Prospectivity of the Nigeria-São Tomé & Príncipe Joint Development Zone – an integrated geoscience approach

Matthew Tyrrell[1*], Muhammad Tammanai[1] and Sam Hosseinzadeh[1] present a dataset over a prolific hydrocarbon producing region.

The area of the Joint Development Zone (JDZ), between Nigeria and São Tomé & Príncipe, lies on the southern front of the Niger Delta. The delta is a prolific hydrocarbon-producing region with numerous commercial discoveries of oil, condensate and gas. The JDZ is divided into 11 hydrocarbon exploration blocks that have undergone competitive bid licence rounds; notably in 2004 when nine blocks were offered and a year later when five blocks were offered.

To date, eight wells have been drilled within the waters of the JDZ by major international oil companies and all are believed to have encountered hydrocarbons. Obo-1, Obo-2 and Enitimi-1 wells encountered oil and gas whilst Lemba-1X, Malanza-1X, Oki East-1X, Bomu-1 and Kina-1XR found gas. These eight wells have only targeted structural traps – six of these wells have been drilled on hanging walls of the toe-thrusts, while only two (Obo-1 and -2) have targeted reservoirs within a footwall, encountering oil.

In 2002, PGS acquired a 3000 km^2 multi-client 3D seismic dataset over the northern part of the JDZ waters; this dataset was then reprocessed in 2007 through a Pre-Stack Time Migration sequence. The seismic survey covers Blocks 1 to 4 (and partially Blocks 5 and 6) covering the eight exploration wells and is situated in water depths of between 1500 and 2300 m.

Geological setting

The JDZ is situated over the outer compressional zone of the Niger Delta. This zone is typically associated with east-west trending toe thrusts that are apparent within the Agbada Formation and are seen detaching within the Akata mobile shales (Figure 1).

In this outer distal section of the delta two formations are present; in the lower part of the stratigraphic section is the Akata Formation, comprised of deep-water muds whilst the upper part of the section consists of the deltaic sand and shale sequences of the Agbada Formation. Deposits of the

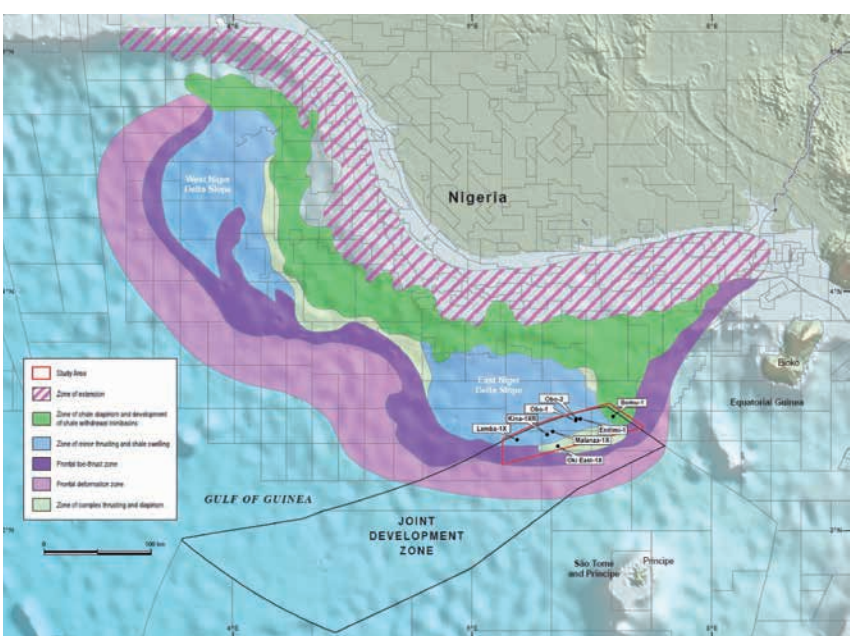

Figure 1 Map showing the tectonic zones of the Niger Delta together with the location of the Joint Development Zone (black outline), the PGS multi-client 3D seismic survey study area (red outline) and the location of the eight study wells.

