8th Biennial International Conference
& Exposition on Petroleum Geophysics

"HYDERABAD 2010"

P-270

Significant Impact of Look Ahead VSP on Understanding The Sub-Surface Ahead of Bit – Demonstrated Value Addition as Well as Cost Savings in Deepwater Environment

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Summary

The use of VSP is not limited to G&G applications, it can play crucial role in well planning and drilling risk mitigation. This is a Case Study of three cases in which Look Ahead VSP was the technique that offered assurance against potential future loss of hole (worst case scenario), or huge in fructuous expenditure likely to be incurred implementing non productive lines of action towards securing the drilled hole , while drilling ahead.

The potential of VSP Look Ahead, in reducing uncertainty and in allowing risk mitigation to be effected through effective timely mid course corrections and choice of the right alternatives, while planning future course of action while drilling wells, is too well known to merit re-emphasis.

The cases elaborated in this paper are somewhat unique in the sense that these are examples where in Look Ahead VSP was the only possible alternative, that could lead to viable planning for avoidance of major financial losses from future possible loss of hole, or at least assure avoidance of non productive lines of action for securing hole, during the course of further drilling. The Bayesian Inversion Process used for generating the acoustic impedance and velocity profile ahead of bit, and the way it has been implemented have been elaborated in this paper.

The answers provided by this Inversion Process, if used in isolation, are by no means unique, as is well known. However, as has been demonstrated in this paper, the Inversion Process, does lead to the most likely true answer, when the critical attributes of the Inversion Process, namely, Time Window, Frequency Band, and Time-Depth Constraint are correctly optimized. Our work demonstrates that such an optimization is feasible through effective integration of surface seismic data.

Validation of this optimization has been attempted by processing only part of the data and getting a look ahead that could be checked against actual data. The results are seen to be well validated by actual data, which in turn establishes robustness of the technique used, and its wide applicability.

Introduction

Till date main use of the VSP had been restricted to being a post drill analytical tool with its main deliverable being to get velocity information in the wells and to get high frequency images. Largely VSP is being increasingly used as pre-drill and syn-drill analytical tool with deliverables critical to well planning and drilling. The corresponding value addition to deliverables from VSP in terms of safety, money and time are well established in the industry in deep offshore environment becomes all the more crucial, where the operating costs are huge. Advantages of the VSP inversion are discussed by different authors e.g. (Brewer, 2000), Campbell e. al. 2005.

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Look Ahead VSP is one technique to generate the velocity profile ahead of the bit. Look Ahead VSP is a special processing technique of the zero offset VSP (ZVSP). In ZVSP the data is acquired by placing source very close to the well and receivers inside the wells. In VSP data a very accurate velocity information of the formation passing through the well. A seismic trace at the well head as an end product is generated, known as corridor stack. In VSP the reflections from the reflectors sitting several meters (depending on data quality and length of data acquisition, usually two three hundred meters cane be predicted with confidence) below the TD are recorded. By using inversion techniques (details of technique have been given else where in this paper) this information can be used to generate the velocity profile ahead of the TD. And this information can be used to predict the depth of the deeper reflector, possible overpressure zone as well as gain an understanding of the lithology and presence and absence of reservoir development ahead of bit.

Prediction and evaluation of overpressured formations are critical for the exploration and production of hydrocarbon reservoirs. The problems associated with overpressured formations are of direct concern to all phases of exploration and production operations: drilling, casing, completion and reservoir evaluation. Knowledge of expected overpressured formations is the basis for efficiently and safely drilling wells with correct mud weights, properly engineered casing programs and effective and safe completion. Accurate pore pressure gradient and fracture-gradient values are also important assuring wellbore stability, basin modeling, and sand during testing, understanding and apprehending possible causes for avoiding formation collapse etc.

The criticality of having means at the disposal of the operator that enable the operator to have a good idea of formation pressures ahead of bit cannot be overstated in deep water environment. Any anomaly like unexpected over pressure can alter/terminate the drill plan. Having this information before reaching the target helps in revising the drilling plan. By inverting VSP data after each suite a reasonable estimate of Look Ahead velocities for next suite could be made.

