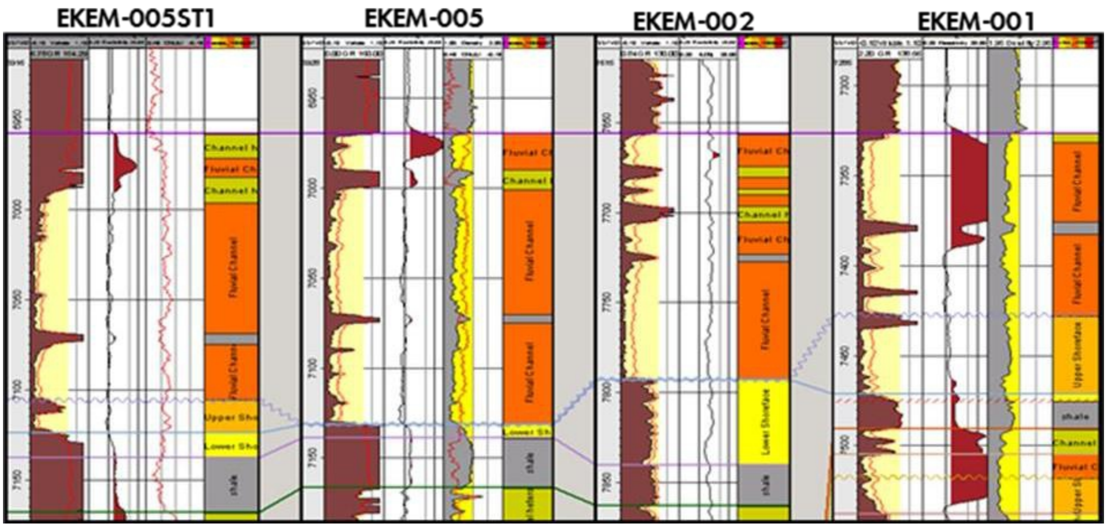

Figure 5: Example facies from E6000 reservoir.

Structural Geology

The EKEM reservoirs form part of a crestal collapsed rollover anticline with an 80º WNWESE trending axis and bounded by parallel arcuate "B- type" growth faults on the north and south (Figure 6). The structuration of the field took place in different stages as large accumulations of paralic sediments of the Agbada formation were deposited over marine ductile shales of the Akata formation, which forms the core of the roll-over anticline. The sequential deposition of coastal and marine deposits and complex synthetic faults being convex to the south (depositional direction) and antithetic faults convex to the north. The maximum vertical displacement of these arcuate faults occurs at the middle and decreases toward their tips. The sealing capacity of the faults is thought to be determined by the shale gauge ratio, which depends on fault throw dimension and amount of clay or shale that has been smeared along the fault plane of adjacent reservoir sands. In the EKEM collapsed crest, antithetic and synthetic faults intersect each other at their tip ends. It appears as if the dip

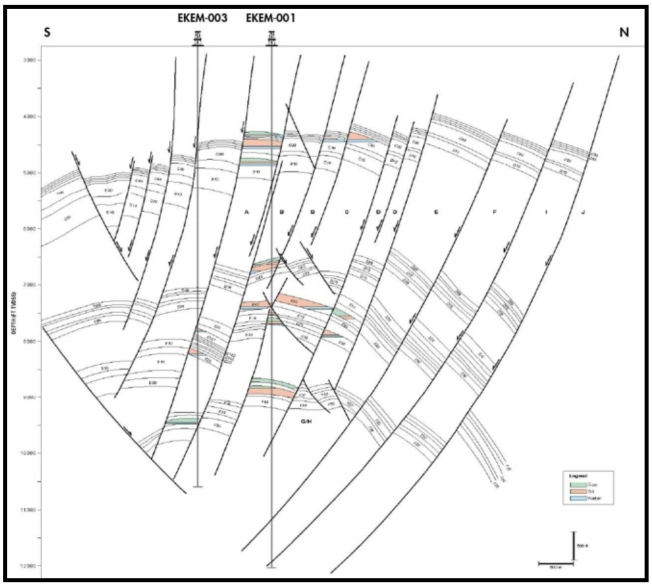

Figure 6: General perspective of EKEM crestal collapse structure.

direction of these faults changes along their strike, creating 'flipping' faults. At an intersection point, the vertical displacement along such a fault is minimal, and hence the sealing potential is reduced. The locations of the flip points are consistent throughout the stratigraphy and are believed to be caused by deep-seated N-S structural features.