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coastal dominated Benin Formation, which typically overlie the Agbada Formation, are not present in this distal setting (Corredor et al., 2005).

An integrated interpretation approach

In order to accurately assess the results of the recently drilled exploration wells and to determine the hydrocarbon prospectivity of the area, PGS adopted an integrated geoscience approach that incorporates the recently reprocessed 3D seismic volume together with the processed results of the operator well log data and reports.

Well data integration and interpretation

The operator well log data from the eight drilled wells was catalogued, digitized and processed to generate a workstation-ready log suite. The processed well log data then underwent petrophysical analysis to determine reservoir and fluid properties and CPI (Computer Processed Interpretation) log sets were generated. The results of the petrophysical work confirmed the log properties of discovered hydrocarbons and allowed an assessment of net-to-gross ratios, reservoir qualities and fluid-fill responses and also provided input parameters for quantitative interpretation work.

The workstation-ready log suites for the eight wells were then interpreted using sequence stratigraphic techniques, corroborated with operator's biostratigraphic report data. This approach enabled the identification of stacking patterns that correspond to relative sea-level controlled depositional packages as well as thrust-related unconformities (Figure 2).

In the uppermost part of many of the sequences identified, the log patterns suggest that sediment supply began to exceed accommodation space as demonstrated by occurences of coarsening upward sandstone bodies that may be indicative of higher energy depositional processes. Here, the sediments are assigned to a highstand systems tract and the depositional environments are interpreted to be lowermost shoreface dominated. These highstand sandstone bodies have unconformable tops where they are overlain by deeper water mudstones.

In the middle and lower part of each sequence, abundant accommodation space resulted in the deposition of sands in mass flow depositional processes. Here, the sediments are assigned to a transgressive or possibly lowstand systems tract and the depositional environments are interpreted to be offshore transition or outer shelf dominated. Stacked, fining-upward well log characteristics indicative of amalgamated channel deposits are seen in many wells within these systems tracts (Chapin, 2002).

The sequence boundaries identifiable from log data and deemed indicative of major regional events, are the transgressive mudstones that uncomformably overlie the shallower water highstand deposits. These transgressive mudstones typically have high gamma ray responses and slow sonic velocities and they are expected to be time synchronous and

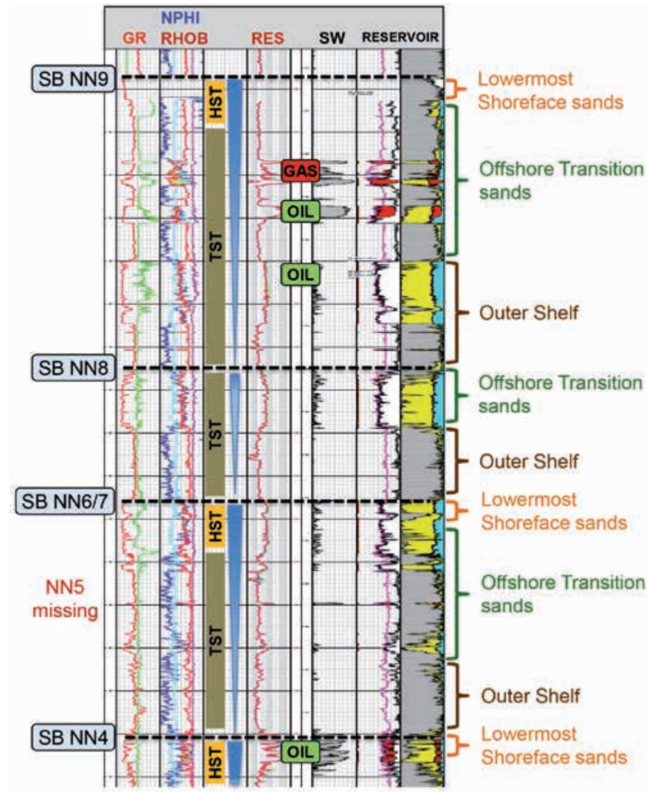

Figure 2 *An example of a processed, workstation-ready well log from the study showing the sequence stratigraphic and depositional environment interpretation together with encountered hydrocarbons.*