The depth information of the deeper target can help in the decision making of the casing setting. The velocity information in a well can also add in the drilling plan of nearby wells.

In this paper three cases studies demonstrate how Look Ahead VSP was the only answer in risk mitigation associated with the drilling and aid decision making in drilling program in deepwater environment as well as have the information sought could be obtained, to avoidance of huge time loss and financial outgo, by the operator, the huge application of the technique is detailed.

Objective of the Surveys

The main objective of the surveys other than T-D information up to TD and generation of the corridor stack were:

- Predicting the seismic field velocity trend below TD
- Generate a Time – Depth listing below the TD
- Interpreting the seismic in the upgoing wavefield of VSP in terms of interface and interval properties from which lithological, reservoir and Pore Pressure prediction can be done.

Data Acquisition and Quality Assurance

In these cases it has been ensured that the input data met with the requirements of inversion technique, which is very stringent in terms of input data set as well as quality of data. In order to ensure that the VSP data was acquired using VSI* Versatile Seismic Imager tool which uses Q-Technology* single-sensor seismic hardware and software and advanced wireline telemetry for efficient data delivery from borehole to the surface. The tool design focuses on data fidelity and quickly adapts to changing survey needs avoids the compromise in data quality that often results from efficiency limitations. Sharper, more accurate images and reduced operating logistics vindicated the choice of acquisition. It is needless to reiterate that these elements are fundamental to addressing complex surveys and cost-effectiveness and to delivering timely answer products.4 shuttle were used with an interval spacing of 15.12m for

quicker acquisitions. And the spacing modified to 7.5 m in one of the case to ensure enough data availability for Look Ahead.

Methodology

Most of the quantitative geophysical studies are inverse problems, and as inverse problems they are non-unique problems. In an inverse problem the interface and interval properties are inverted which would minimize error (difference between the forward model derived outputs with respect to acquired data), honor the data acquired and is dependent on a viable forward model. A large number of solution sets can fit a particular data set. Linearization and adequate constraining mechanisms make the solution space to have maximum overlap with the set of meaningful potential realistic solution. As inverse problems are per se non-unique, a number of methods have been introduced to reduce the uncertainty and to attain the viable solutions. With highest reliability one of the common and popular methods is to use the Bayesian Inversion Technique (Ulrych et. al. 2001). The more insight on the Bayesian inversion has been given by. Scales et.al 1997 and Ullrych et.al 1990. The main advantage of the Bayesian is that it uses the prior information of the model and combines it with the information contained in the data and helps in reaching at a more refined statistical distribution, i.e. a posteriori model distribution. A posteriori model information constrains the model and focuses the solution towards more realistic answer. The adaptive flavor is one of the strong points of this technique.

The methodology used here is Bayesian Acoustic Impedance Inversion which is aimed at performing 1-D inversion to generate acoustic inversion. The downgoing and upgoing after deconvolution are used to derive the reflectivity and acoustic impedance profile. The output is broad band sparse reflectivity sequence and the associated impedance curve. The solution is constrained by observed time-depth information. Synthetic is also generated from the inverted data. This synthetic is compared with corridor stack and residual is minimized in least square sense, to give more accurate results. VSPs in a look-ahead mode can detect changes in acoustic impedance ahead of the bit. A one-dimensional Bayesian inversion of an intermediate VSP corridor stack can estimate acoustic impedance below the bit. Readers are invited to reference Figure 1b showing the predicted acoustic impedance (black curve) derived from the VSP corridor stack. The black curve closely overlays the pink acoustic impedance from the sonic log, which gives confidence in the data below total depth (TD). For the inversion to be accurate, wide-bandwidth data is a necessity. Longer wavelength components of the seismic wave packet control the depth of penetration below any given interface and hence assume critical importance in inversions that have forward predictions as their objectives. On the other hand modeling the propagation of shorter wavelength components is necessary where vertical resolution in depth and time domains is a favored objective of an inversion exercise. The current problem being VSP lookahead objectives such as prediction is best met by ensuring low frequency data presence and modeling the wave propagation while preserving advantage to be favored from the high frequency content. In particular, the low-frequency part of the spectrum is critical; because this is where the low-frequency trend in the inversion result is derived Estimates of density below TD are necessary for converting acoustic impedance to velocity (blue curve in Fig. 1). The missing high frequency component in Fig 1b is outcome of a deliberately chosen method of projection of data. While VSP inversion cannot match log resolution, the same however enjoys higher confidence in inversion results by virtue of the VSP being a Zero Offset VSP, definitely has more resolution when high frequency content is also compared to surface seismic. The results using high frequency is present here in a plate.The velocity profile can be derived from the acoustic impedance by using density approximation, which would be valid for the well. One method to obtain density information is Gardner's relation (Gardner, 1971).

