Integrating Vertical Seismic Profiling (VSP) Data for Safe Drilling of High Pressure (HP) Frontier Exploration Onshore Niger Delta

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ABSTRACT

To improve reserve replacement and meet increasing energy demand, finding and maturing new hydrocarbon deposits below existing and producing fields are the main available options. In the Niger delta, the bulk of these prime leads and prospects are mostly deep high pressure, footwall (up-thrown) and / or horst block (back-to-back) fault enclosures. The main challenge therefore, is to safely drill these narrow margin high pressure formations. Conventionally, formation pore pressure modelling requires the use of surface seismic velocity, integrated with pressure cell modelling and basin modelling to generate a robust pre-drill pore pressure model, which is then used for well design, mud program and efficient drilling operations. However, the quality of surface seismic velocity deteriorates with depth and consequentially, increases the uncertainty margins of pre-drill models at depth. In 2014, Shell Nigeria Exploration team began a HP drilling campaign that culminated in five wells drilled so far. This paper highlights the use of vertical seismic profile (VSP) data to predict pore pressure ahead of the bit which has been deployed in drilling some of the Exploration targets. This approach begins with Real Time Pore Pressure Prediction (RTPPP) over the wide drilling margin section down to the expected high overpressure ramp, section TD call and set casing. A high resolution vertical seismic profiling (VSP) data is then acquired and processed to predict seismic acoustic interval velocities ahead of the bit. This is applied to update the pre-drill pore pressure model to reduce the uncertainties, deployment of Managed Pressure Drilling (MPD) and further RTPPP monitoring over the narrow drilling margin/high overpressure section while drilling to final well TD. Overall, integrating VSP data has led to the safe unlocking of hydrocarbons in deeper, overpressure exploration targets, with positive impact on reserve replacement and exploration business performance.

INTRODUCTION

The Frontier Exploration Onshore Niger Delta are plays with high reserves replacement potential, high-pressure and maybe, high-temperature environments. They are subject to significant overpressure, which is pore pressures above “normal” or hydrostatic. In this environment the pore pressures can reach values very close to the fracture gradient, leading to extreme drilling challenges. Drilling and other well maintenance operations in these zones could be carried out safely and more cost effectively when an accurate pore pressure prediction is assured. Estimating the pore pressure ahead of the bit is a major challenge while drilling. Predictions are based mainly on a combination of remote data, such as seismic and basin modelling, and/or by analysis of nearby (offset) wells. Only few direct measurements of pore fluid pressures (for example, wireline pressure tests such as RFT/MDTs or production tests such as DSTs) are available to calibrate any prediction. Vertical seismic profiling is a powerful tool from which travel times, wave amplitudes, and reflection coefficient data can be acquired, offering a more detailed seismic view of the subsurface in the vicinity of the borehole than conventional surface seismic data. Among others, it is now widely reputed for its potential to provide estimation of pore pressure ahead of the drill-bit.

STUDY AREA

The Niger Delta is situated in the Gulf of Guinea and extends throughout the Niger Delta Province as defined by Klett et al., (1997). The province contains only one identified petroleum system (Kulke, 1995; Ekweozor and Daukoru, 1994) which is referred to as the Tertiary Niger Delta (Akata –Agbada) Petroleum System. It occupies an area enclosed by the geographical grids of latitude 5.30 and 5.40N and longitude 6.00 and 6.20E. The Delta is rich in both oil and gas. Three (3) main formations have been noted in the subsurface of the Niger Delta (Frank and Cordy, 1967). They are the Benin, Agbada and Akata Formations which were deposited in continental,

We thank the following persons for sponsoring and supporting this work: Shell Nigeria GeoSolutions and Onshore/Shelf Exploration Managers. Special appreciation goes to the JV partners for permission to publish this work. The authors are also thankful the Well Engineering department, Yamusa Idris, Uraechu Deborah, Kate Iwe, Irifeta Owen, Olafiranye Kehinde, Kunle Bakare, Eteh Enyinna, Chibuzor Chejineh and Baker Hughes staff, for their contributions.