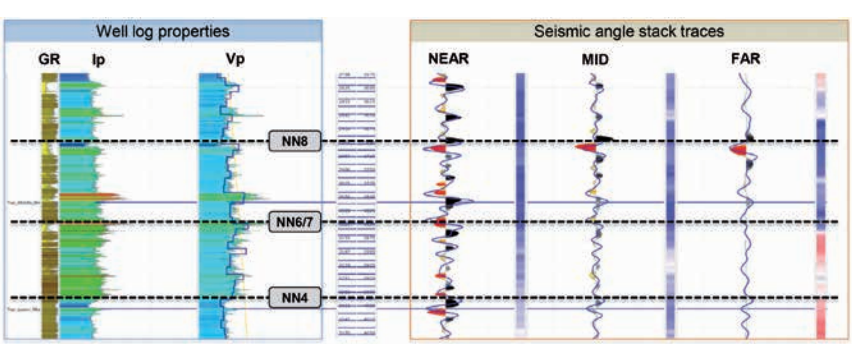

Figure 3 *An example of the pre-stack well-to-seismic tie.*

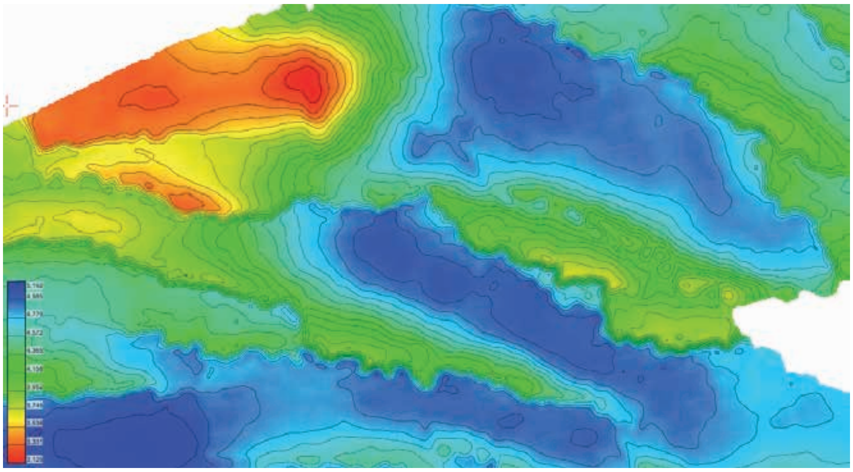

Figure 4 *An example of a two-way time horizon surface indicating the fault orientations and structures of the toe-thrust and diapiritic shale zones. It is these structures that provide the migration pathways and trapping mechanisms for the encountered hydrocarbons.*

regionally correlatable events (Reijers, 2011). In addition to these transgressive mudstones, toe-thrust controlled unconformities were identified using biostratigraphic data together with correlation with unconformities seen in the seismic data.

To allow correlations to other parts of the Niger Delta as well as nearby exploration hotspots in São Tomé & Príncipe and Equatorial Guinea, a nannofossil zone nomenclature (NN) was assigned to each of the transgressive surfaces (Martini, 1971). Where available, operator biostratigraphic report data was used to guide the assignment of these zones.

Well to seismic tie

Wells have been tied to the pre-stack seismic data using available operator checkshot and VSP information together with the elastic attribute logs (p- and s-wave velocities) from the processed well data suite. Where necessary, small time-to-depth adjustments have been applied to allow for more accurate correlation between the seismic trace events and well log elastic attributes (Figure 3).