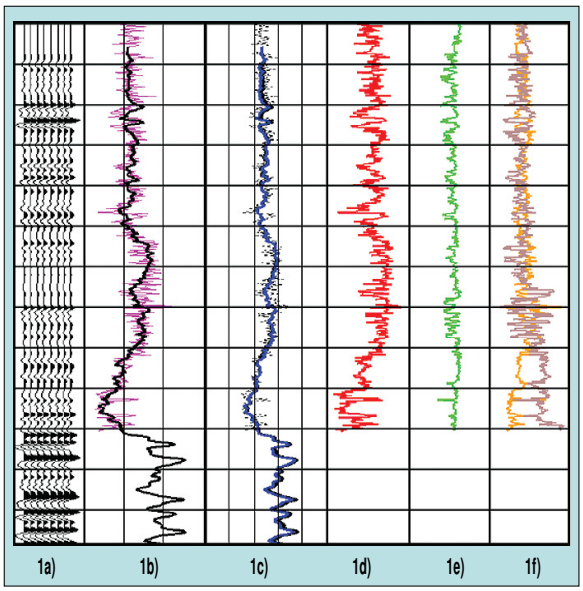

Figure1. Acoustic impedance inversion 1a) Corridor Stack, 1b) Inverted Acoustic Impedance (Black Curve overlaid on Impedance from Logs(Pink Curve) 1c) Inverted Velocity (Blue Curve) overlaid on Compressional velocity (Black Curve) 1d) Compressional Slowness 1e) Density 1f) Resistivity and Gamma Log

Gardner's relation takes the form (originally derived from brine-saturated sediments composed predominantly of shale)

$\rho = aV^b$

Where **ρ is density, V is velocity and, a and b are constants.**

a and b can be regionally determined using recorded sonic and density data. Thus by estimating coefficients a and b, the inverted acoustic impedance can be transformed to velocity. From the interval velocity at each two-way time sample below the intermediate TD a time versus depth profile is then obtained (Leaney, 1995).

Once velocity versus depth is estimated with the above technique, any method relating pore pressure gradient and velocity or slowness could be used. When combined with logs and surface seismic data, the look-ahead VSP results can be used to update a pore pressure cube in real time, while drilling.

Discussion on Case Studies

CASE 1:-

In this case operator was drilling a well in deep water and had encountered major losses in shallow section and very soft sediments were encountered in the shallow section under such conditions any unexpected gas in Water Based Mud (WBM) would have resulted in hydrates formation. Operator was considering abandoning drilling and going for contingency plans such as additional casing.

Under such challenging situation the Look Ahead VSP was the only imperative answer. For enough data availability as only 240 m of open hole (drilled with heavy losses owing to which regular mud could not be used, thereby affecting hole profile) and about 717 m of cased hole (cement quality being unknown)hence; shuttle spacing of 7.5m was proposed. Excellent data was acquired in open hole (of unpredictable hole profile) including cased hole (20").

Operator needed the solution in quick turn around time to take an important decision. Also from the Operator's perspective, it was absolutely critical to have assurance that no potential hydrocarbon (gas) accumulation was likely to occur shallower than the originally planned 13 3/8" casing string level. This was all the more critical because hydrate inhibition capability was limited by constraint of having low mud weight. The data was processed and results were of good quality and reduced uncertainty. The VSP results are displayed in Figure 2. In Figure 2, in the first panel inverted velocity is displayed, from Inverted velocity profile it can be easily inferred that there is no sudden drop in the velocities ahead of TD and hence, discard the presence of any anomalous zone. Look Ahead VSP showed absence of any anomalous zone ahead and drilling was continued safely with low mud weight. Operator made a timely drilling decision & avoided having to short land 13 3/8" casing string. Operator drilled ahead as per original plan without encountering any problems and hence saved additional casing strings. Post drilling results are also displayed in the last panel of Figure 2, in which Inverted velocity is overlaid on the post

drilled sonic velocities. The predicted velocities are very well accordance with observed velocities.

