# Look ahead well pore-pressure prediction using full waveform inversion

*Subrata Chakraborty*, Kanharol K Hari and Krishna Kumari*
*Reliance Industries Ltd., Mumbai. India*

**Summary**

Knowledge of formation pore pressure is not only essential for safe and cost-effective drilling of wells, but is also critical for assessing exploration risk factors including the migration of formation fluids and seal integrity. Usually, pre-drill estimates of pore pressure are derived from surface seismic data by first estimating seismic velocities and then utilizing velocity-to-effective stress transforms appropriate for a given area combined with an estimated overburden stress to obtain pore pressure. So, the accuracy of velocity models used for pore pressure determination is of paramount importance.

In this paper, an attempt has been made to predict an accurate formation pore pressure, in real time, within a deep water high temperature high pressure (HTHP) well using the full waveform inversion velocity. The initial models of P-wave velocity, Poisson's ratio and densities for the inversion process are taken from the drilled section of the same well to predict the formation pressure in the high pressured shale section ahead of drilling bit.

## Introduction

Estimation of pore pressure is becoming essential for successful drilling and completion of exploration and development wells. During all phases of oil/gas operations such as well planning, casing design and reservoir characterization, reliable pore pressure prediction is a major requirement.

Pore pressure estimation using seismic data such as velocity is well known and routinely used in the industry (Sayers et al., 2002, Dutta and Khazanehdari, 2006, Chopra and Huffman, 2006). It is well documented that significant differences exist between the velocity field obtained using different seismic techniques such as a conventional method based on the Dix conversion, stacking velocity analysis and reflection tomography. A standard NMO stacking velocity analysis can be insufficient in complex media because of its simplified layered velocity model. Although the velocity methods discussed above yield detailed pressure variation within a mini basin, such analysis are not appropriate for drilling applications and especially for HTHP wells. In these cases interval velocities at much finer scales are required, and can be obtained using pre-stack full waveform inversion (FWI).

The full waveform inversion uses the reflectivity modeling method (Kennett, 1983), as forward model, which is capable to model all kinds of waves e.g. reflection, transmissions, conversions of all wave modes, multiples in 1D domain. Here, in this study, we have generated synthetic seismograms using primary only option to make it comparable with the multiple free processed CDP gather.

The methodology does not use any approximation to the reflection and transmission coefficients for the primary and converted wave modes. Consequently, all the interference and transmission effects present in the data are correctly and accurately modeled. Inversion of the data is performed through a class of non-linear Monte-Carlo type of optimization, known as genetic algorithm (Sen and Stoffa, 1992, Mallick, 1995, 1996).

## Methodology

FWI starts with an initial (a-priori) model consisting of P-wave velocity, Poisson's ratio, density and pre-stack time migrated CDP gather (without NMO correction) at current well location. The initial P-wave velocity model is obtained from the handpicked velocity. The initial Poisson's ratio and density models are computed using the P-wave vs S-wave and P-wave vs density trends of the nearby well-logs. FWI randomly generates a number of earth models in the specified P-wave, Poisson's ratio and density ranges. Then the synthetic seismograms of these randomly generated models are and compared with the field gather in angle domain to get their respective error values.

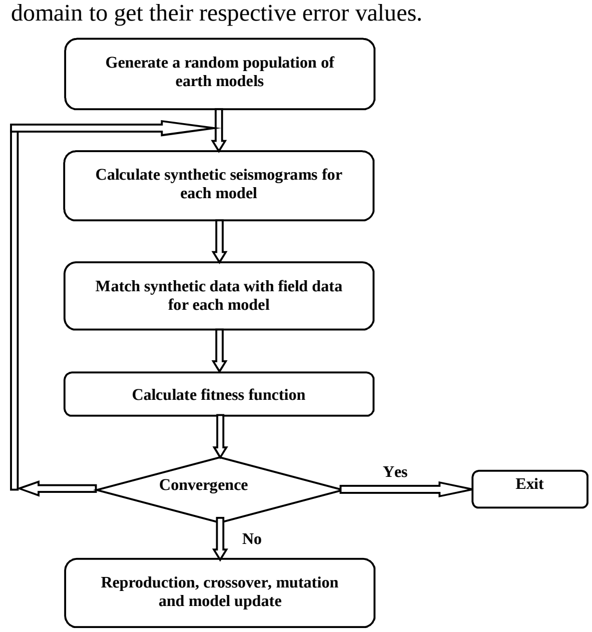


Figure 1: Flow diagram of the full waveform inversion process.