transitional and marine environments, respectively. The fields under consideration are located in the mid-belt CRS of the Niger delta. The HP Exploration zone is notable for scanty data. Majority of the fields are covered only by 3km offset 3-D seismic data of not great quality and only very few direct measurements of pore fluid pressures to calibrate any prediction. Mild to hard overpressures have been identified beginning from a pressure gradient of 0.7 psi/ft. As no common depth can be ascribed to overpressure regimes, it has been noted that

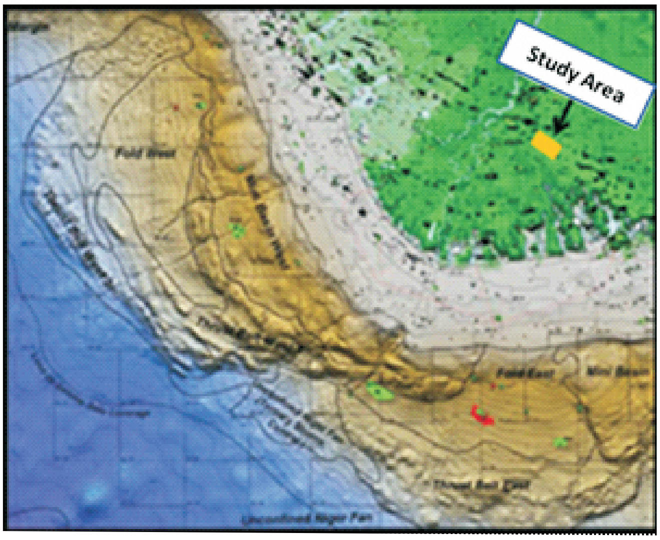


Figure 1: Niger Delta map with shaded relief and sea-floor topography showing location of study area.

that the onsetoverpressures is typically capped by regional MFS which varies in age, understandably across various depobelts (Figure 1).

CASE FOR STUDY

Drilling one of the earliest Exploration HP wells, NARGBA-001 proved very problematic with two pore pressurerelated Well Control Incidents. The predicted pore pressures were based on 3 Km offset 3-D seismic data which was not robust enough for pore pressure prediction below depth of 3.5 Km. Rapid Pore Pressures (PP) transition in exploration objectives were not captured and as such kick pressures were outside of predicted range. These Pore Pressure induced well control incidents provided enough justification for Look ahead VSP to be used as an alternative method to predict what is beneath the drill bit. This was carried out on NARGBA-002, Craak Deep and ZUBIN-05 (Figure 2.).

Pre-Survey Modelling

The VSP acquisition is usually underpinned by a robust pre-survey modelling. The purpose of this is to determine if it is possible to meet the objective of the VSP, visualize reflected arrival, identify ideal source and receiver locations, acquisition parameters, understand the limitations and uncertainties with chosen geometry, amongst others in the presence of operational constraints.

VSP acquisition and data processing

The VSP acquisition system comprised of a Sercel G-Gun array buoyed in a pit from a crane at the source location. A reference hydrophone positioned 5 ft above the source was used for timing and monitoring purposes. The surveys were recorded using 3-Component geophones in a 5-level Geowaves tool spaced 33 ft apart. At the start of the survey, the wireline depth sensor was zeroed at the KB elevation and the receiver array was lowered down the well. During the downtrip, the geophone was stopped at a number of depths to check the equipment performance and for time QC of the main survey data. The surveys were recorded while pulling out of the hole with toll spacing as indicated above.

