Successful Prediction of Depth and Velocity using Look-Ahead Vertical Seismic Profile Inversion to Reduce Drilling Uncertainties

M.L. Khaitan, P. Tyagi and A. Dwivedi[1], D. Srinivas[2]

[1]*Schlumberger*

[2]*Adani Welspun Exploration Limited (AWEL)*

Abstract

The main use of vertical seismic profiling (VSP), which provides velocity information and high-frequency images, has been mostly restricted to post drill analysis. However, with the increase in uncertainties while drilling, the application of VSP as a predrill and syn-drill tool is increasing significantly. The corresponding added values of safety, capital, and time, especially in virgin, unexplored fields has been well-established in the industry. Advantages of VSP inversion are discussed by various authors, including Brewer (2000) and Campbell et al.(2005). Common drilling uncertainties include target confirmation ahead of an intermediate-depth section and pore-pressure prediction. One approach to reducing these uncertainties is using borehole seismic technologies to record a VSP at an intermediate depth to look ahead and perform VSP inversion

An operator began a drilling campaign offshore western India. The company was faced with limited well control as well as uncertainty in depth prediction based on surface seismic velocities. Depth-prediction uncertainty became more critical because they expected two porepressure ramps within a 410-ft [125-m] interval near the well TD. Well planning included optimizing mud weight and casing design, depended on the successful prediction of depth and velocity. The operator decided to run an intermediate look-ahead VSP survey to perform acoustic impedance inversion, both to confirm the velocity trend and to predict depth from the inverted velocity to know the pore-pressure boundaries. Depth prediction ahead of the bit was performed using the inverted velocities in which VSP inversion was constrained by using knowledge from an offset well. The inversion results were successful in predicting the distance to the pre interpreted targets, while the inverted velocity was successful in identifying the major pore pressure boundaries. With the help of VSP inversion results, real-time monitoring of LWD logs, and drilling parameters, the operator was able to make better informed decisions. Further, the landing of a 9.625-in [24.5-cm] casing was successfully performed at a depth 154 ft [47 m] deeper than the planned predrill survey.

After the section was drilled, a sonic log was acquired, and the look-ahead results and the sonic results were compared. It was found that constrained VSP inversion was able to predict the Target 1 (2.25 Sec) depth at an accuracy of 23 ft [7 m] from a distance of 613.5 ft [187 m], while the Target 2 (2.32 Sec) was predicted at an accuracy of 43 ft [13 m] from a distance of 971 [296 m] above it

Introduction

Look-ahead VSP is one of the techniques that can be used to generate the velocity profile ahead of the bit. Look-ahead VSP is a special processing technique of the zero-offset VSP (ZVSP), in which data is acquired by placing source very close to the well and receivers inside the wells. As an end product, a seismic trace at the well head is generated; this is known as a corridor stack. In VSP, the reflections from the reflectors sitting several meters below the TD are recorded. By using inversion techniques, this information can be used to generate the velocity profile ahead of the TD. This velocity can be used to predict the depth of the deeper reflector, possible overpressure zones, lithology, and the presence and absence of reservoir development ahead of the bit. Prediction and evaluation of overpressure formations are critical for the exploration and production of hydrocarbon reservoirs. The problems associated with overpressure formations are of direct concern to all phases of Kale A.S., Saha P.K., Agrawalla R.C., Ray G.K. and Baruah R.M., (2007) Miocene-Pliocene sequence stratigraphy of Tripura, India and it Implications on Hydrocarbon Exploration : APG Bulletin v.I p.75-84 exploration and production operations: drilling, casing, completion, and reservoir evaluation. Knowledge of expected overpressure formations is the basis for efficiently and safely drilling wells with correct mud weights, properly engineered casing programs, and an effective and safe completion. Accurate pore-pressure- and fracture-gradient values are also important in assuring wellbore stability.

In this paper, we discuss a case study in which look-ahead VSP was used for depth prediction and prediction of the pore-pressure profiles ahead of the bit. It was found that VSP inversion was able to predict the Target 1 (2.25 Sec) depth at an accuracy of 23 ft [7 m] from a distance of 613.5ft [187 m], while the Target 2 (2.32 Sec) was predicted at an accuracy of 43 ft [13 m] from a distance of 971 [296 m] above it. This helped the operator in landing the 9.625-in [24.5-cm] casing at a depth 154 ft [47 m] deeper than the original plan.