Trapping

The majority of the trap-styles in the EKEM field are of a dipping fault-sealed type. The northern portion of the structure is dominated by south dipping synthetic faults cutting north-dipping layers, thus creating fault traps in the up-dip boundary of downthrown blocks. Wells intersecting this type of trap include EKEM-005, EKEM-004, and EKEM-002 (Figure 7). In the central part of the structure, including the crest, conjugate faults predominate, of which the sealing capacity is less certain. EKEM-001 is located slightly off the crest at C, D and E levels, and on the crest at the F reservoir level intersecting these traps. EKEM-003 intersects similar traps as the northern wells, but with both the layers and the faults predominantly dipping to the south, thus creating fault dependent traps in the up-dip boundary of up thrown blocks. The steepness of the layers increases with depth, so traps generally have a smaller area and larger vertical closure going down in the stratigraphy. At the C level, traps are flat and extensive, but at the F level, traps are steep and narrower.

The top structural map below shows fault dependent closures for the F3000 level that are potential exploration prospects. The main thrust of this paper showcases quantitative interpretation technique that was adopted in de-risking hydrocarbon fluid type across these prospects with the F3000 reservoir level being the case study for this paper.

DATA AVAILABILITY

The focus of this study is to use 3D seismic angle stacks and well data to characterize reservoir within the fault assisted prospects within the F3000 level, particularly to delineate the presence and type of hydrocarbon (gas or oil). The data sets available for this study include a full-stack PSDM 3D seismic volume, pre-stack gathers and associated partial- angle stacks of near (0°–15°), mid (15°– 30°), and far (30°–45°) angles with a recorded duration of 5s and sampled at 4 ms. The signal-to-noise ratio is good, with a vertical resolution in the focus interval of interest of about 39ft (12m). Seismic data conditioning was applied to remove noise and to correct for time misalignment. The wells in EKEM field generally have full suites of wireline logs, although shear sonic log was acquired only in EKEM-004. This well formed the main

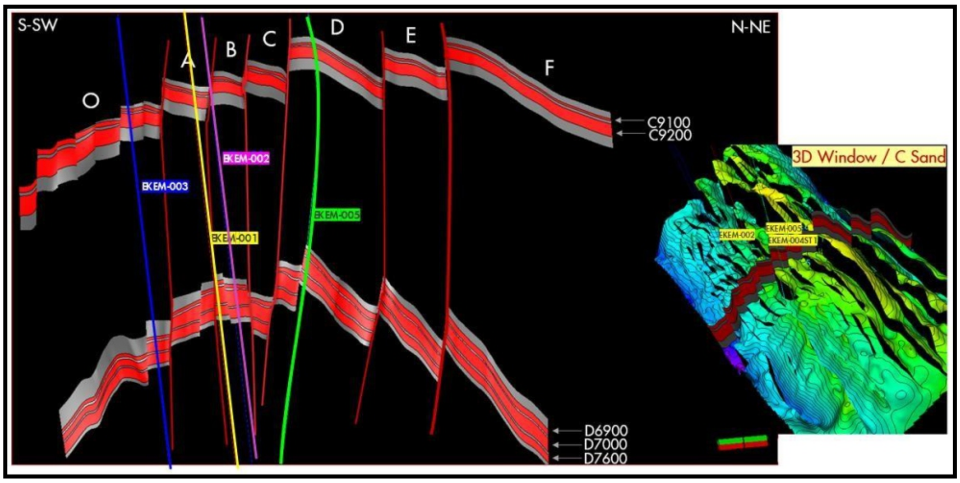

Figure 7: Cross section across the EKEM field illustrating the fault dependent trapping style.

