7th International Conference & Exposition
on Petroleum Geophysics

"HYDERABAD 2008"

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Forward Modelling PSEI* Using Well Data: A New Approach Towards Risk Mitigation in Exploration

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Summary

AVO interpretation has been the most common pre- drill hydrocarbon prospect identification methods. However as a predictive tool AVO has got lithofacies and acoustic profile of rock framework affecting the amplitude, in addition to fluids. Even though gas is known to give the maximum AVO differentiation, widely different lithofacies such as mud-filled channels, distal debris flow facies, fizz water sands are known to have gas AVO in terms of brightness and geometry. PSEI in place of AVO has less of uncertainties as it is not the results of convolution and arrived at through simple deconvolution. Our work, to actually to predict PSEI from wireline logs has led us to the important finding that we can immediately recognise potential false AVO from being possible in a horizon and thus of immense value addition to risk mitigation in exploration and amenability to statistical uncertainties predictions. On a practical case, in spite of positive AVO response, there have been some surprises encountered when some of the observed bright amplitudes in the sediments of shallow as well as deep-water basins as they have been explored. The lithofacies, fluids, log responses and the total outcome of the drilling had opacity and ambiguity to a level not amenable for the required clarity for enabling decision making. The log response and seismic characters of the bright amplitude intervals agree with each other, yet are found to be non-hydrocarbon bearing. This paper presents an application of near and far offset P to S Elastic Impedance (PSEI) at 10^0 and 50^0 respectively as a better discriminator as compared to the normal methods on the log data, for economic to non-economic gas intervals or fizz water intervals. The application of PSEI property using log data gives great confidence about its discriminating capability in the seismic domain as a prediction tool. Further studies related to PSEI attributes are in progress.

Introduction

The seismic amplitude interpretation has advanced a long way starting from the Ostrander's verification in 1982 till date. Starting from 1- statistical cross-plotting of rock properties and AVO attributes, 2- quantitative inversion of prestack data, 3- integration of rock physics and well-log data, 4- modelling prestack seismic changes, 5- anisotropic AVO analysis, 6- AVO: 3-D, 4-D, ocean-bottom & multi- component, to 7- long-offset and post critical AVO, amplitude interpretation has evolved through time and has been applied for pore-fluid typing, dim-out evaluation, fracture detection, DDI (HCI) in carbonates, reservoir characterization, etc. (Castanga, 2000). But, in spite of advances, we fall a little short of adequacy of knowledge to understand fluids and reservoir distribution fully. The current paper gives an example of such lucrative amplitudes, which did not yield commercial hydrocarbons upon drilling. Methods to explain and discriminate spurious amplitudes due to economic or non-economic gas saturation, fizz water, or lithology, were running out. With positive class-3 AVO response on seismic data and yet the normal attribute cross-plots being unable to explain adequately the strange amplitudes, it was really reversing Hasbrouck's corollary to "Geophysical dat a can't be interpreted even knowing the answer". However, the new property of angle dependent P to S Elastic Impedance (PSEI), using well logs, promises to explain and discriminate both lithology (mud-filled channel) and gas saturation as pore-fluid (fizz water and sub-commercial and commercial gas).

Scope of Study and Background of Study Area

The present work explores the utility of forward modelling of PSEI as an application of the above to four example data sets in the study area situated off the East Coast of India. The geology of the study area is depicted as vertically stacked and laterally isolated amplitude geobodies in the seismic, embodying the sub-aqueous, stacked, highly sinuous or meandering channel and levee complex. The pay zones are confined to a) clean, coarse to medium grained, sometime pebbly channel sands, b) highly laminated fine sand and clay alternation of the levee facies and c) amalgamated shaly sand and silts of overbank facies.