After data acquisition, the direct component was used for further processing. A compensation for amplitude decay due to spherical divergence was applied on the vertical component data using an exponential gain function of

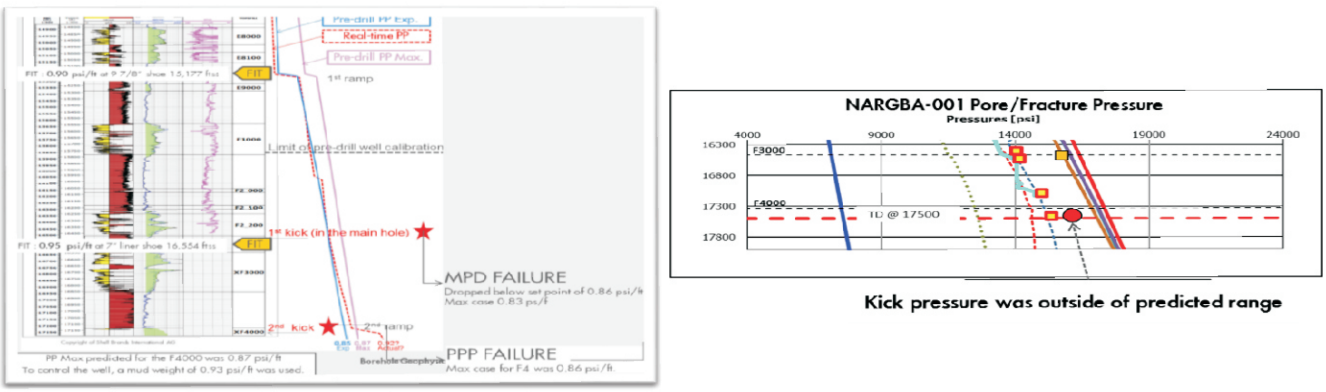
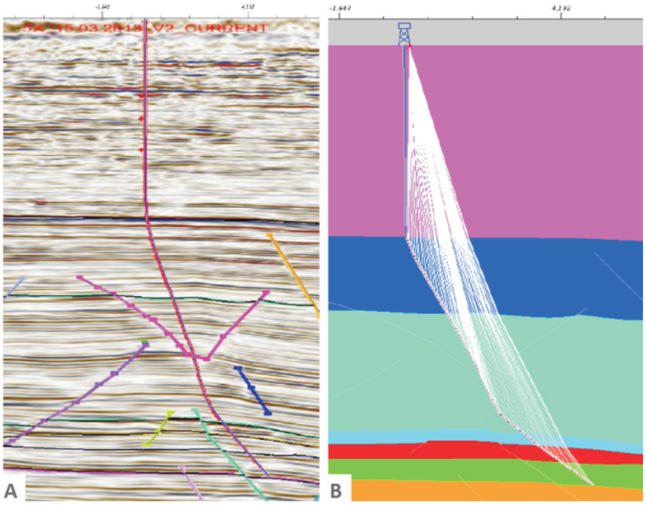


Figure 2: Seismic velocity-based Predicted vs Actual pore pressure. Kick pressure was outside of predicted range.



Acquisition Parameters	Cased Hole	Open Hole	Cased Hole	Cased Hole	Cased Hole	Cased Hole-R
Station Interval	53′ (16 m)	33′ (10 m)	53′ (16m)	53′ (16m)	16m Staggered	16m Staggered
Nominal Fold @ Shallow	85	140	110	250	360	85
Nominal Fold @ TD	450	700	570	1150	1800	450
Fmax	78 Hz	125 Hz	78 Hz	78 Hz	156 Hz	156 Hz
Station Roll Size	5	5	4	2	2	5
Initial Depth of Measurement	165′ (50 m) from surface	165′ (50 m) from surface	165′ (50 m) from surface	165′ (50 m) from surface	165′ (50 m) from surface	165′ (50 m) from surface
Listening Time	5000 ms	5000 ms	5000 ms	5000 ms	5000 ms	5000 ms
Sample Rate	1 ms	1 ms	1 ms	1 ms	1 ms	1 ms
No of Station Moves along 2000 m	25	40	32	62.5	250	53

C

Figure 3: A: Model based on surface seismic data (in depth); B: Rig Source VSP – Direct Arrivals; C: Table of modelling outcomes for various geometries and parameters.

T**1.5 where T is the recorded time (Figure 4B). F-K and spectral analyses were performed (Figure 4C). Processing trials were carried out and a 15-point horizontal median filter was chosen to separate the downgoing P wavefield from the upgoing P wavefield, followed by a zero-phase bandpass filter. The upgoing P wavefield was then shifted to the corrected two-way time below datum. A deterministic deconvolution was performed on the downgoing and upgoing wavefieldsafter tests for optimum parameters. The intent is that the operators should be stable enough and possess ability to collapse data into a zero-phase wavelet.