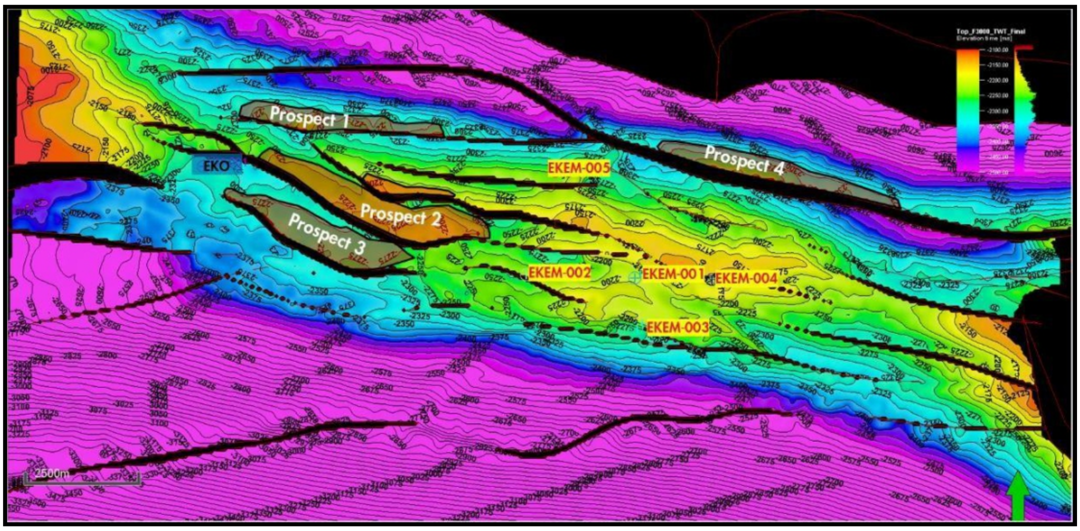

Figure 8: Top structure map showing potential prospects at the F3000 level.

input into the modelling workflow. Fluid typing within the prove blocks was largely based on integrating well logs (resistivity, density & neutron) and side wall sample. The fluid distribution plot below for the F3000 reservoir shows the encountered fluid type at well locations. This data formed the basis for calibrating results from the seismic study.

help polarize oil versus gas within the prospects. The simultaneous inversion workflow was adopted, and rigorously quality controlled to produce fit for purpose elastic rock property models calibrated to well log data and consistent with geological information. The study revealed that P-impedance and Vp/Vs volumes can be interactively integrated to de-risk hydrocarbon fluid types.

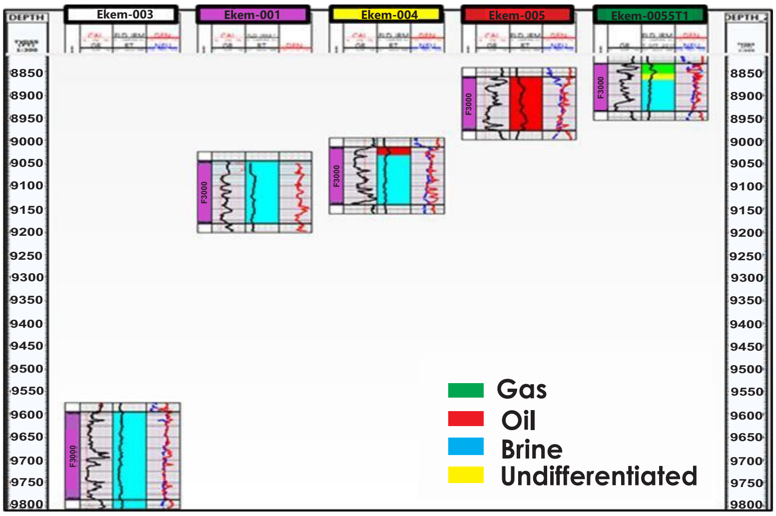

Figure 9: Hydrocarbon fluid distribution plot for F3000 reservoir.

METHODOLOGY

Firstly, the evaluation of amplitude variation with offset (AVO) or in this case angle (AVA) provides a powerful technique in this study for the assessment of direct hydrocarbon indication (DHI) for the prospects within EKEM field. Secondly, simultaneous AVO inversion was built using the partial-angle stack seismic volumes (near, mid & far) inverting for seismic elastic properties that can

DHI Assessment

Direct hydrocarbon Indicators (DHI) are seismic amplitude anomalies caused by the presence of hydrocarbons (Roden et al., 2014). The amplitude map below for the F3000 show amplitude anomalies that conform to structure which are indicative of hydrocarbon presence at the prospect locations. These anomalies are consistent with amplitude signatures at the proven blocks with well penetrations. Wells drilled in the vicinity of this prospects establishes a) reservoir presences and properties b) a well-defined structure and most importantly c) hydrocarbon presence indicative of a working petroleum system. Hence the overall geologic chance of success for these prospects was adjudged to be high.