Identification and extrapolation of sequences and depositional facies in the 3D seismic volume

With a depositional sequence framework in place, together with an accurate well-to-seismic tie, the sequence boundary transgressive surfaces identified in the wells could be associated with seismic reflectors and unconformities in the full stack 3D seismic volume. The transgressive mudstones that are interpreted to bound sequences in the well log data, have been picked as unconformities in the seismic data and these are seen as continuous, high-amplitude reflectors. When extrapolated away from well control, throughout the seismic volume, these reflectors prove to be regionally extensive, confirming them as regional transgressive events.

Of the seven sequence boundaries identified within the well interpretation, four regional flooding surfaces have been picked in the 3D seismic volume across the JDZ study area (Figure 4). In addition to the seabed and the Top Akata Shale horizons, the picked flooding surfaces were Messinian (NN11b), Near Top Tortonian (NN11a), Intra-Tortonian (NN9) and Top Lower Miocene (NN4).

The sequence constrained interpretation of the well log data has shown the presence of lowermost shoreface sands within the highstand systems tracts, immediately below transgressive surfaces and offshore transition to outer shelf mass flow sands, fans and channels within the transgressive or lowstand systems tracts. Within the seismic horizon framework these depositional facies can be identified locally at the wellbores although due to post-depositional thrusting, the extrapolation of these seismic facies characteristics away from wellbore control is difficult and may be less reliable.

Petroleum systems and plays

Reservoirs

The results from this interpretation study, integrating both well and seismic data, have shown that the depositional setting of the Agbada Formation within the area of the JDZ multi-client 3D is predominantly outer shelf to pro-delta.

Interpretation carried out on processed log data for the eight wells has identified that the most sand-prone facies belong to lowstand or transgressive systems tract outer shelf mass flow deposits (with evidence for channels and fans) and highstand systems tracts lowermost shoreface deposits. The most mud-prone facies belong to lowstand or transgressive systems tract deep water deposits.

From the interpretation work carried out on the 3D seismic volume, the most continuous reservoirs are thought to be outer shelf mass-flow sands deposited during periods of transgression and numerous sinuous channels and mass-flow lobes and fans can be identified and mapped throughout the Agbada section.

Within the study area, reservoir rocks can therefore be categorized and are expected to be present as part of:

- Highstand systems tract lowermost shoreface sandstone deposits

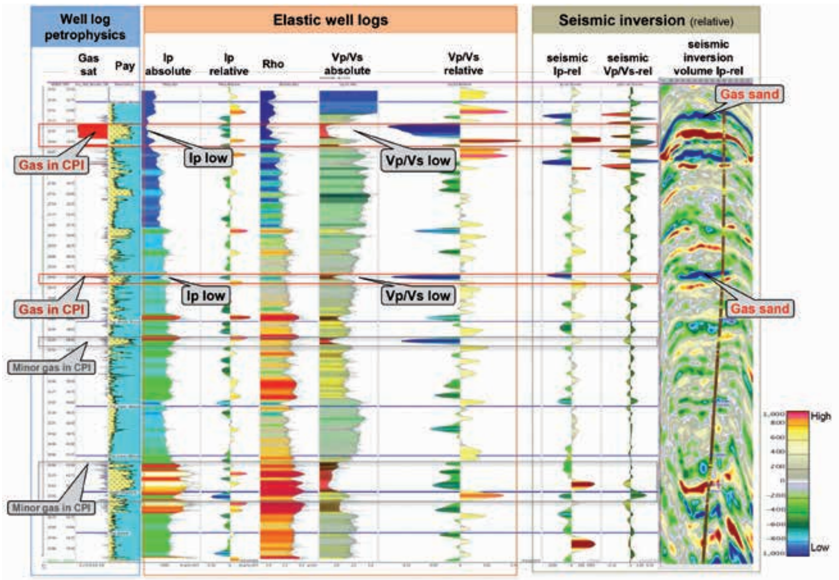

Figure 5 *An example of a well log elastic attribute to seismic inversion volume comparison display showing the correlation between the presence of hydrocarbons and the seismic inversion volume responses.*

- Transgressive systems tract pro-delta/offshore transition mass flow sandstone deposits with channel, fan or lobe geometries.
- Transgressive or lowstand systems tract outer shelf mass flow sandstone deposits with channel, fan or lobe geometries.