Theory/Methodology

Most of the quantitative geophysical studies are inverse problems, which are, therefore, non-unique. In an inverse problem, the interface and interval properties are inverted, which minimizes error (i.e., the difference between the forward-model-derived outputs with respect to acquired data), honors the data acquired, and depends on a viable forward model. A large number of solution sets can fit a particular dataset. Linearization and adequate constraining mechanisms ensure that the solution space has maximum overlap with the set of meaningful potential realistic solutions. As inverse problems are non-unique, a number of methods have been introduced to reduce uncertainty and to attain viable solutions. One popular method is the highly reliable Bayesian inversion technique (Ulrych et al. 2001), which has been given more insight by Scales et al. (1997) and Ullrych et al. (1990). The main advantage of the Bayesian technique is that it uses the model's prior information, combines it with the information contained in the data, and helps reach a more-refined statistical distributiona posteriori model distribution. Posteriori model information constrains the model and focuses the solution toward a more realistic answer; adaptation is one of the technique's strongest features.

The methodology used here is Bayesian acoustic impedance inversion, which is aimed at performing 1D inversion to generate acoustic inversion. The downgoing and upgoing after deconvolution are used to derive the reflectivity and acoustic-impedance profile. The output is a broadband-sparse reflectivity sequence and the associated impedance curve. The solution is constrained by observed time-depth information. Also generated from the inverted data, synthetic is compared with corridor stack, and residual is minimized in a least-square sense to give more accurate results. Look-ahead VSPs can detect changes in acoustic impedance ahead of the bit, and a 1D Bayesian inversion of an intermediate VSP corridor stack can estimate acoustic impedance below the bit. Fig. 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 TD. For the inversion to be accurate, wide-bandwidth data is necessary. 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 (the blue curve in Fig. 1). 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).

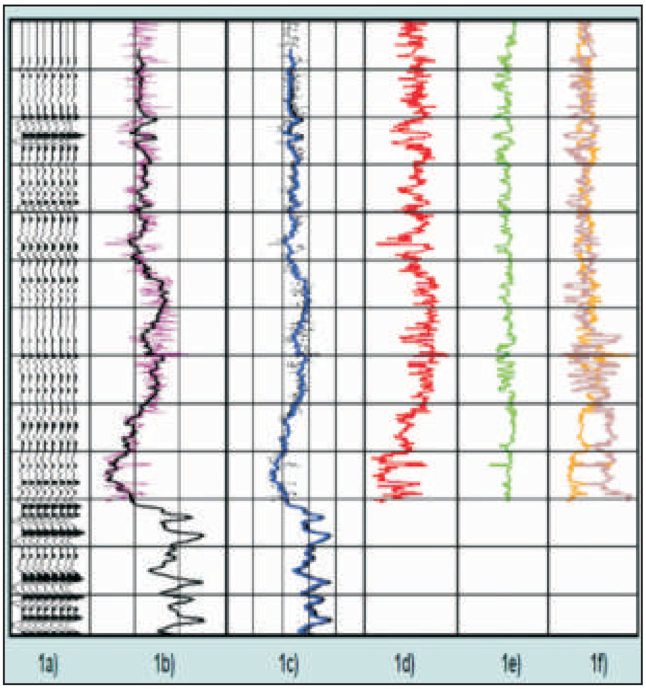

Fig. 1: Acoustic impedance inversion. 1a) corridor stack; 1b) inverted acoustic impedance (black curve overlaid on impedance from logs (pink curve); 1c) inverted velocity (blue curve) overlaid on compressional velocity (black curve); 1d) compressional slowness; 1e) density; 1f) Resistivity and gamma log.

Once the inverted velocity is attained, it can be used to predict depth ahead of the bit, and the same velocity can be used for pore-pressure prediction.

Case Study

The operator was drilling its first exploratory well offshore western India and was facing uncertainties in their depth predictions. Resolving these uncertainties became more critical, because they were expecting two pressure ramps within an interval of 410 ft [125 m] near the well's TD. Well planning which included mud weight and casing design, depended on the successful prediction of the depths. Under such challenging situations, a look-ahead VSP was the only solution. It was decided to run an intermediate look-ahead VSP and perform acoustic impedance inversion for depth and velocity prediction. The operator also needed a quick turnaround time to take important decisions on casing and further drilling. The client had interpreted two targets at a two-way time (TWT) of 2.25 s (Target 1) and 2.32 s (Target 2) corresponding to the pore-pressure ramp and wanted to confirm the same. It also sought to predict the depth corresponding to the two targets with the intermediate VSP. A ZVSP was acquired down to 7,858 ft [2395 m] MD which, upon analysis, corresponded to a TWT of 2.13 sec. The quality of data was good. An inversion was performed on the data using knowledge from offset well and surface seismic velocity constraints.