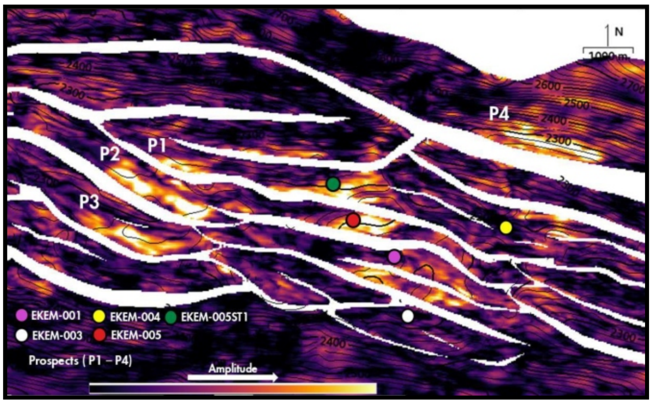

Figure 10: RMS amplitude map from the full stack seismic volume. High amplitude anomalies are seen at the prospects –P1 to P4 consistent with amplitude at the proven blocks.

The AVO behavior based on amplitudes from seismic angle stack and from pre-stack gathers taken from the prospective blocks indicates a Class II/III anomaly consistent with the AVO response at the proven blocks where wells have been drilled (Figures 11 and 12). This therefore provides confidence of hydrocarbon presence at the prospective blocks. Haven established the presence of hydrocarbon at the prospect location the key question yet to be answered is what type of hydrocarbon are present in these prospects - gas or oil?

Simultaneous Inversion

Simultaneous AVO inversion utilizes a set of angle stacks, each with their own wavelet and low frequency models for P-impedance, S-impedance and density to estimate simultaneously inversion volumes for P-impedance, S-impedance and Vp/Vs. The choice of this elastic attribute was largely based on rock physics cross plots that shows a clear discrimination of different fluid types (see Figure 13).

Feasibility study: Rock physics cross plot based on P-impedance and Vp/Vs reveals that hydrocarbon distinctions can be made by interactively interpreting P-impedance and Vp/Vs models where P-impedance shows a distinction of hydrocarbon from non-hydrocarbon bearing fluids while Vp/Vs ratio distinguishes gas bearing reservoirs from oil reservoirs. The integration of these two models (P-impedance and Vp/Vs ratio) can be compared respectively to the application of resistivity and density-neutron logs for fluid typing in formation evaluation.

Wavelet Estimation: Well to seismic tie was carried out on the wells for all seismic volumes. Three wavelets were estimated from the near, mid, and far sub-stack seismic volumes. The character of all three estimated wavelets are consistent with the seismic data – zero phased with stable amplitude over the seismic frequency band (Figure 14). The extracted wavelets have a length of ca.120 ms and a phase of approximately 180° across the usable frequency spectrum. Wavelets are important components in inversion workflows and have a significant effect on the quality of the inversion result.

Low Frequency Model: To obtain formation properties from reflectivity seismic, the conversion to absolute acoustic impedance, requires frequencies down to zero,

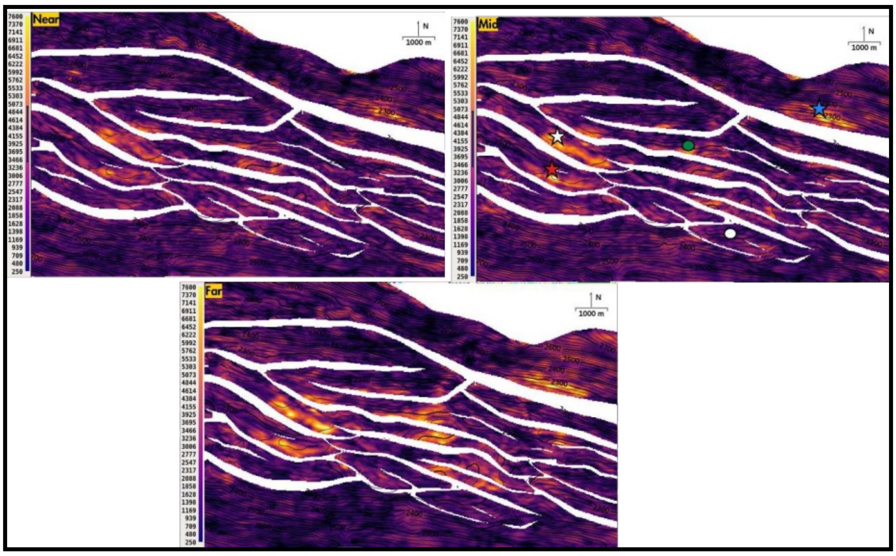

Figure 11: RMS Amplitude extraction for the sub-stack seismic volumes showing amplitude increasing with offset (angle) from Near to Far sub-stacks across the prospective blocks. Star symbol (at prospect locations) and cycle (proven blocks)- these are locations where pre-stack gathers were analyzed.