In this case it is quite clear that without the use of Look Ahead VSP Operator would have incurred huge losses for unplanned casing strings, which would result in loss of time and money. Look Ahead VSP was the only solution under such scenario which enabled Operator to take an informed drilling decision. As per the Operator, the VSP was a real value addition and the only answer in such critical situation of drill ability in deepwater environment

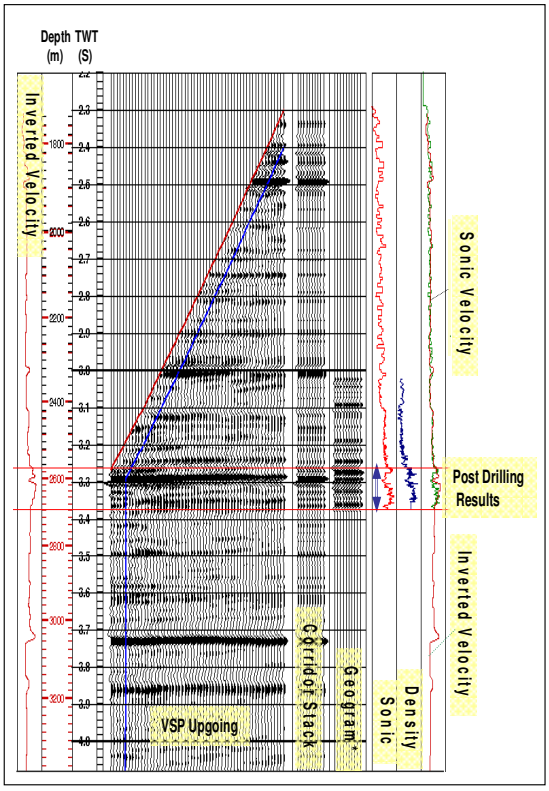

Figure 2. VSP/Geogram* & Inversion Results for Case-1 showing inverted and post drilled results

CASE 2:-

In this case the operator was faced with the challenge of drilling ahead in the volcanics basement. Operator had go 428m more to reach their planned TD. And they were quite uncertain of the presence of reservoir below the current TD and were also wondering the extent of the volcanics. All this included a risk of 3½ weeks Deepwater Rig Time. They wanted to be assured before investing any further on the well whose actual planned TD was 4415m. Under such challenging situation the Look Ahead VSP was again the only imperative answer. In this scenario VSP using VSI* (4-shuttle) was purposed. Acquisition and Processing teams worked in unison, cutting down total turnaround time to record low.

Results of VSP inversion is displayed in Figure 3. The inverted velocity profile derived from VSP data is displayed in the figure. By using inputs from VSP inverted velocities and other prior geological knowledge, Operator inferred that there is no prospective reservoir beneath the basalt. Based on the results from VSP inversion the operator stopped the drilling. Thereby, avoid loss of time and money. The drilling to plan TD would have entailed expenditure of at least 3½ weeks drilling time which in turn would have costed the Operator hugely. The unambiguous result from high quality data and processing was instrumental in Operator saving 3½ weeks plus Deepwater drilling time and thereby savings running into Millions of US$.

