Reducing Exploration Drilling Uncertainty in Overpressured Zones using Seismic Interval Velocity and AVO Modeling in Deepwater Niger Delta

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ABSTRACT

Key challenges of deep exploration drilling include understanding the onset of abnormal pressure and effects of overpressure on reservoir seismic response. These are critical for de-risking deep exploration opportunities and safe drilling. The major overpressure generation mechanism in the Niger Delta is sub-compaction dewatering of sediments. This study was carried out in a deepwater acreage, offshore Niger Delta focusing on (i) using seismic interval velocity to detect onset of overpressure, and (ii) predicting seismic Amplitude Variation with Offset (AVO) response in reservoirs within the overpressure zones.

Six wells that have penetrated the onset of overpressure were used for the study. Using seismic and well data, the Top Abnormal Pressure Equivalent (TAPE) surface was mapped stratigraphically across the area of interest. Different seismic interval velocity models from Pre-Stack Time Migration (PSTM), Pre-Stack Depth Migration (PSDM) and Full Wavefield Inversion (FWI) processing were used to QC and validate the TAPE surface using observed seismic interval velocity inversion.

2D forward seismic models were generated for different reservoir fluids(gas, oil and brine)and rock properties within the overpressured intervals of the six calibration wells. Modeling results showed that AVO response in overpressured intervals varies with fluid type, porosity and depth of burial. Furthermore, for the same fluid phase, there is an upward shift in AVO intercept and higher AVO gradient in overpressured rocks relative to normal pressured rocks.

Conclusively, overpressure affects the rock elastic properties which could cause significant changes in the AVO attributes. Detection of onset of overpressure and modeling of seismic AVO response in overpressure zones will help in safe, cost effective drilling and geophysically de-risking deep exploration opportunities to increase the chance of commercial discoveries.

INTRODUCTION

Overpressure in the subsurface occurs where there is excess pore fluid due primarily to either fluid retention during pore space reduction or fluid expansion during diagenetic transformation e.g. dehydration reaction or organic maturation of source rocks (Swarbick and Osborne, 1996)

In clastic basins, pore pressure largely influence the changes in seismic velocities. The primary cause of abnormal pore pressure is the disequilibrium compaction of shale caused by sub-compaction dewatering. Pore pressure has a greater influence on the elastic properties of shales than sands because water tend to be adsorbed on the clay particles (Buginga and Toledo, 2004)

The problem of overpressure influence on rock property and the corresponding effect on seismic attributes, reflectivity modeling and AVO response has been widely investigated in recent years. Lindsay and Towner (2001) showed in their study how pore pressure effects on anoverlying shale changed the top hydrocarbon reservoir response from an otherwise positive AVO anomaly into a negative AVO. Buginga and Toledo (2004) also confirmed in their case study how changes in the elastic properties of the overpressured shale have induced strong AVO anomalies which are not related to the presence of hydrocarbons. Therefore, it is apparent from these examples that the knowledge of the abnormal pore pressure zones and its effect on rock elastic properties

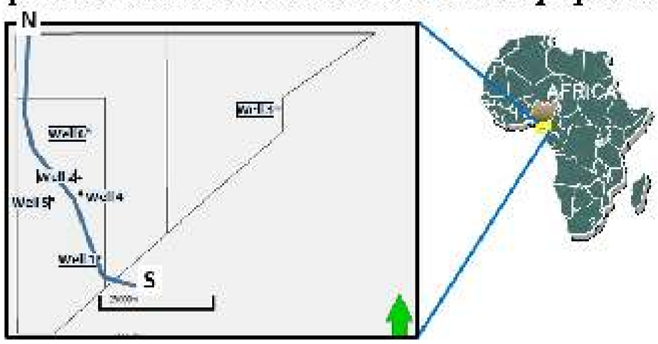

Figure 1: Africa map showing study area in the Niger Delta.

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needs to be included in AVO modeling.

In this study, we have looked in details to changes in rock properties and AVO behavior below an estimated onset of overpressured surface. Geophysical validation of the interpreted Top Abnormal Pressure Equivalent (TAPE) surface was done using seismic interval velocity. 2D forward seismic models were generated for different reservoir fluids (gas, oil and brine) and rock properties within the overpressured intervals in order to understand the implication of overpressure on the expected seismic response in the study area. The study would help to identify, de-risk and safely drill deep exploration wells for resource addition in the Niger Delta.

REGIONALGEOLOGY SUMMARY

The study area is a basement detached, linked extension-contraction deepwater system located in eastern Niger Delta Basin, Offshore West Africa (Figure 1). Sedimentary deposits are mainly series of NW-SE trending deepwater slope channel complexes comprising of confined, weakly confined and distributary channel networks.

The main phase of contraction in this basin, dated Late Tortonian to Early Messinian was likelydriven by large scale growth fault in northern parts of study area. Stacked thrust sheets (imbricate systems) in the frontal parts acted as a local buttress and initiated observed back-thrusts.Figure 2 illustrates the structural domains showing linked extension-contraction system. The key play types are thrusted anticline (moderate-high relief fault propagation folds), sub-thrust and faulted (rollover) anticline

(Figure 3). All available 3D seismic data contain full and angle stacks. Also 3D migration velocity models are available for all data vintages
Eighteen exploratory wells were initially selected across the study area. Using the pore-pressure information from the end-of-well geologic report, this was reduced to 6 wells (Figure 4) that penetrated overpressure lithology (pore pressure > 11ppg). The penetrated overpressure lithology are mostly shale with sand stringers (<10m) below tuning thickness except Well 04 containing about 45m net sand in overpressured zone.