Fig. 2 shows the surface seismic correlation with the corridor stack generated from the ZVSP data. The corridor stack and surface seismic shows a good correlation with some shift in TWT times in the deeper sections. The targets and the intermediate TD is also displayed in Fig. 2. As discussed previously in this paper, the corridor stack is then converted to acoustic impedence. The velocities can be dervied from this acoustic impedance by assuming a density function that can be valid in the well.

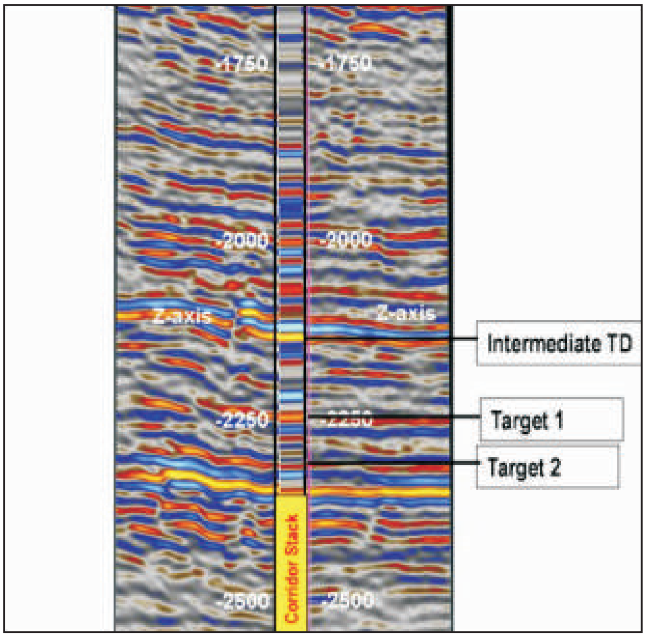

Fig. 2: Correlation between surface seismic and corridor stack (time domain), and the targets and the intermediate TD at which VSP was acquired

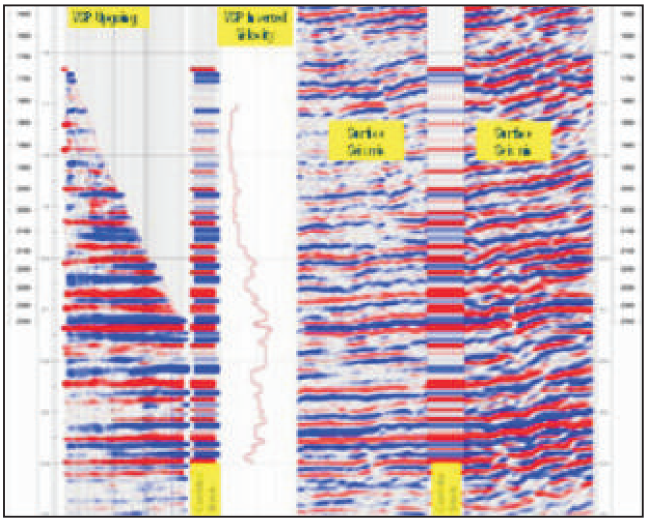

Fig. 3: VSP upgoing in TWT displayed with surface seismic and corridor stack along with the inverted velocity below the TD.

The result of VSP inversion is displayed in Fig. 3, which displays the inverted velocity profile along with the VSP upgoing and surface seismic correlation. Depth prediction below the TD was done using inverted velocities while the inverion was constrained using the PSTM velocity below the TD as well as knowledge from offset well. The depth corresponding the two targets was predicted and based on the depth prediction, real-time monitoring of LWD logs, and drilling parameters. Ultimately, landing the 9.625-in [24.5-cm] casing was performed 154 ft [47 m] deeper than the predrill plan.