Reliance Industries Ltd., Ghansoli, Navi Mumbai. E-mail: Subrata.S.Chakraborty@ril.com 

These initial models are then modified iteratively till the error function (between the observed and the synthetic data in angle domain) is reached to a specified minimum value or the maximum iteration. Fig. 1 explains the flow diagram of the full waveform inversion process.

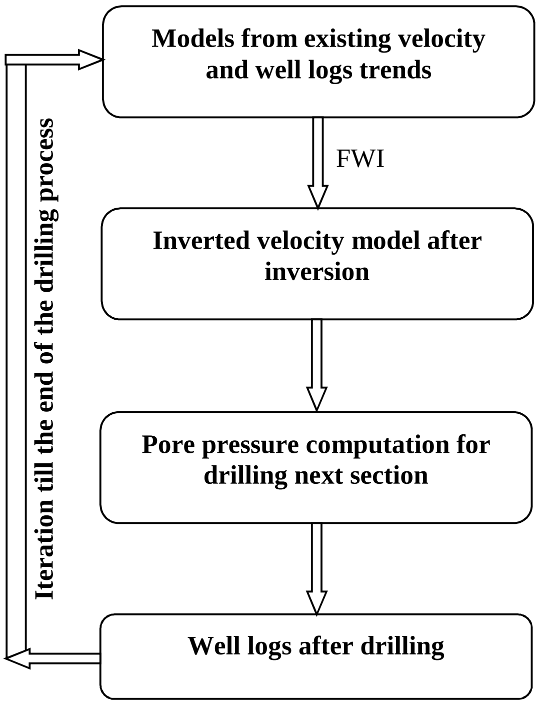


Figure 2: Flow diagram of the methodology

In this paper we adopted a methodology for iterative refinement of pore pressure required for drilling. The initial handpicked velocity model and the well logs trends were input to the inversion engine. This velocity model and the well trends are then updated iteratively for computing pore pressure in successive drilling sections with the help of the velocity and the well log trends of the already drilled section. This iterative process goes on till the end of the drilling activity. The methodology of this refinement of the pore pressure is depicted in Fig. 2.

**Case study**

The Early Miocene shales in Krishna-Godavari basin were deposited in a very high energy environment coupled with rapid burial of sediments. This probably caused generation and preservation of pressure in the sediments ranging from Late Cretaceous till Early Miocene. The uncertainty associated with the pore pressure prediction using the conventional seismic velocities, especially PSTM, is much higher.