Analysis of the wireline log data provides some evidence that the sandstones of the highstand systems tract lowermost shoreface deposits may possess the best reservoir qualities.

Source rocks

Within the area of the JDZ multi-client 3D survey the Akata Formation is taken to be the deep-water mudstones beneath the detachment zone with the overlying strata assigned to the Agbada Formation.

The primary source rock within the JDZ area is interpreted to be the shales of the Akata Formation, which are shown to be approximately 2000 to 3000 m thick. The Akata Formation has not been penetrated by the eight study wells and thus no direct source rock data or properties are available.

Well log analysis also indicates that a secondary source rock may be present within the intra-formational mudstones of the lower part of the Agbada Formation. This section has been penetrated by the eight study wells and interpretation of this data shows that the intra-formational mudstones with the best source potential are lowstand or early transgressive systems tract deposits associated with the cyclical flooding of the delta.

Present-day oil window estimation

Six of the eight wells available for this study had corrected bottom-hole temperature available. This data was used in conjunction with the depth converted seismic horizons to establish a present-day geothermal gradient which, when combined with interpreted seismic grids, allowed estimation of present-day temperatures throughout the 3D seismic volume.

Optimal expected present-day oil window temperatures are taken to be between 70 °C and 120 °C, with the expulsion temperature considered to be 110 °C. Using the present-day geothermal gradient values, the vertical depths that are calculated to be at 70 °C and 120 °C have been marked as the top and base of the present-day oil window together with the 110 °C isotherm, below which significant expulsion of oil is expected to occur.

Two different possible geothermal gradient cases have been evaluated to provide oil generation windows, with the assumption that burial depths are greatest at present-day. Using a geothermal gradient of 35 °C/km, the present-day oil window has been estimated between 1900 m to 3300 m below the seabed. Similarly for a geothermal gradient of 40 °C/km, the oil window has been estimated to exist between 1650 m to 2900 m below seabed.

The results of the present-day oil window estimation indicate that the upper part of Akata Formation and lower part of Agbada Formation are within the present-day oil window.

Quantitative seismic interpretation (QI)

Pre-stack seismic inversion was conducted on the full extent of the survey to produce elastic properties; relative and absolute acoustic and shear impedance (Ip and Is) and P-wave and S-wave velocity ratio (Vp/Vs).

Interpretation was then performed on the derived seismic volumes. This process included the calibration of known reservoir fluids from the operator well results, together with interpreted reservoir fluids from the petrophysical interpretation, to identify further hydrocarbon accumulations away from existing well bores (Figure 5).

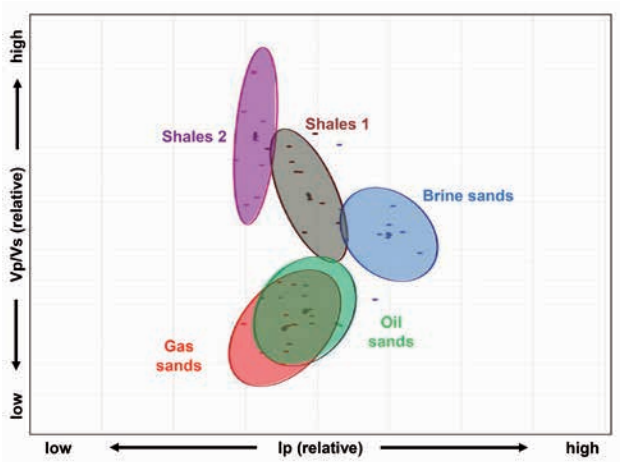

***Figure 6** A cross-plot comparing Vp/Vs and acoustic impedance values (Ip) demonstrating the differentiation between shales, gas-bearing sands, oil-bearing sands and brine sands. This cross-plot represents the results of the PGS depth dependent rock physics trend analysis starting from end-member picking and stochastic forward modelling. The above ellipses (shales 1-2, brine sands, oil and gas sands) represent two standard deviation contours of the fitted 2D probability distribution function (PDFs). These ellipses come from the rock physics analysis and incorporate uncertainties to cover the expected distribution of values that a particular fluid/lithology might have.*