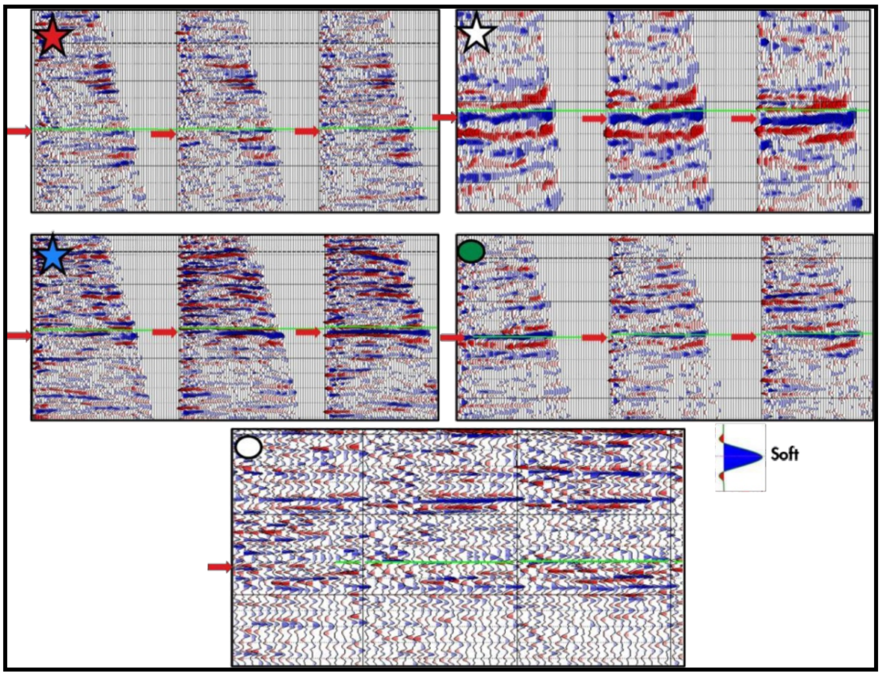

Figure 12: Pre-stack gathers at the prospect locations(stars) (see Mid amplitude map above) show Class II/III AVO anomalies consistent with AVO behavior at the well location (cycles). Observe the flat AVO response at the location with white cycle where brine bearing sand was encountered by EKEM-003 well (see Figure 9). Red arrow on the gathers indicates F3000 level.

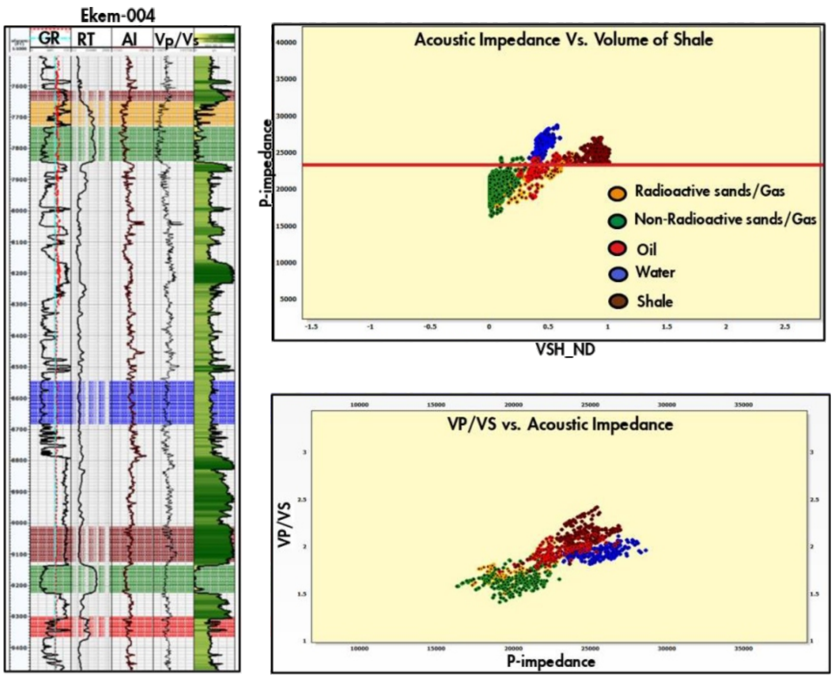

Figure 13: Cross plot of P-impedance and Volume of Shale shows a separation of hydrocarbon and non- hydrocarbon along the P-impedance axis. While cross plot of Vp/Vs and P-impedance shows a separation of gas from oil bearing reservoirs on the Vp/Vs axis. The data displayed on the cross plot are highlighted on the well log.