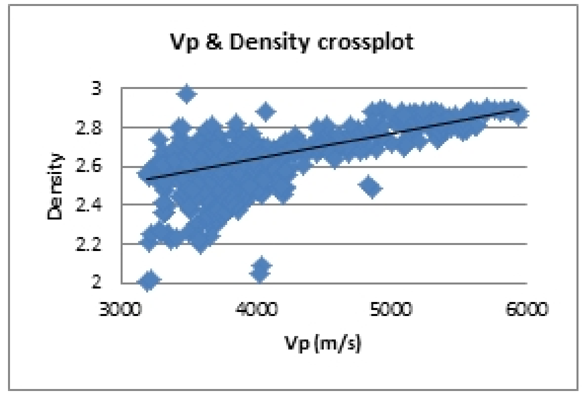


Figure 3a: A representative P-wave velocity and Density crossplot

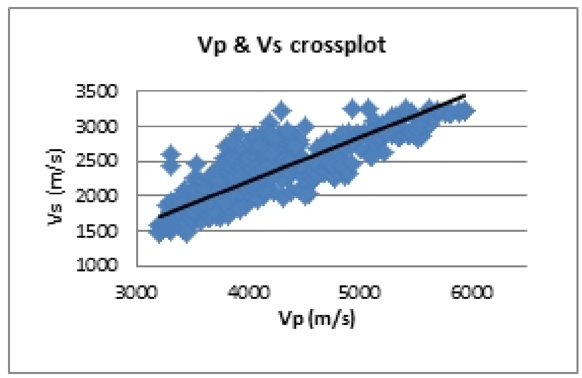


Figure 3b: A representative P-wave velocity and S-wave velocity crossplot

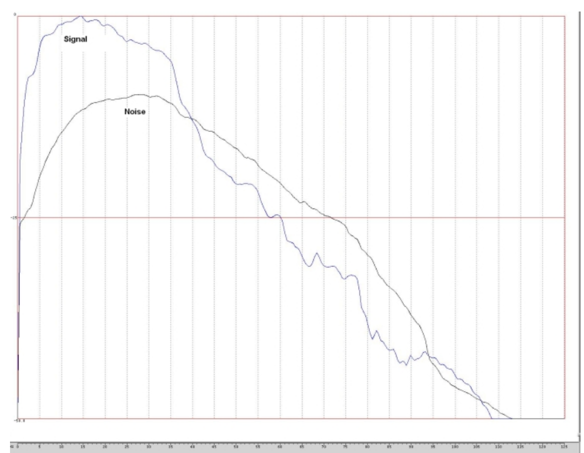


Figure 3c: A representative Signal and noise spectra in the deeper inversion window. Based on these spectra the dominant frequency and the frequency ranges required for FWI are determined.

Two wells drilled in the Krishna-Godavari basin encountered high pressure in the thick shale section. To predict this phenomenon in Well-3, in the same basin, a high resolution interval velocity model is required to know whether the same pressure regime extends to the well. Accordingly, this study was taken up to get the formation pore-pressure in this thick shale section.

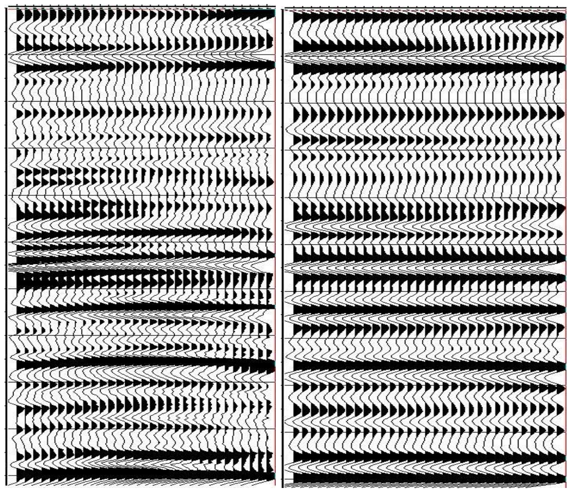

Figure 4: Real seismic angle gather (left) and synthetic inverted angle gather (right) at Well-3.

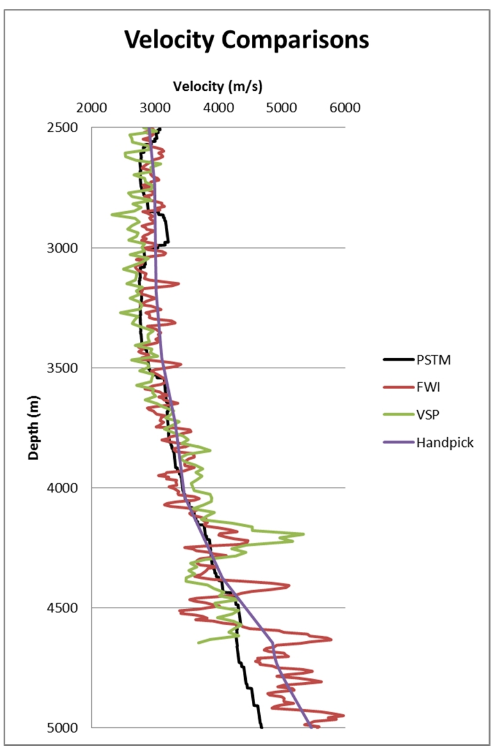


Figure 5: Comparisons all the available velocities at Well-3. FWI velocity shows better mach with VSP than PSTM.