The workflow applied used elastic attributes in the well log curve data to understand their responses in relation to reservoir lithologies and fluids. The inversion attributes (relative acoustic impedance (Ip and Is) and P-wave and S-wave velocity ratios (Vp/Vs)) used for lead identification and evaluation purposes demonstrate a good match with the well log data.

The results of the quantitative interpretation clearly show the differentiation between shales, brine-filled sandstones and hydrocarbon sandstones in the inversion derived seismic sections with strong changes at hydrocarbon water contacts (Figure 6). It was concluded that the combination of low Ip and low Vp/Vs values represents the presence of hydrocarbon-bearing sandstones, hence the combination of these two attributes have been used to delineate sandstone reservoirs charged with hydrocarbons.

Fluid replacement response modelling suggests that these reservoirs may contain light hydrocarbons (gas or light oil).

Identification and interpretation of leads

The depositional sequence framework has shown that within the eight wells drilled in the study area, reservoir quality sandstones are present in different systems tracts; in the lowstand or transgressive systems tracts as outer shelf and pro-delta mass flow deposits, with evidence of channels and fans, and in the highstand systems tracts as lowermost shoreface deposits. Analysis of the density and neutron logs together with the reservoir fluids interpreted within the CPI petrophysical logs suggests that of these systems tracts the highstand systems tract lowermost shoreface sandstones may have the best reservoir qualities.

Interpreting the seismic data in conjunction with this sequence framework (which allows an assessment of the reservoir depositional facies) has allowed for a significant number of leads, both structural and stratigraphic, to be

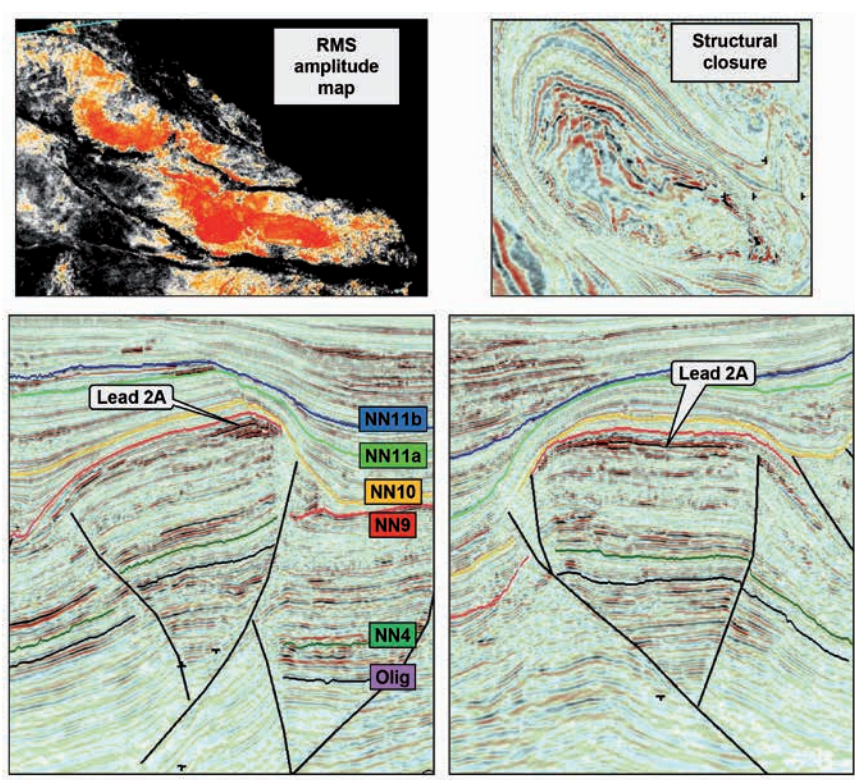

***Figure 7** An example of a lead identified using the sequence stratigraphic interpretation of the full stack seismic data. In this example, the bright amplitudes immediately below the NN9 sequence boundary are likely to be lowermost shoreface sandstones of the highstand systems tract while the sealing sediments above are likely to be deeper water transgressive mudstones.*