TAPE Surface Definition and Validation

Using the seismic-to-well ties from six wells that penetrated overpressured lithology as calibration, the seismic reflector associated with the onset of overpressure was interpreted starting from Well 01 location. This was observed to be a laterally extensive reflector and could represent a sub-regional onset of overpressure. Age stratigraphic equivalent of this seismic event was mapped on the blockwide PSTM data across the entire study area using sub-regional seismic transects (Figure 5) taken along different mini-basins in the area. The mapped surface (Figure 5) was named Top Abnormal Pressure Equivalent (TAPE).

The understanding that overpressure effects result in porosity preservation and potential interval velocity inversion in the overpressure zone was used to validate the mapped TAPE surface. 3D seismic migration velocities from PSTM, PSDM and FWI processing were converted to interval velocities using Dix's equation. The interpreted TAPE surface was overlaid on the several seismic interval velocity transect lines taken across the study area (Figure

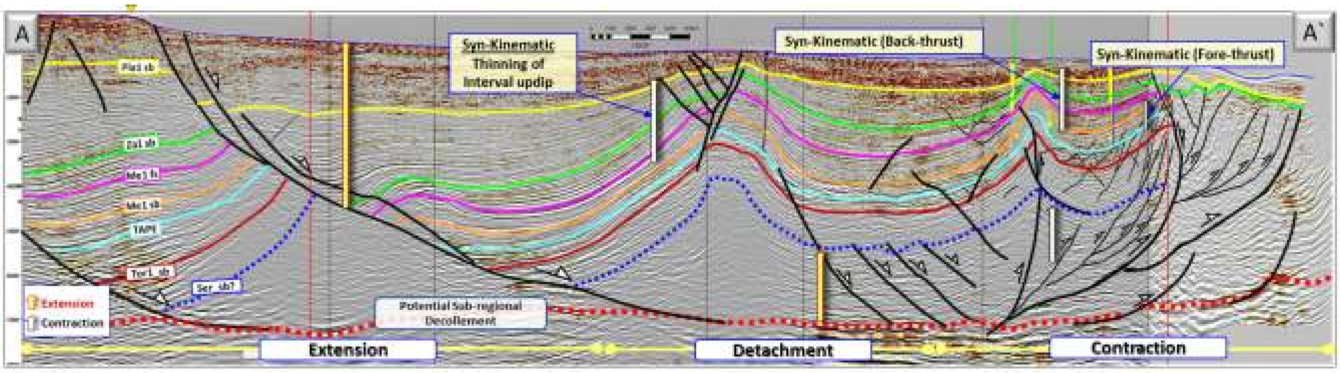


Figure 2: Subregional seismic transect across study area showing linked extension-contraction structural domains.

6). The TAPE surface generally correlates to observed seismic interval velocity inversion. This validated the interpreted TAPE surface as a good estimate of the onset of overpressure.

However due to better quality and resolution of the PSDM

Seismic and Well Database

Several vintages of 3D seismic data were used for this study.First is a regional 3D PSTM data covering the entire location. Other volumes include 3D PSDM and FWI data covering different subsets of the study area