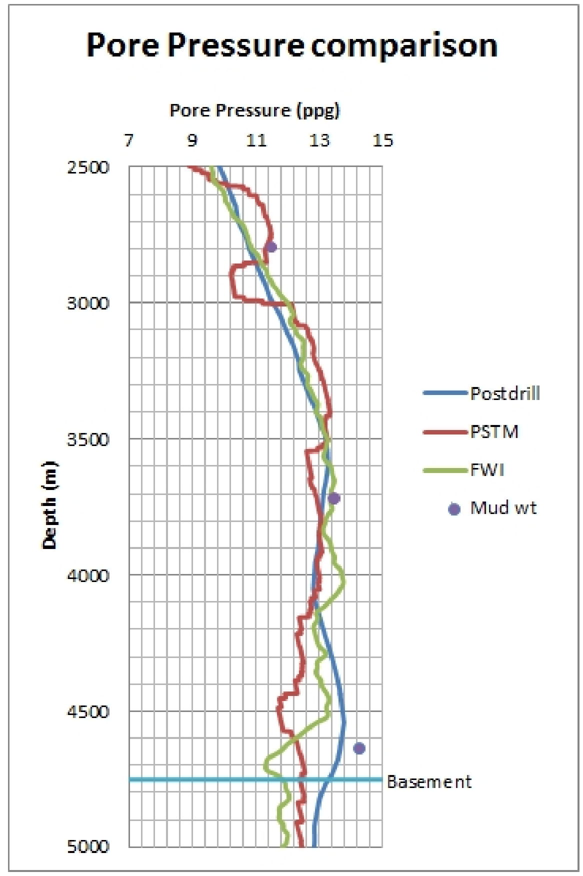


Figure 6: Comparison of pore pressure computed from different velocities with the postdrill in Well-3. The FWI pore pressure curve shows better match with the postdrill than that of PSTM.

The initial P-wave velocity model is obtained from the handpicked velocity on the CDP gather at Well-3 as shown in Fig. 5. The initial Poisson's ratio and density models are computed using the P-wave vs S-wave (Fig. 3b) and P-wave vs density (Fig. 3a) trends from the well-logs of the drilled section of Well-3. P-wave velocity, Poisson's ratio and density ranges of ±10-20%, ±5% and ±5% are used respectively for randomly generating the initial earth models. The full waveform inversion ran upto 60 iterations. The synthetic and the field CDP gathers are compared in the angle domain in the range of 5-35° (Fig. 4). The full waveform inversion is carried out in two parts – one for shallower window and other for deeper window. The ricker wavelets of dominant frequencies 24Hz and 20Hz, are computed from signal and noise spectra at shallow and deeper (as shown in Fig. 3c) inversion windows respectively and have been used in the inversion processes.

Fig. 4 shows comparison of field and inverted synthetic data in angle domain. From the velocity plot at Well-3 (Fig.

5) it is evident that the inversion velocity is matching well with the VSP velocity. The same phenomenon is also reflected in the pore pressure plots of Fig. 6. In the shallower section pore pressure computed from inversion almost follows the postdrill curve. In the deeper section, though the matching is not as good as that of shallower section, but still it could predict the high pressure zone.

## Conclusions

A pre-drill estimate of formation pore pressure is a key for a safe and economic drilling of deep water wells. Although the use of seismic velocities for pore pressure prediction is well known, the interval velocities need to be derived using a method capable of capturing the finer details for correct calculation of mud weights. FWI gives an improved vertical resolution of P-wave velocity and thus allows a more reliable and consistent pre-drilled pore pressure to be obtained.

From this real field data example, shown above, it is now evident that this methodology can be used in HTHP well conditions for predicting formation pore-pressure in real time with reduced uncertainty.

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