A sonic log was acquired in the subsequent run after the VSP inversion. This sonic velocity was compared with the previously inverted velocity from VSP to judge the accuracy of depth prediction by the inverted data. Fig. 4 shows a comparison between the Sonic and VSP inverted velocity. Velocities from VSP inversion show a very good match with the Sonic Velocity; however, the match becomes poorer with increase in depth. Once the velocities were compared, a difference in depth predicted from VSP and as observed from sonic was calculated at the two predefined targets.

Fig. 5 shows the depth difference between VSP predicted depth and depth calculated from sonic with respect to the two way time from MSL. It was found that VSP constrained inversion was able to predict Target Depth 1 (2.25 Sec) depth at an accuracy of 23 ft [7 m] from a distance of 613.5 ft [187 m], while the Target 2 (2.32 Sec) was predicted at an accuracy of 43 ft [13 m] from a distance of 971 [296 m] above it.

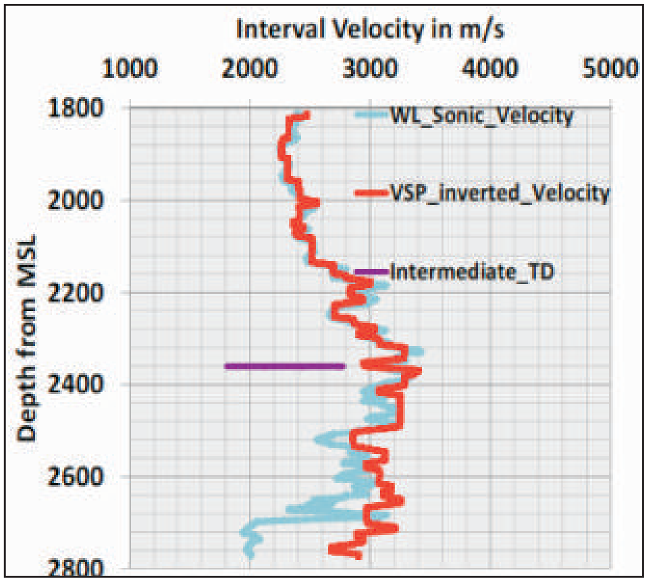

Fig. 4: Comparison between the sonic and VSP inverted velocity.

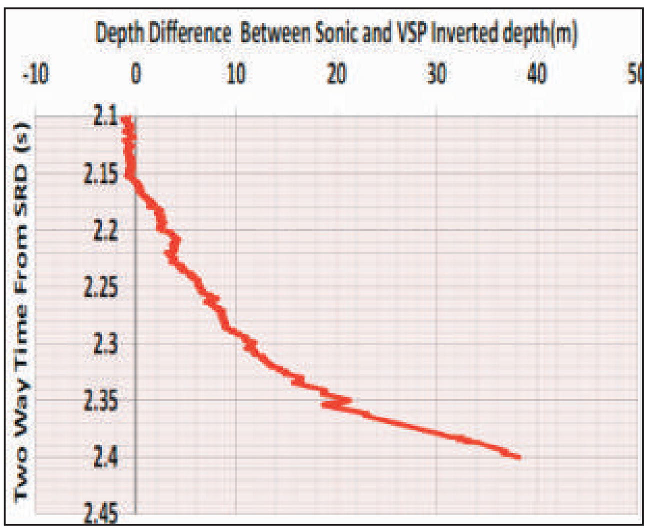

Fig. 5: Difference between the depth predicted by VSP and as seen by sonic.

Conclusions

The use of Borehole Seismic Technology to predict the depth and reach the geological target with an excellent accuracy has been presented in this case study. VSP helped to reduce the drilling uncertainty and in the process helped the client to land the 9 5/8 "Casing to the correct depth. One of the limitations of the technology is due to VSP data being band limited, particularly on lower side of the spectrum. Because of that the look ahead predictions have an inherent uncertainty which is proportional to the distance between deepest receiver and the target. This is reflected in Figure 5 which displays the difference between the actual and predicted depth and it can be seen that the difference increases with depth. Hence the success of correct prediction decreases with increase of target depth.

This case history establishes Look Ahead VSP as prime risk mitigation tool, especially in an exploratory environment. The confidence in the look ahead can be increased by combining other data such as Seismic Velocity (Migration velocity), offset well information, and real time drilling information including LWD logs.

Acknowledgments

Authors would like to sincerely thank Adani Welspun Exploration Limited (AWEL) for allowing them to publish this case study

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