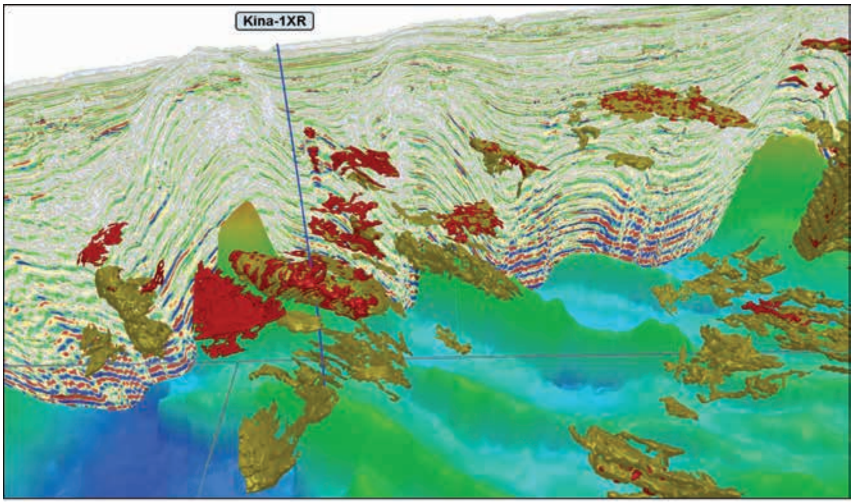

Figure 8 *An image showing the reservoir geobodies extracted from the seismic inversion volume together with the location of the Kina-1XR wellbore. A number of stacked, undrilled targets can be seen.*

identified. The mapped structural leads comprise four-way dip closures associated with toe thrusts and shale diapirs whilst the stratigraphic leads comprise sandstone-bodies with pinch-outs controlled by the same trusts and diapirs. The location of the sandstone bodies within the systems tract hierarchy can be used to predict whether the sandstones are lowermost shoreface, pro-delta or outer shelf deposits and thus inferences can be made about their potential reservoir quality (Figure 7).

The integrated G&G workflow described above has provided a robust depositional sequence framework and demonstrated a good correlation between the wireline log and seismic inversion volumes that can be used to identify and high-grade leads.

Having established a good correlation between reservoir fluid properties and the seismic inversion volumes, quantitative interpretation can also be used to identify reservoirs and the nature of their fluid fill; where low Vp/Vs and low Ip values are estimated through the pre-stack inversion process, they can be associated with hydrocarbon-bearing sandstones and thus leads can be derisked. Using this approach, 30 of the identified leads have been high-graded where it is considered there is a good chance of finding hydrocarbons in reasonable quality reservoirs (Figure 8).

The key to future success

The eight wells drilled to date have all been exploration wells that have typically sought to test single prospects. The results of these wells have shown the discovery of hydrocarbons; either oil, gas or in some cases both and this success has confirmed the presence of the necessary elements of a working petroleum system.

The integrated G&G study presented, using processed operator well data and the recently reprocessed 3D seismic dataset, has sought to understand these petroleum system elements and place these within a regional depositional sequence framework.

As well as seeking to understand the depositional, reservoir and fluid characteristics of the discoveries that have been drilled, this study has used quantitative interpretation to identify and high-grade an additional 30 leads. These leads, in conjunction with the drilled prospects, provide numerous opportunities for stacked reservoir targets as well as near-field development opportunities.

Recent activity in Equatorial Guinea at the Fortuna Field complex, as well as in Nigeria in fields such as Egina indicates renewed interest in the region and has improved understanding of the hydrocarbon systems that the JDZ is a part of.

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