Theory - (PSEI)

Use of P-to-S converted waves (PS) have been suggested for obtaining additional information to solve the two specific problems of lithology identification and distinguishing between sub-commercial or fizz water and commercial gas saturation as against from PP seismic alone. In this regard, the work of Engelmark (2000) in low-impedance contrast reservoir imaging and that of Wu (2000), and Zhu et al (2000) for high Vs and low gas saturation identification are worth mentioning, where the interface properties like PP/ or PS reflectivity (Rpp, Rps) are used. Another work is that of Landro et al (1999) along the same lines, where "shear wave elastic impedance" (SEI) h as been derived from a linear approximation of Rps, assuming weak contrast and small incidence angle.

The P-to-S converted wave "elastic" impedance (PSEI) is derived (Gonzalez et al, 2003) in a similar way as the PP "elastic" impedance (EI) by Mukerji e t el (1998) and Connolly (1999) and is defined with analytical expression as:

$$PSEI\ (\theta\theta p) = \rho^{c} Vs^{d}$$

Where, θθp=P-wave incidence angle and

$$c = [K\sin\theta\theta p/(1/K^2-\sin^2\theta\theta p)^{1/2}\ ][\ 2\sin^2\theta\theta p - (1/K^2)- 2\cos\theta\theta p\ (1/K^2-\sin^2\theta\theta p)^{1/2}]$$

$$d = [4K\sin\theta\theta p/(1/K^2-\sin^2\theta\theta p)^{1/2}\ ][\ \sin^2\theta\theta p - \cos\theta\theta p\ (1/K^2-\sin^2\theta\theta p)^{1/2}]$$

In the above equations K is a constant equal to the average Vs/Vp ratio of the zone of interest. Assuming the validity of convolution model for PS converted waves and weak contrast between layers, the PSEI(θp) theoretically becomes a direct density estimator for a particular analytically defined angle $\theta p = 1/K$, as shown by Gonzalez et al. (2003). In other words θp is the root of the non-linear trigonometric equations for c and d. For the equation d = 0, the root $\theta p = \arctan(1/K)$, defines a specific angle, where PSEI (θp) = 1/ ρ.

As is known the forward model is based on well known equations, with no model uncertainty. This feature imparts a degree of robustness to the forward modeling process which is a positive of the technique.

Workflow

The forward modelling of PSEI workflow followed in the study in four data sets (Example-I, II, III & IV) using the log data is given in Figure 1. The results of workflow are compared with other cross plots used routinely in the industry. The comparison brings out that fluid differentiation and lithology differentiation is much improved when we operate in the PSEI domain rather than in the dimensions normally sought to be plotted in the routine cross plotting techniques.

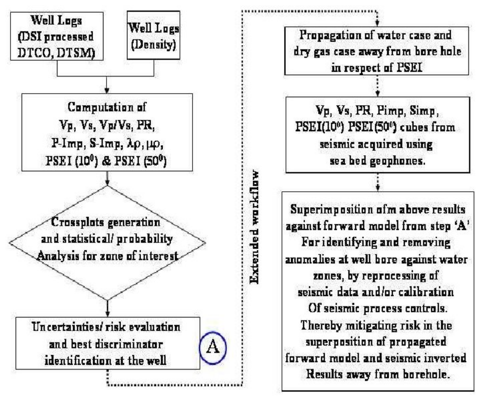


Figure 1: Flowchart of the PSEI study. The current work is up to step 'A'. Please see propagating away from the bore hole section for future work of extended workflow.

Results of PSEI vis a vis other methods: Example- I

Logs (Figure 2) and all properties and cross-plots from figure 3a through 3e suggest strongly a gas sand effect, as compared against the background shale/ clay data cluster and trends except for Figure 3f. The PSEI (10^0) and PSEI (50^0) properties derived from the log data and analysis are consistent with the actual drilled information and facts. However, pre-drilled AVO and the P, S-sonic and density log derived cross-plots, are completely misleading about the encountered lithology and fluid in data set Example-I in the young unconsolidated sediments of Pleistocene.