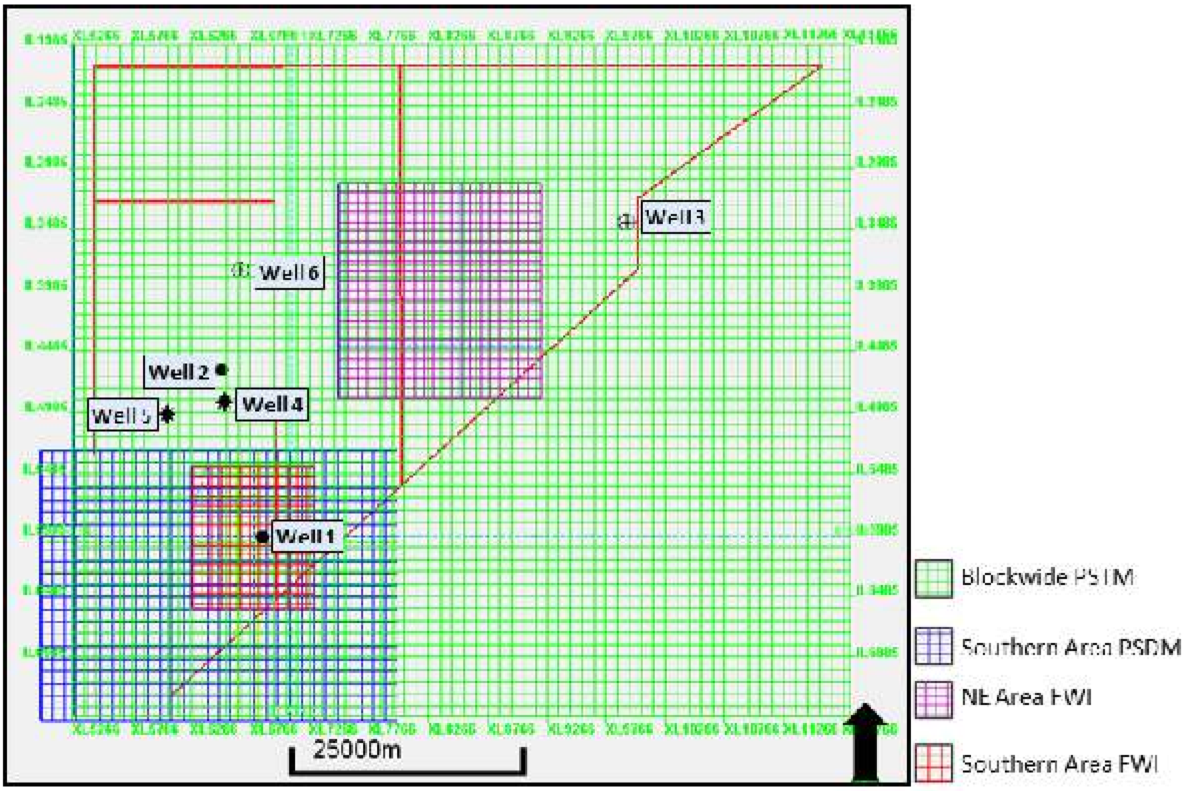


Figure 3: Location map showing seismic surveys and calibration wells in the study area

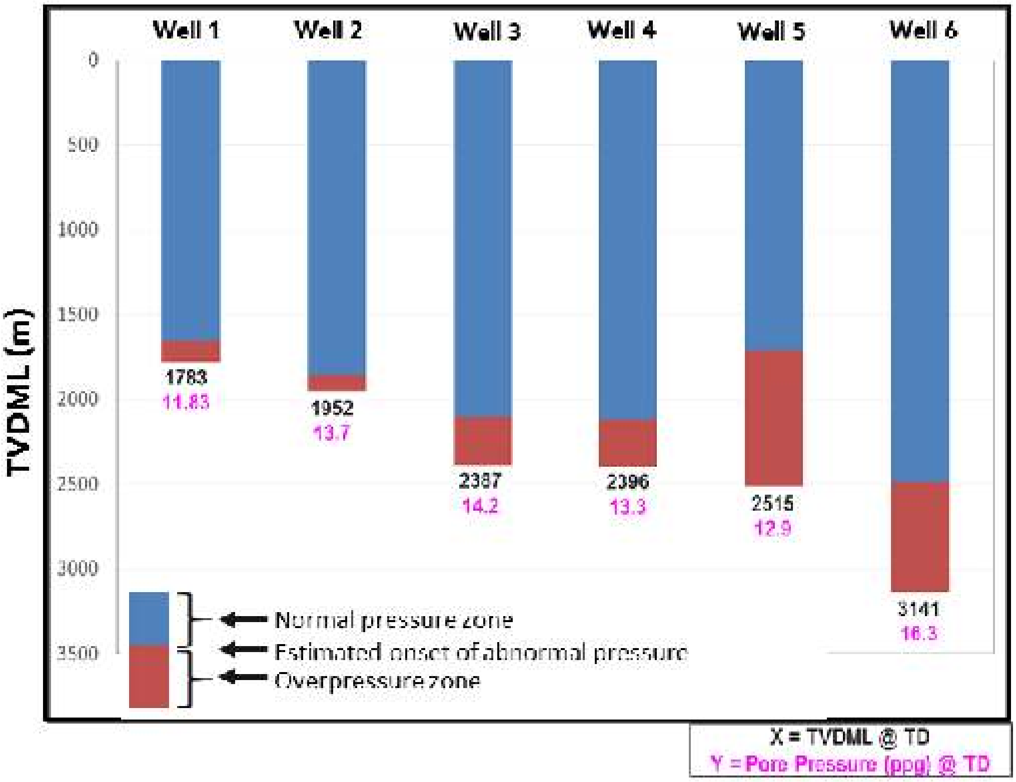
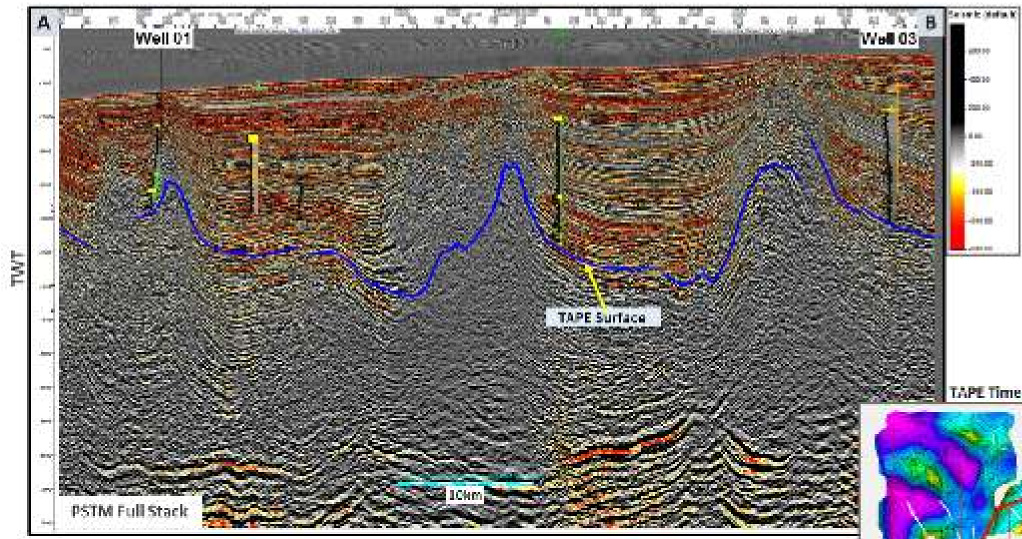


Figure 4: Chart showing selected overpressure wells (pore pressure >11ppg @TD) vs. TVDML(m)



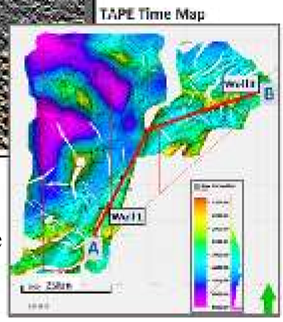


Figure 5: Seismic transect across the study area showing the Top Abnormal Pressure Equivalent (TAPE) interpreted close to Well 01 TD and then mapped across entire study area to generate TAPE time structure map.