A corridor stack was produced by interactively picking a corridor of data along the first arrival curve, which was then stacked and spliced into surface seismic data at the well location at the same polarity (see Figure 4E).

Processing for and Prediction ahead of the bit

The data was processed to predict seismic acoustic interval velocities ahead of the drill bit which would be subsequently used to predict pore pressure. Usually, a liner would be set and an intermediate wireline VSP was acquired prior to drilling the exploration objectives. While the pipe was run back in to drill the next phase, VSP processing was carried out. Normal VSP processing was carried out up to the generation of a corridor stack and then sparse spike VSP inversion was performed to predict seismic acoustic interval velocities below TD. Predicted velocities below section TD were delivered within 11 hours typically.

The sparse spike inversion concept uses a specified velocity change to generate a synthetic reflection

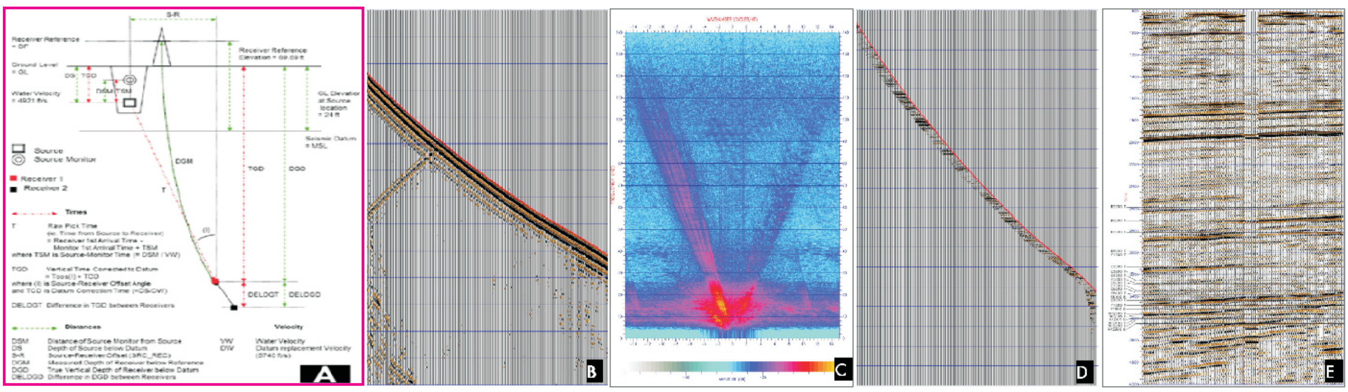


Figure 4: A: Onshore acquisition parameters for NARGBA-2; B: Total wavefield; C: Total wavefield – F-K analysis; D: Corridor Mute; E: Corridor Stack at 50Hz into surface seismic in time.

2-Way Time	TRUE Vertical Depth	Predicted Vertical Depth	Predicted Interval Velocity
ms	ft	ft	ft/s
3620	16214		11603
3641	16346		10376
3649	16379		9010
3660		16429	9704
3670		16477	10848
3680		16532	12334
3690		16593	13712
3700		16662	10405
3710		16714	10744
3720		16768	10835
3730		16822	10715
3740		16875	11429
3750		16932	11945
3760		16992	11682
3770		17051	8451
3780		17093	8451
3790		17135	9759
3800		17184	10102
3810		17234	10770