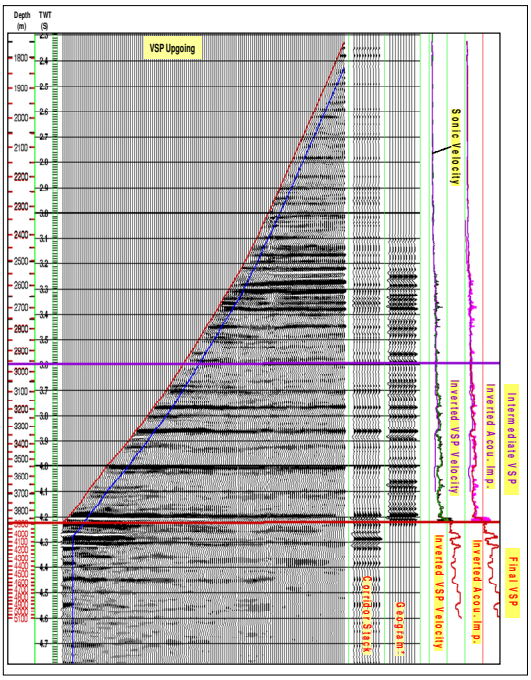

Figure 3. VSP/Geogram* & Inversion Results for Case-2. VSP inversion results for an intermediate and Final VSP results

CASE 3:-

In this case when well was drilled down to about 3945m depth, some kicks were noticed. The formation pressure obtained from SICP and SIPP was a cause for concern, because the Operator had certain misgivings regarding the feasibility of continuing drilling with the type of casing in the well given the pressure obtained. Then operator had to stop drilling and run an intermediate VSP to see the velocity changes ahead of the bit, to avoid encountering any drilling hazards. That could prove the VSP processing was insurmountable importance given the scenario. Figure No.4 shows the results. From Figure it can be clearly seen that the velocity is dropping after around 3980m. The decision making was clearly helpful by Look Ahead VSP and this was the only means available for having an estimate of the possible range of pore pressure.

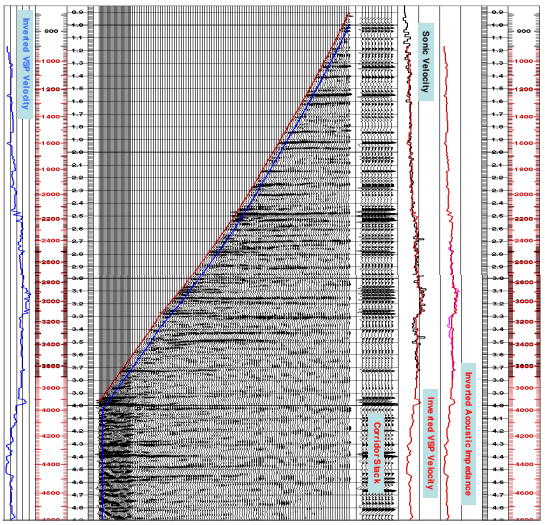

Figure 4 VSP & Inversion Results

Conclusion

The applications of Zero Offset VSP to see ahead of the bit and its utilization in the drilling operations in the deep water environment have demonstrated in the current study.

- Excellent VSP data quality from the high-fidelity tool VSI* - Versatile Seismic Imager having tri-axial sensors was extremely helpful in providing Look Ahead VSP results which is dependent a lot a on good quality data.
- In the above cases Look Ahead VSP was the only answer to help Operator make informed drilling decision. And avoid major financial losses from possible loss of hole, and at least avoiding unwanted mitigatory action for securing hole.
- The acquisition type, equipment selection and acquisition technique ensured adequate data input meeting the stringent data quality requirements of inversion technique. The results successfully demonstrated in the paper.
- The successful avoidance of loss of hole to avoidance of major drilling surprises stem from the Bayesian Acoustic Inversion for hugely successful ahead of bit predictions of acoustic impedance, velocity profile which in turn lead to significant control on pore pressures, lithology

and drillability ahead of bit. Utilization of VSP applications and a very small turn around of processing time encourage its use in planning and drilling operations in additions to G&G applications.

Future Scope

Present work can also be considered as a facet for the larger endeavor of interpretation of well seismics with surface seismics. Future work is aimed at integrating Borehole Seismic with Borehole Petrophyscis to achieve the frequency bandwidth enhancement needed for comprehensive Seismic Inversion. Ways to integrate VSP data from high angle wells and walkaway VSP adapt with interpretation of high angle and mid angle seismic gathers are being explored for calibrating seismic attributes with well data and propagation of well bore and interface and interval properties in 3D volume. Another area of interest is extension of Look Ahead VSP technology on zero offset VSP to Walkaway VSP data which would greatly enhance the utilility of the exploration.

Acknowledgement

The authors would like to thank the management for a permission to publish this paper.

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