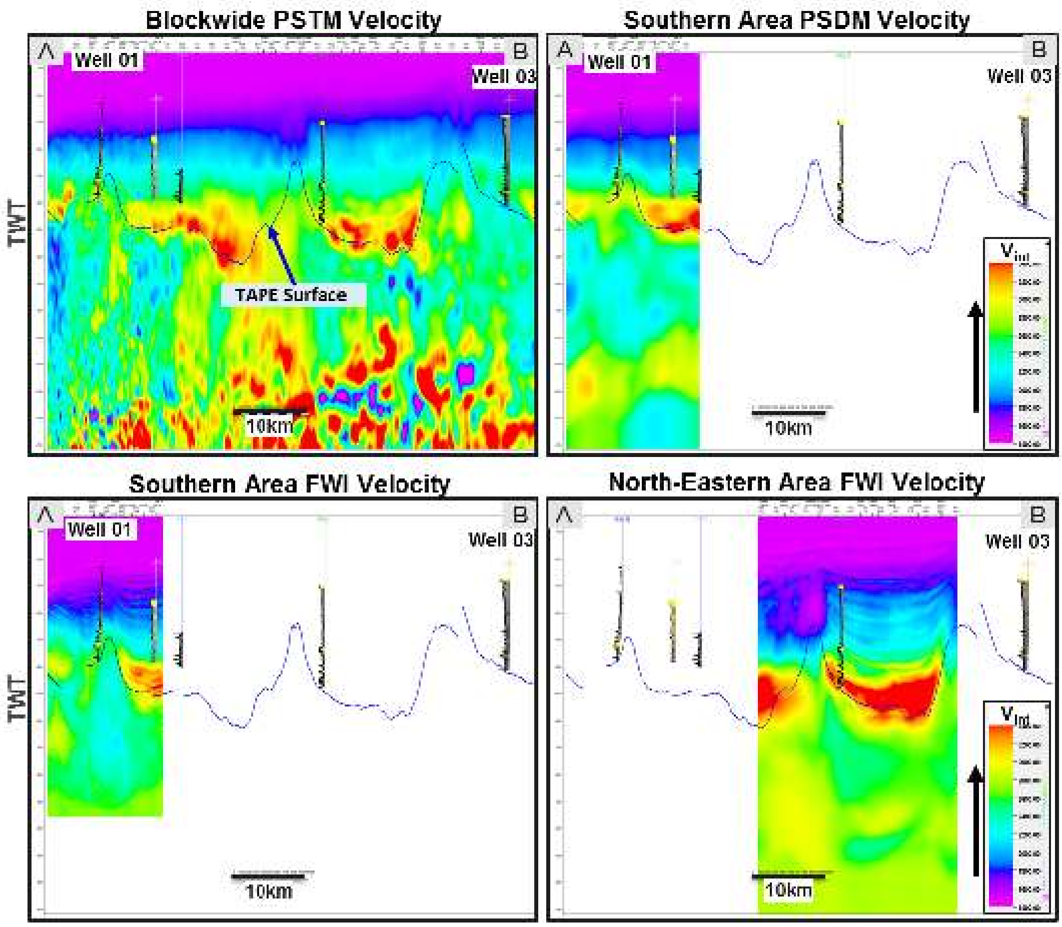


Figure 6: TAPE surface overlaid on different seismic interval velocity models. Correlation to observed seismic interval velocity inversion validates mapped TAPE surface as estimated top of overpressure.

and FWI velocities relative to the PSTM velocity, the TAPE surface correlates better to the interval velocity inversion observed in the PSDM/FWI compared to that of PSTM model.

Fluid Substitution and AVO Modeling in Overpressured Zone

The second phase of this study involved generating a 2D seismic model of the HC and non-HC bearing reservoirs in overpressure zones using the six analogue wells. Due to the poorly developed reservoirs in most overpressured intervals of the wells, simple 2D blocky seismic models were generated using the average rock properties.

Using Gassmann's equation, the in situ reservoir fluid was substituted to brine, oil or gas as necessary and the corresponding rock elastic properties logs (P-Sonic, S-Sonic and Density) were generated. Figure 7 shows the measured and calculated well logs of one of the analogue wells (Well 04) with in situ brine substituted to oil and gas. Top seal (shale), reservoir and base seal intervals in the overpressured intervals were defined using specified Vshale (VSH) and water saturation (SWT) cut-offs