A

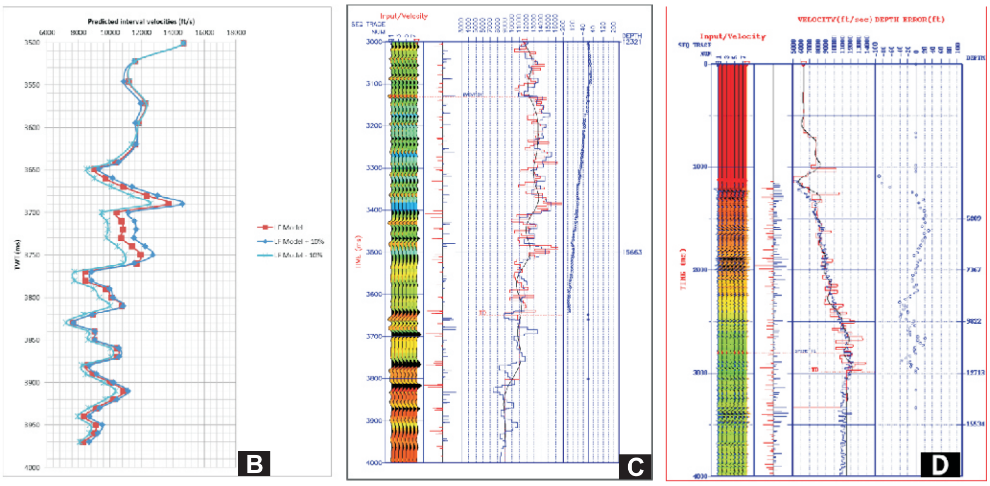


Figure 5A: NARGBA-2 VSP predicted depth and interval velocity; B: Sparse Spike Inversion sensitivity test for low frequency model below TD; C: Sparse Spike Inversion results for NARGBA-2; D: Sparse Spike Inversion results for ZUBIN-5.

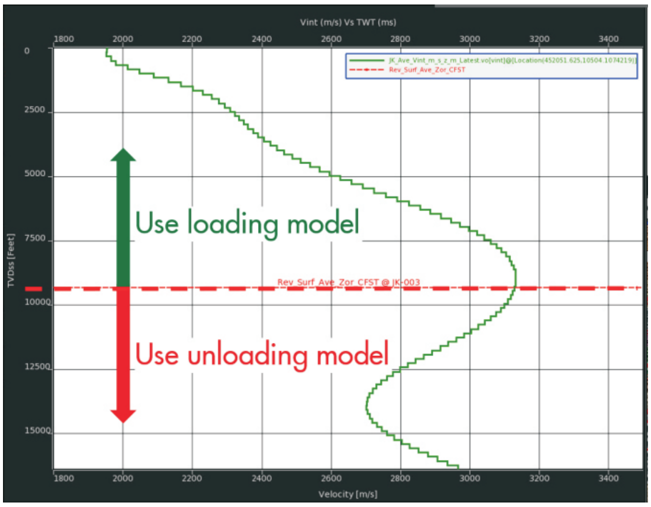


Figure 6: Seismic interval velocity (green curve) plotted as a function of depth. The red line shows the depth of interval velocity reversal. Below this depth, the unloading curve is used for pore pressure prediction.

coefficient which is then filtered to the VSP bandwidth and calibrated to the VSP amplitudes. This is used to create reflection coefficients which are then combined with a low frequency trend generated from the velocity profile to produce a synthetic Acoustic Impedance log. The density element is then backed out using Gardner's formula to create a velocity log which is simply integrated to generate depth. The inversion works upwards and downwards from the calibration point allowing us to compare the generated time/depth relationship to the real data and it is subject to carefully chosen and practical constraints in order to reduce the range of possible solutions.

RESULTS AND DISCUSSION

Pore pressure for undrilled prospects is generally assessed from an integrated analysis that includes offset well analysis and seismic velocity-based pressure prediction.The seismic velocity (Vint = interval velocity) based PPP modelling approach generally incorporates two different relationships between Vint and VES (VES=vertical effective stress). The VES = overburden pressure (OP) minus pore pressure (PP). The model parameterization used most commonly in the Niger Delta is Bowers loading for the shallower stratigraphy and Bowers unloading for deep stratigraphy.One relationship is used for shallow rocks and another for deep rocks.It is widely believed that the reason why two different relationships are used is that rocks in the Niger Delta often show a shallow compaction behavior ("loading") while the deeper rocks are often unloading. The switch from loading to unloading is usually applied at the depth of the seismic velocity reversal (see Figure 6 for an example). Note that the loading and unloading curves always need to be locally calibrated for the area of interest.