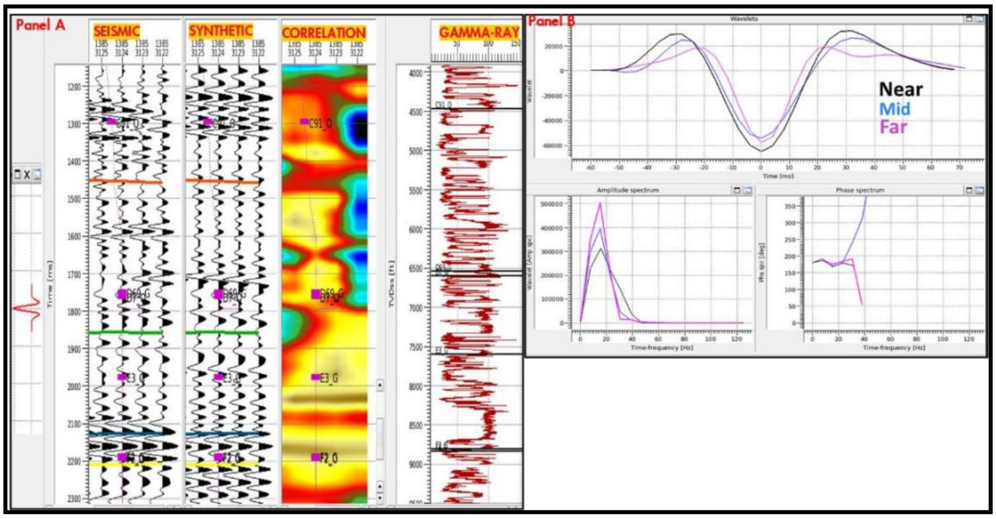

Figure 14: Well-to seismic tie with derived wavelets for sub-stack volumes.

lower than that contained in the input seismic (Brown, 2011, Ronghe and Surarat, 2002, Humberto et al., 2017). The absolute acoustic impedance was obtained by combing relative acoustic impedance model from seismic frequency range with a low frequency model (Figure 14) derived from well data, resulting in a full band inverted impedance volume. Low frequency models were built for P-impedance, S- impedance and Vp/Vs ratio.

bearing sands and the white background are brine sands or shale. While on the Vp/Vs maps, the low Vp/Vs values shown in green are indicative of gas bearing sands considering that gas have very low Vp/Vs values and the background (white) are oil, brine, or shale prone areas. Hence by matching the impedance map where low P-impedance values (red) are indicative of hydrocarbon

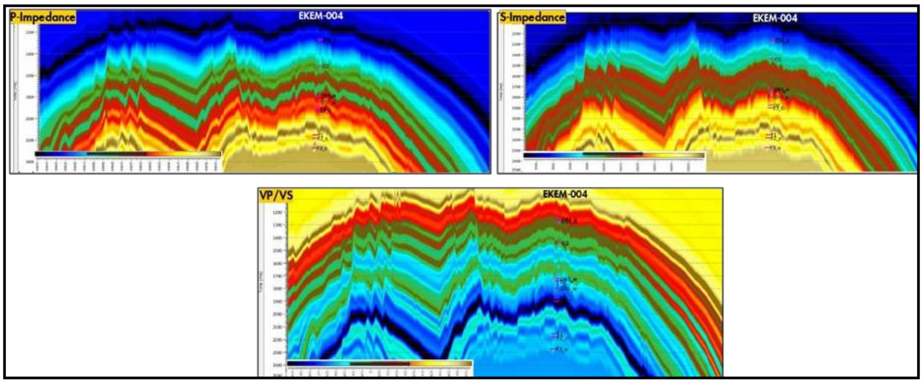

Figure 15: Low frequency models of P-impedance, S-impedance and Vp/Vs calibrated at well location.