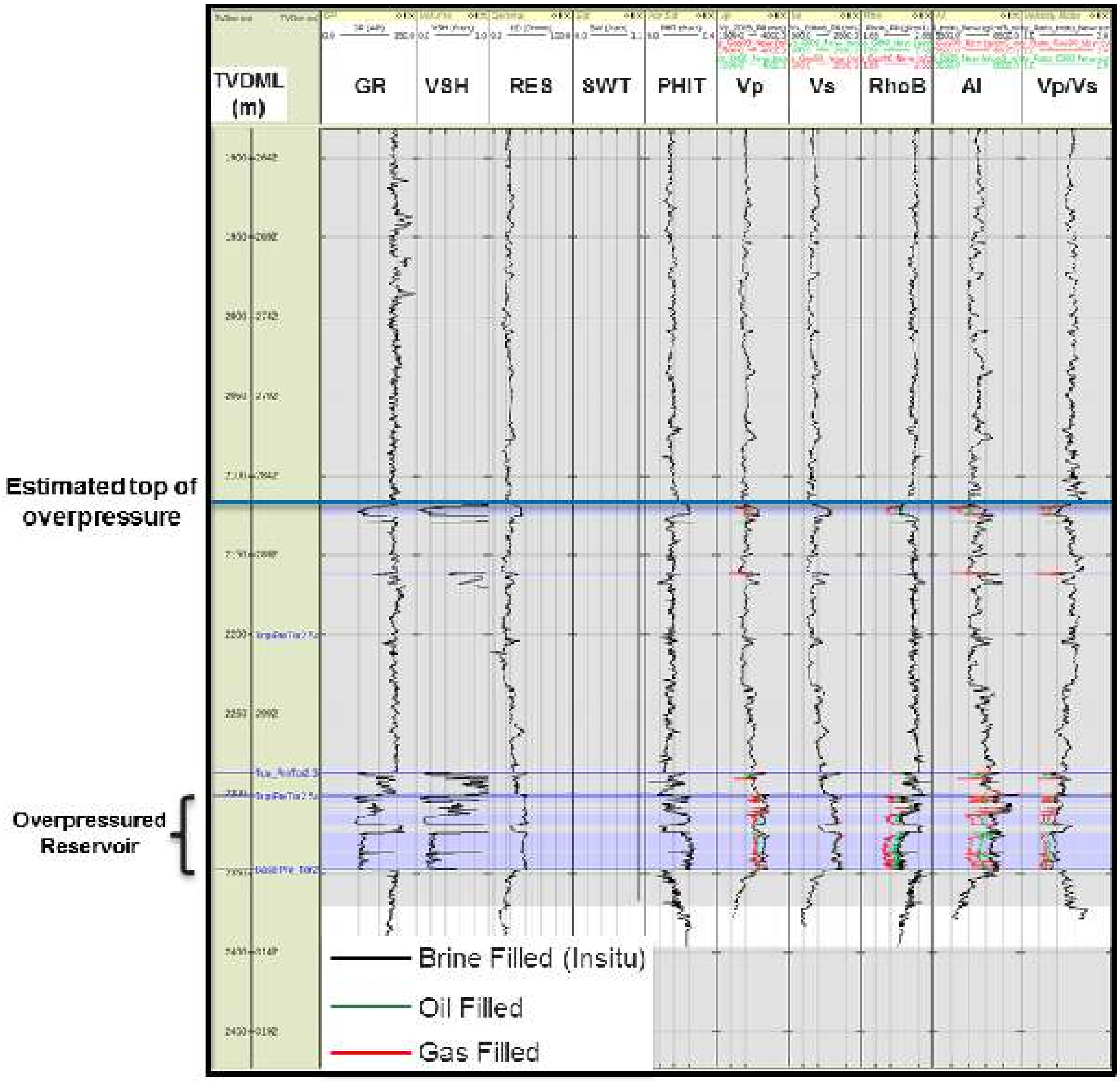


Figure 7: Well 04 Overpressured reservoir zone fluid substitution. In situ brine reservoir was fluid substituted to oil and gas and corresponding elastic property logs generated.

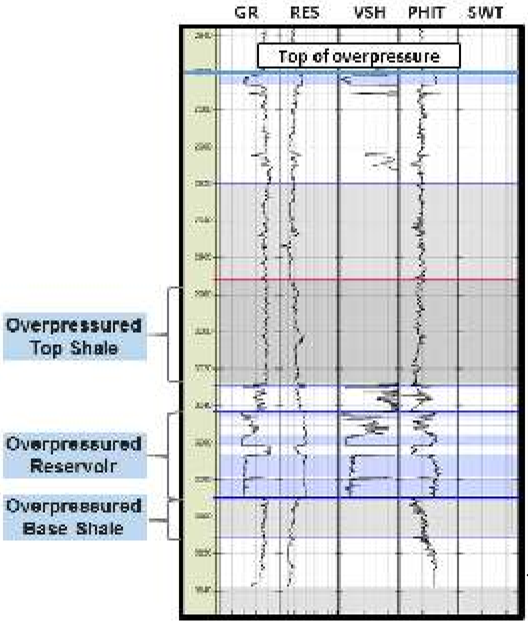


Figure 8: Defined Well 04 overpressured zone top seal, reservoir interval and base seal used to obtain average elastic properties.

	Top Shale	Gas Sand	Oil Sand	Brine Sand	Base Shale
Por (%)	15	23	23	23	15
Vp (m/s)	2445	2844	2910	3144	2421
Vs (m/s)	1127	1875	1830	1789	1202
Rho (g/cm3)	2.38	2.06	2.16	2.22	2.37
Vp/Vs	2.17	1.52	1.59	1.76	2.01
AI (g/cm3_m/s)	5819.10	5858.64	6285.60	6979.68	5737.77

Table 1: Well 04 average rock properties of the top, base seals and different reservoir fluid fills used for the 2D seismic model.