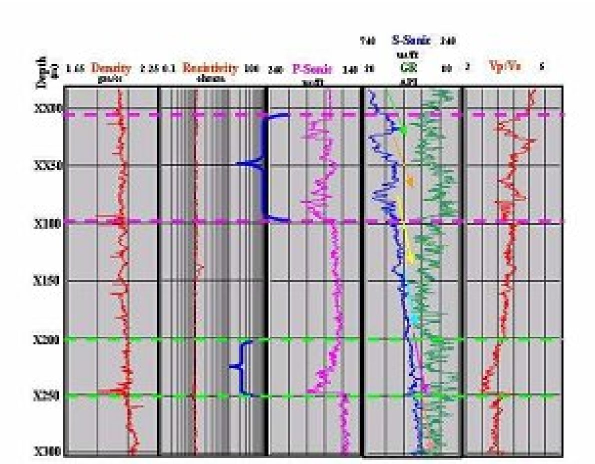
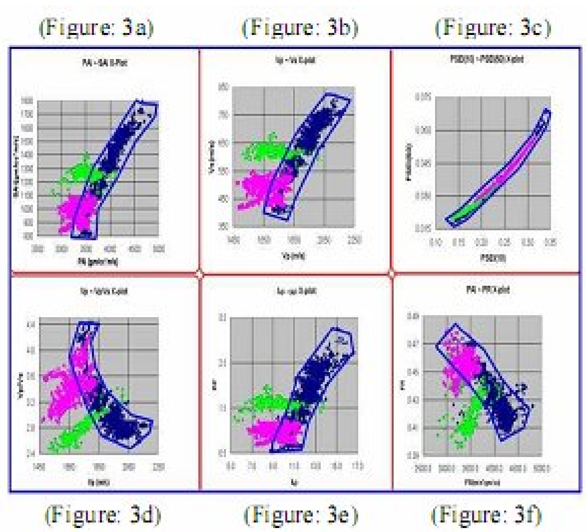


Figure 2: Log panel showing Data set of Example-I



Example- II

Log panel (Figure-4) shows Pliocene amplitude package equivalent section of Low Gas Saturated Sand and Fizz-Water, High Gas Saturated Gas Sand and Wet Sand encountered through data set Example-II. The Pliocene sequence penetrated in this well was more interesting and challenging to discriminate lithology and fluids from cross-plots (Figures 5a-5f). The low gas saturation or sub-commercial gas accumulation as supported by the test results of gas flow with water. Fizz Water was indexed to the strong amplitude equivalent interval with high compressional transit time and slightly low density on P-sonic and density logs respectively, which was validated by MDT collecting water sample. All attribute cross-plots from Figure 5a through 5e were unable to discriminate the fizz water and sub-commercial gas accumulations, as they have got almost overlapping properties with the gas sands, which was in confirmation with the pre- drilled AVO and strong seismic amplitudes. However, the Figure 5f with near and far angle PSEI attributes discriminates the commercial, sub-commercial and fizz-water better. In the lower part of gas sand the calcareous lithology with low gas saturation overlaps the gas sand polygon and could be clearly picked in all cross-plots.

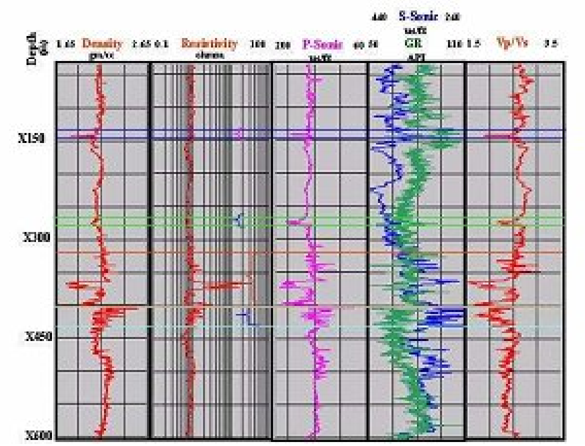
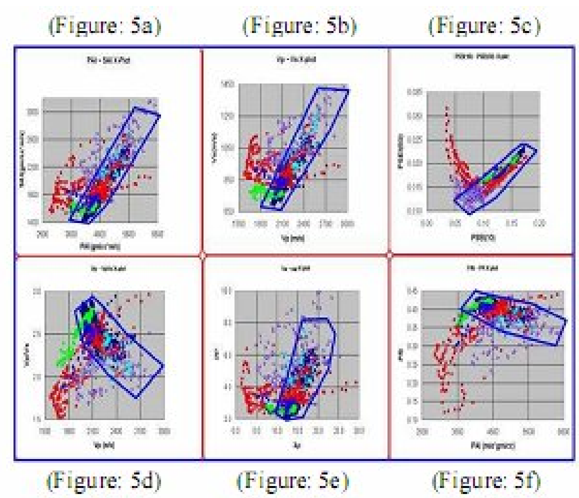