NARGBA-002 was the first ever VSP interval velocity-based PPP in SPDC and matched measured pressures accurately and provided guidance to the F4000 sand pore pressure and depth uncertainty. VSP based predictions combined with wet sands in the shallow section helped us call the early TD of the well. Craak Deep provided an opportunity to consolidate the establishment of VSP technology in PP Prediction and depth uncertainty as the effective use of VSP velocity-based PPP matched

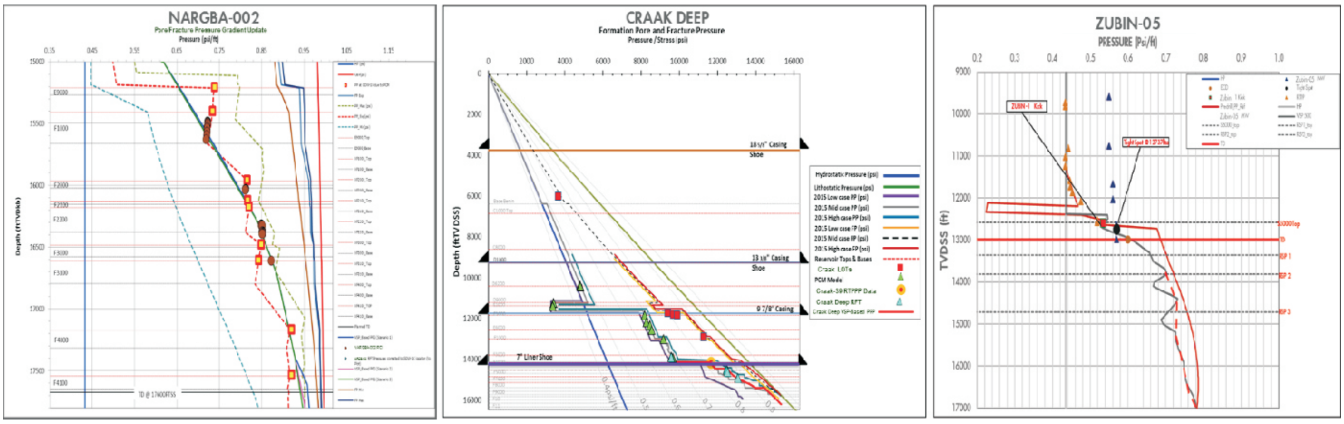


Figure 7: Left: Pore pressure prediction from VSP plot for NARGBA-2; Middle: Pore pressure prediction from VSP plot for Craak Deep; Right: Pore pressure prediction from VSP plot for ZUBIN-05.

measured pressures accurately and provided guidance to the XF8000 sand pore pressure and depth uncertainty.

In ZUBIN-005, look-ahead VSP proved valuable in highlighting potential lithological changes ahead of the bit. Integration of Sonic and look-ahead VSP allowed update of depth model and very accurate depth prognosis before reaching bed boundaries or potential pressure changes.

CONCLUSIONS

Borehole Geophysics (VSP) has proven central to enhanced maturations, and safe delivery of wells in the ongoing HP frontier exploration in Shell Nigeria. The case studies presented in this paper demonstrate that look-ahead VSP data can be a powerful tool in providing a pore pressure prediction ahead of the bit, as shown by the small differences between the predicted and the measured formation pore pressures. However, the accuracy of the inversion result depends on a few factors. Key is the geometry of the well. Normal or vertical incidence VSP is more likely to give wavefield measurement with less slant time error correction to deal with. Also, the presence of very low frequency range of the spectrum which plays a crucial role in Bayesian inversion, and application of constraint point(s) below the VSP intermediate TD are some influencing factors. Other factors affecting the outcome of a look-ahead pore pressure prediction include understanding pore pressure generation mechanisms and uncertainties in the predicted pore pressure and applying appropriate pore pressure prediction model. The prediction model should be robust enough to capture loading and unloading (undercompaction and fluid expansion) overpressure generation mechanisms.

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