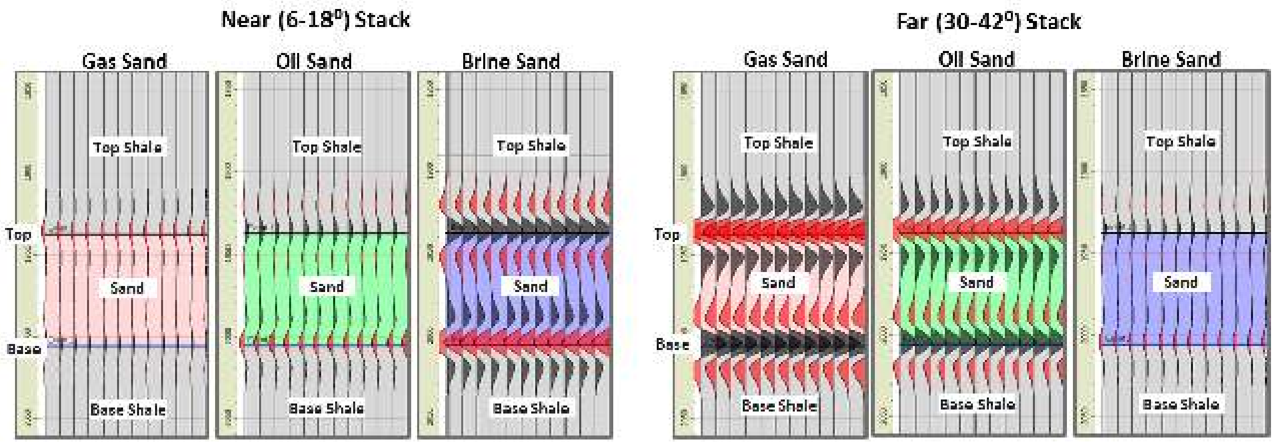


Figure 9: Well 04 blocky 2D seismic model in overpressure zones showing top and base reservoir response on Near and Far stacks for different fluid fills.

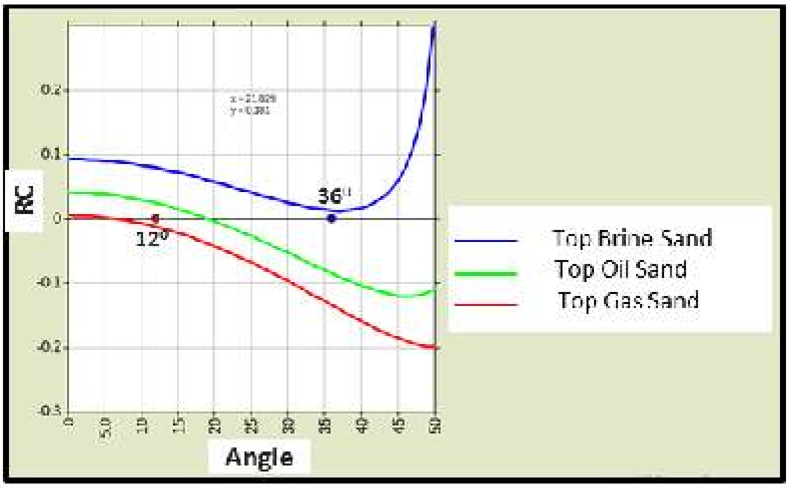


Figure 10: Well 04 reservoir AVO plot in overpressure zones for different fluid phases.

(Figure 8). Table 1 shows the average rock properties of different reservoir fluid types with the top and base shales. These average elastic rock properties were used to generate 2D seismic models for Near stack (6-18o) and Far stack (30-42o) using 25Hz Ricker wavelet. Figures 9 and 10 show the well 2D seismic model and the AVO plot. Model results in Well 04show a Class 1 brine sand response, Class 2P oil sand response and Class 2 gas sand response in the deep overpressured zones.

Similar methodology of fluid substitution and AVO model of reservoirs in overpressured zones was applied to five more calibration wells and table 2 shows the summary of the results.

Comparison of Predicted AVO Responses in Normal Pressure and Overpressure Zones

In other to understand the implications of overpressure on expected seismic response within the study area, a normal pressured reservoir interval was buried deeper within an overpressured shale using two of the calibration wells. Afterwards,normally pressured and overpressuredAVO model scenarios were generated by keeping the reservoir elastic properties constant while using the top seal (shale) normal pressured and overpressured elastic properties respectively.

Figure 11shows Well 03logsand Table 3 containsthe input parametersused for the normal pressured and

Table 2: Summary of the six calibration wells predicted reservoir AVO response for different fluid fills in overpressured intervals.