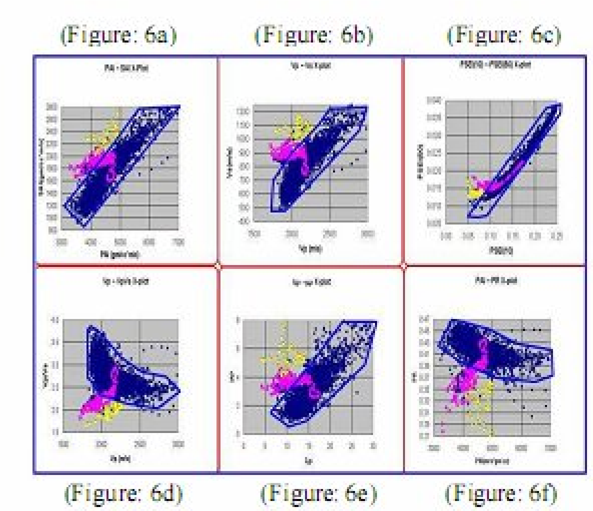
Figure 4: Log panel showing data set Example-II



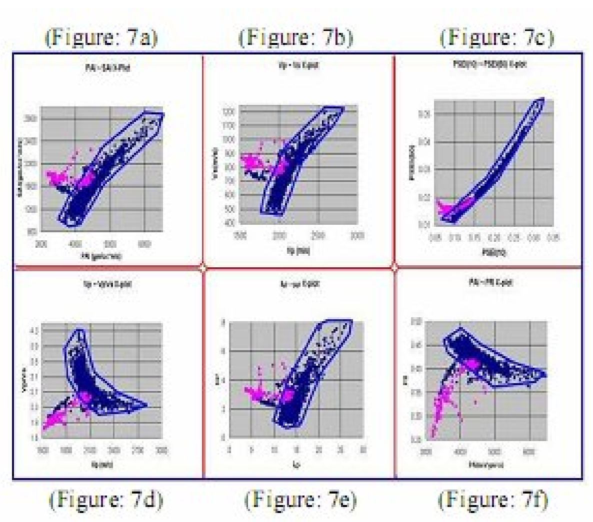
Examples- III & IV

Similar responses were found in data set Example-III and IV as shown in the Figure (6a-6f) and Figure (7a-7f) respectively.

Example-III



Example-IV



Anomaly due to lithology (Example-I)

The PSEI discrimination plot clearly confirms the lithology effect. From mud log and drilling results and formation evaluation results the corresponding amplitudes were found to be related to clay/ claystone to siltstone lithology, devoid of any potential hydrocarbon. The reservoir facies were missing, as were the reservoir fluids. Those amplitudes turned out to be upper mud-filled channel and lower possible mud-rich debris-flow sequences. However, the log properties, particularly the P-sonic, S-sonic and density, showed ambiguous characteristics, justifying a possible hydrocarbon effect causing that seismic amplitude, when plotted in various cross-plots. Figure (3a-3f) shows six different cross-plots (including the PSEI near and far angle (3f) cross-plot) between various elastic properties, colour indexing interesting amplitude zone equivalents.