RESULTS AND DISCUSSION

Hydrocarbon typing

Integrating the map displays of P-impedance and Vp/Vs inversion models (Figure 15) proof to be useful in discriminating gas bearing sands from oil bearing reservoirs. Based on the feasibility cross plot (Figure 13) that reveals hydrocarbon bearing sands can be distinguished from brine sands and shale, suggesting that on the P-impedance map the red patches with low p-impedance values are hydrocarbon bearing sands and the equivalent location on the Vp/Vs map are white reveals that the reservoir sands at that prospect location are oil prone. The model was calibrated at the proven blocks with well penetration where the P-impedance and Vp/Vs model predicted the exact fluids encountered in the wells particularly for EKEM-1, EKEM-003, EKEM -004 and EKEM-005St1 (see hydrocarbon distribution plot- Figure 9).

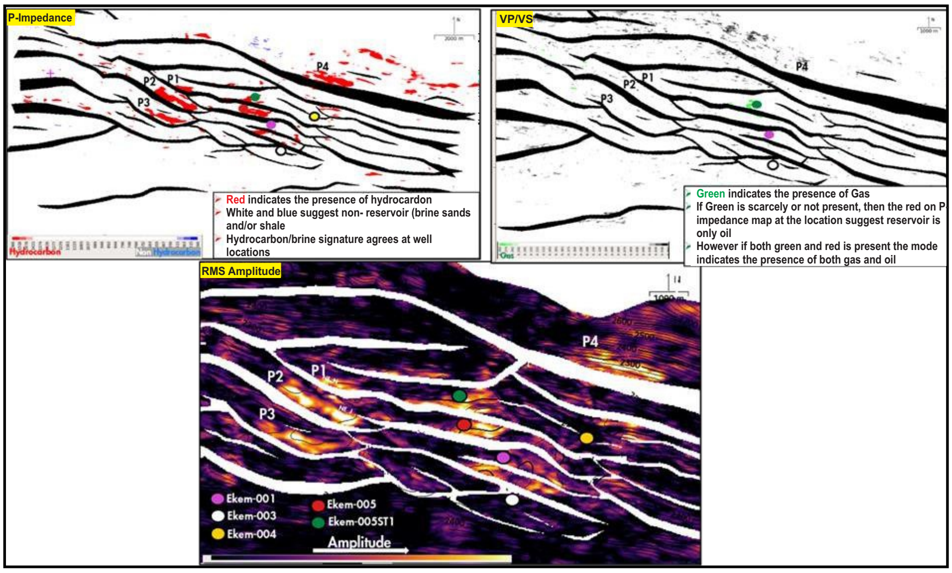

Figure 16: P-impedance and Vp/Vs maps interactively used to discriminate gas and oil-bearing sands at the prospect locations (P1 – P4) that matches high amplitude anomalies observed from the RMS amplitude map.

CONCLUSIONS

The EKEM field located in the shallow water space of the Niger Delta holds significance promise for future oil and gas exploration. The field is characterized by structurally complex faulting pattern that appear to have compartmentalized the reservoirs into different blocks leaving untested blocks with potential exploration and appraisal opportunities. Considering that wells have been drilled in the vicinity of this prospects confirms a) reservoir presences and properties b) a well-defined structure and most importantly c) hydrocarbon presence indicative of a working petroleum system. Hence increasing the chance factor of finding reservoirs at the prospect blocks. One key uncertainty within the prospective blocks is de-risking hydrocarbon type. Integrating AVO analysis and pre-stack simultaneous inversion model revealed encouraging results. The AVO analysis of sub-stacks maps and pre-stack gathers show classic Class II/III AVO response indicative of hydrocarbon presence at the prospect locations. Simultaneous inversion model collaborated the AVO results and further provided an opportunity of polarizing gas and oil-bearing reservoirs at these blocks. The P-impedance model was used to discriminate between the hydrocarbon bearing reservoirs from the non-reservoir (brine sands and shale). While for oil and gas differentiation, the Vp/Vs model imaged the prospective blocks that are gas bearing. The integration of these two models (P-impedance and Vp/Vs ratio) can be compared respectively to the application of resistivity and density-neutron logs for fluid typing in formation evaluation. This paper illustrates this technique for one of the key reservoir levels in EKEM field – the F3000 reservoir. The seismic reservoir characterization study indicates that all 4 exploration prospects (P1, P2, P3 & P4) in F3000 are mostly oil prone. As part of EKEM prospect maturation plan, result from this study was used to improve its probability of success (POS) and high grade commercial prospectivity of the blocks.

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