S/N	Well	Onset of Overpressure Depth BML approx (m)	TD BML	Formation Pressure @ TD (ppg)	Avg Shale PHIT (%)	Avg Sand PHIT (%)	Modeled Reservoir Depth (TVD BML)	Insitu Fluid	Gas Sand AVO Response	Oil Sand AVO Response	Brine Sand AVO Response
1	Well 01	1650	1783	11.83	22	28-29	1700	Oil	Class 3	Class 2	Class 1
2	Well 02	1848	1952	13.7	16	26	1843	Oil	Class 3	Class 2	Class 2P
3	Well 05	1714	2515	12.9	23	29	2040	Brine	Class 3	Class 2P	Class 1
4	Well 03	2110	2387	14.2	23	29	2140	Brine	Class 2	Class 2P	Class 1
5a	Well 04	2123	2396	13.3	13	23	2300	Brine	Class 2	Class 2	Class 1
5b	Well 04	2123	2396	13.3	15	23	2300	Brine	Class 2	Class 2P	Class 1
6	Well 06	2491	3141	16.3	15	19	2618	Oil	Class 2P	Class 1	Class 1

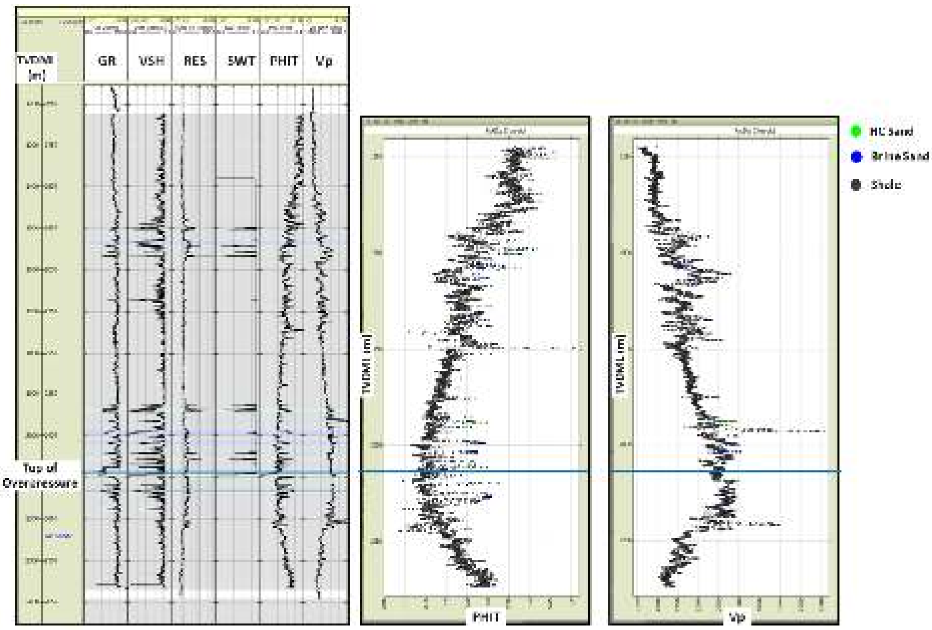
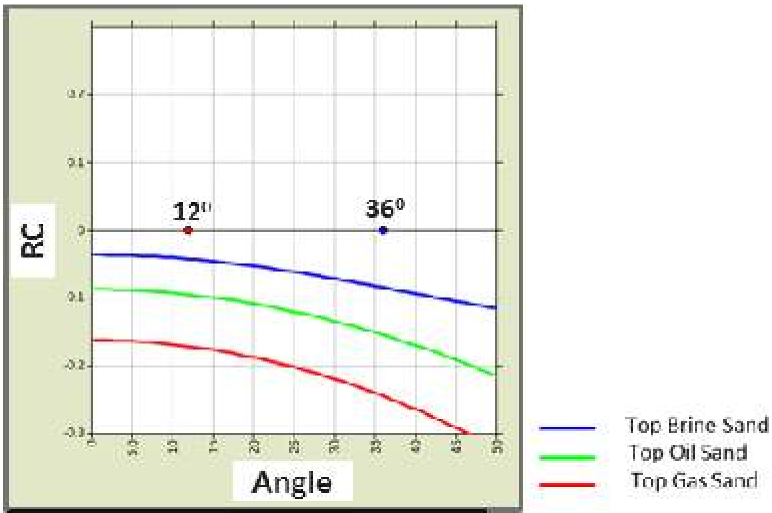


Figure 11: Well 03 logs showing the estimated top of overpressure and the change in the PHIT and Vp trends with depth due to overpressure effect.

overpressure AVO plots. The overpressure effect in the shale caused a lower Vp, Vs, RHOBand a higher Poisson's ratio (or Vp/Vs) than expected for a normally pressured shale at similar depth of burial. These changes resulted in higher values of AVO gradient and an upward shift in AVO intercept in overpressure relative to normal pressure scenario (Figure 12).

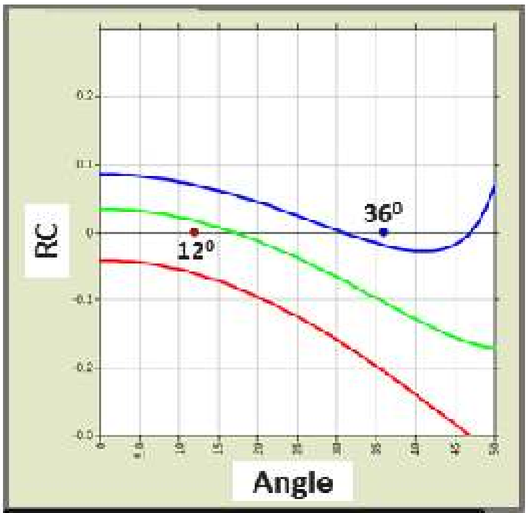
Comparison of Synthetic Model to Actual Seismic Data

The seismic model results of the six calibration wells for the insitu fluids were compared to the actual seismic data using different vintages (PSTM, PSDM and FWI). Figure 13 and 14a showed an example using Well 04 where the



	AVO Intercept	AVO Gradient
Gas Sand	-0.165	-0.256
Oil Sand	0.037	0.148
Brine Sand	-0.088	-0.202

Figure 12a: Well 03 reservoir AVO plot in normal pressured zone showing expected Class 2 brine, Class 3 oil and Class 3 gas response respectively.