Anomaly due to fizz-water and varied Gas Saturation (Example-II)

The logs of equivalent zones are shown in Figure 3. From mud log and drilling results and formation evaluation results, the corresponding amplitudes were found to be siltstone to fine to coarse-grained sandstone, with either fizz water or commercial and sub-commercial gas. The subsequent DST and MDT concluded the same. However the P-sonic, S-sonic and density and related elastic properties were ambiguous on the explanation of the failure of some bright amplitude. Figure, (5a-5f) show the six different cross- plots (including the PSEI near and far angle (5f) cross- plot) between various elastic properties, colour indexing interesting amplitude zone equivalents.

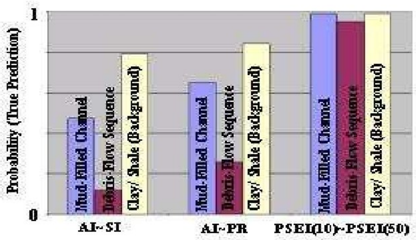
Propagating away from the bore hole

The current work flow as implemented so far, is discrete and deterministic in its out look, and limited to the bore hole but can be propagated away from bore hole. The work flow is amenable to statistical techniques to be brought to bear in order to allow one to assign uncertainties to results of individual components of the work flow. This in turn would allow one to propagate the work flow scope to beyond the bore hole current.

One way to do so is to assume a porosity range validated by well data, for a geobody and propagate the same, to obtain a PSEI (□p) for water case. Since Vp/Vs is constant for dry gas filled sand case, we can obtain PSEI (□p) away from well bore for gas case. We can then compare actual PSEI (□p) from seismic, to identify anomalies. The PSEI (□p) can be calibrated to remove anomaly against known water zone in well bore, to improve predictability away from well bore.

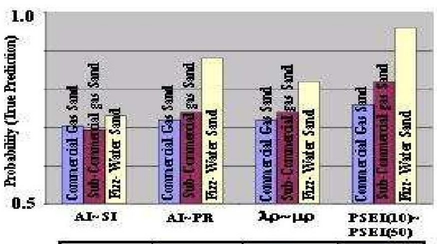
The present work has given sufficient insights to enable us to appreciate the potential rewards of such extensions of the technique as has been alluded to above.

A sample statistical uncertainty Table-1 and Table-2 for Example-I and Example-II respectively, which is the first step towards achieving these goals, is given below.



	MFCh	DFS	BG
AI-SI	0.47	0.12	0.79
AI-PR	0.65	0.26	0.84
PSEI	0.99	0.95	0.99

Table 1: Probability of true litho-class prediction from different cross-plotted parameters in Example-I.



	GS	DST	FW
AI-SI	0.70	0.69	0.73
AI-PR	0.72	0.74	0.88
λρ–μρ	0.72	0.74	0.82
PSEI	0.76	0.82	0.96

Table 2: Probability of true gas-saturation (fluid-class) prediction from different cross-plotted properties in Example-II.

Conclusions

This work conclusively demonstrates the following. •The PSEI plane promises to be a better discriminat ing plane than other common attribute planes for lithology and gas saturation identification.

• PSEI cross-plot classification can be applied as prediction tool to estimate and mitigate risk •Statistical approach in the seismic domain will gi ve risk-weighted planes in 3D

•Propagating a water case PSEI (θp) and dry gas case PSEI (θp) away from well bore can identify anomalies when superimposed on derived PSEI (θp) from seismic.

Acknowledgement

The work presented here is an illustration of a technique of analysis. The authors would like to thank ONGC for availing the data for doing the analysis and permission to present the results.

The authors would like to thank Dr. Tapan Mukerjee of Stanford University, for fruitful discussions, which have proven instrumental in clarifying various conceptual issues which could be addressed and result in the work flow presented here.

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Note: This paper has been prepared for presentation at 7th International Conference and Exposition on Petroleum Geophysics, organised by Society of Petroleum Geophysicists (SPG), at Hyderabad, INDIA, 14–16 Jan 2008.