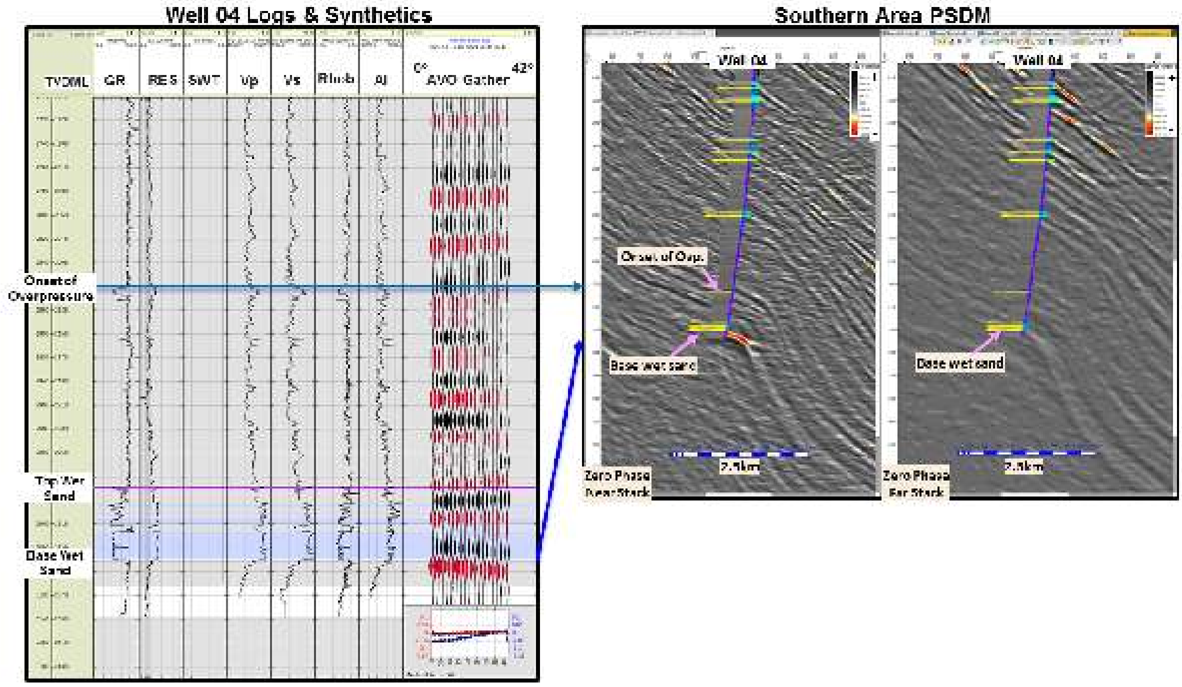
	AVO Intercept	AVO Gradient
Gas Sand	-0.043	-0.593
Oil Sand	0.084	0.397
Brine Sand	0.033	-0.488

Figure 12b: Well 03 reservoir AVO plot in overpressured zone showing expected Class 1 brine, Class 2P oil and Class 2 gas response respectively. Also the AVO gradient is higher. than normal pressure scenario.

Figure 13: Well 04 base reservoir AVO plot in overpressure zone for different fluid phases.

expected base wet sand response (strong trough on Nears that dims at Far stack) matches the actual seismic data response at the well location (Figure 14b).

However, the PSDM and FWI seismic data set generally showed a better match with the expected synthetic response than the PSTM data. This is because of improved imaging and better AVO stacks achieved by the PSDM and FWI processing flows.



Figures 14a & b: Well 04 synthetic model result comparison to actual seismic data showing the base wet sand response as trough on Near stack that dims at Far stack.

RESULTS AND CONCLUSION

This study focused on changes in rock properties and AVO behavior below an interpreted onset of overpressured surface. The TAPE surface was interpreted on 3D seismic using six calibration wells and validated using observed seismic interval velocity inversion in different data vintages. This surface serves as an estimate of the onset of overpressure and a starting point for a more detailedexploration wellspecific pore pressure analysis for safe and cost effective drilling.

To understand the implication of overpressure on the expected seismic response in the study area, 2D forward seismic models were generated for different fluids (gas, oil and brine) using the six wells. Modeling assumes blocky sand and shale due to poorly developed reservoirs in most penetrated overpressured intervals. The AVO model shows that:

- Brine sand expected to be Class 1 AVO
- Oil sand expected to be Class 2/2P and could be Class 1 at much deeper depth BML
- Gas sand expected to be Class 2 or 3 and could be Class 2P at much deeper depth BML

An analysis of overpressure effect on rocks elastic properties showed a reduction in acoustic impedance and anincrease in shale Poisson's ratio. For a shale-sand interface, this resulted in an upward shift in AVO intercept (RCo) and a higher AVO gradient in overpressure relative to normal pressure settings at similar depths.A comparison of actual seismic data to AVO model results at calibration wells location revealed that 3D PSDM and FWI data matched the predictions better than PSTM in the deep overpressured zones.

Conclusively, in other to increase the chance of commercial discoveries, an interpretation of the onset of overpressure and pre-drill 2D AVO modeling are critical to deep exploration opportunitygeneration/maturation and well planning/execution.

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