Overpressure prediction using VSP inversion in Mata Area, East Venezuela

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Abstract

In this paper we present a study of the inversion of Zero Offset Vertical Seismic Profiles (VSP) to detect zones with abnormal pressures ahead of the bit. VSP data recorded in a well which crossed the overpressured zone in the Area Mata, East Venezuela were used to simulate an intermediate VSP. During the study the optimal parameters of inversion were determined. Prior to the VSP inversion, an evaluation from different well logs was made to determine the zone with abnormal pressure and verify the inversion results. The results indicate that the overpressured zones can be determined, but this prediction is only obtained by adding low frequency (LF) information below the total depth (TD). Without LF information changes of impedance are obtained locally but the regional tendency of the velocity in the area is not followed, affecting therefore the accuracy of the prediction. With these values we obtained pseudo acoustic logs with the purpose of estimating the formation pressures.

Introduction

Overpressured formations cause severe problems during drilling and completion in many areas of the world. Therefore, it is necessary predict these overpressures before and during drilling, to design safe casing programs and cementation. Traditionally, in order to detect zones of overpressure, well logs and surface seismic data are used. Well data are evaluated to identify zones of overpressure in wells. These evaluations provide reference points for the 3D pore pressure volumes obtained from the inversion of 3D seismic data.

The 3D pore pressure volume is an excellent tool to handle drilling risks, but also it has certain uncertainties associated to the resolution of the seismic data. For surface seismic data, the low frequency trends in the seismic interval velocity curves are of good quality and lie between 5 and 10% of well velocities when they are processed accurately, but seismic velocities still lack resolution, even when including the high frequency components provided by inversion methodologies (Dutta, 2002). In some areas, where a higher resolution is required, the VSP inversion can be used to compensate the lack of resolution of the prediction obtained from 3D pore pressure volume. One of the applications of the vertical seismic profile (VSP) is to predict the velocity of the formations below the total depth of the well (TD) (Hardage, 1983).

The VSP has advantages over surface seismic data; the lateral resolution is better because the receivers are closer to the objective, reducing the size of the Fresnel Zone. Also, the seismic energy crosses signal attenuating shallow low velocity layer just once. The VSP also measures the velocities until TD, and inversion of the intermediate VSP provides a higher resolution of the velocities below the intermediate TD point with the intention of making decisions related to the drilling. The integration of the data with the field information to solve problems related to the pore pressure is of vital importance.

The primary objective of this work was to study the method of VSP inversion, as a tool for the prediction of zones with abnormal pressures below TD, besides determining optimal parameters of inversion. The effect of the LF behavior in the inversion results was evaluated. To make this study VSP data from a well of the Mata Area, East Venezuela which presented overpressure problems during the drilling was used.

We will present the antecedents of overpressure in the area, the inversion method and the results.

Geological and stratigraphical setting

The Mata Area is located in the South flank of the Eastern Basin of Venezuela, Maturin Sub-basin, in the Area Mayor de Oficina (Figure 1). The Eastern Basin, of type foreland, was formed by the eastward migration of the Caribbean Plate in oblique convergence with the South-American plates.

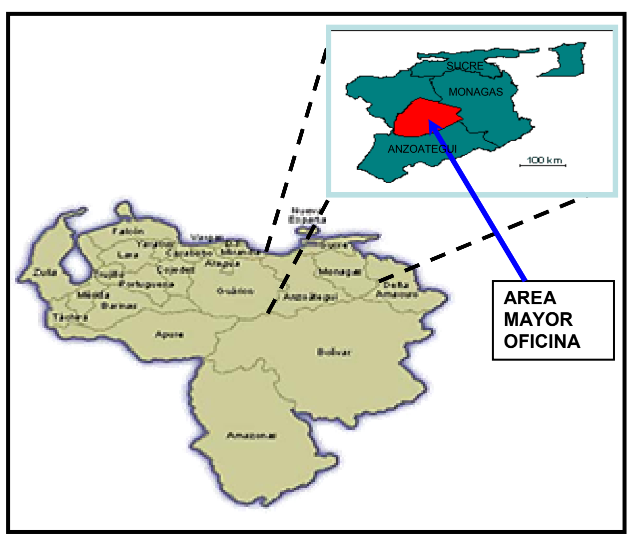


Figure 1. Study Area

The Area Mayor Oficina was affected by a strike slip tectonic regime that generated a regional faulting associated with the development of the basin (Parnaud et al., 1995). The structures are represented by homoclinal dip of low angle (3 to 5 degrees) with dip the North and the Northeast, limited by systems of normal faults of general direction E-W, NE-SW (Figure 2). These two main alignments of faults, in conjunction with a stratigraphical component, define the trap system in the fields of the zone.

The Oficina and Merecure formations are the main hydrocarbon producers in the zone. These formations were deposited in a coastal shallow marine environment, and show an abundant sequence of sands and shales that compose the reservoir and seal rocks of these formations.

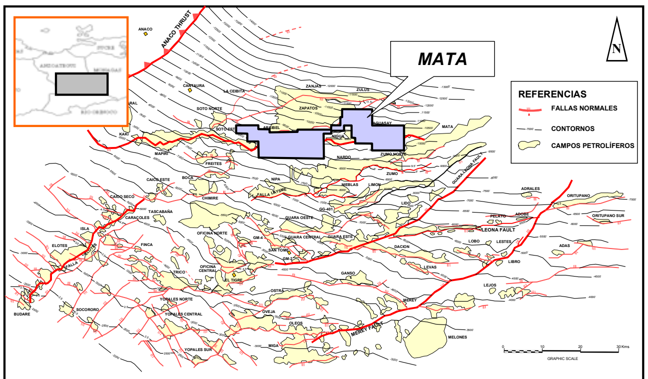


Figure 2. Regional structural map from Àrea Mayor de Oficina (Perez Companc Internal report, 2001)

The stratigraphical column in the Mata Area is constituted of sediments deposited on a pre-Jurassic basement. The formations that compose the litho-stratigraphical sequence are showed in figure 3.

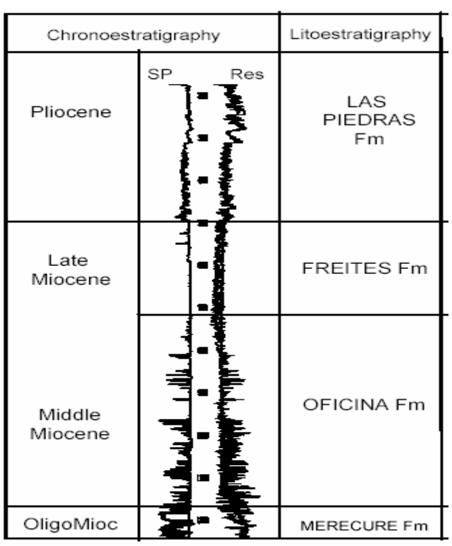


Figure 3. Stratigraphic framework of Mata Area (Modified from Picarelli et al, 2001)

The formations Merecure and Oficina (Late Oligocene – Lower Miocene) are characterized by a high sand/shale relation (70% approximately) and by the predominance of fluvial sedimentation.

The shallower Oficina (Lower to Middle Miocene) formation contains a smaller sand/shale relation (30 to 50%), due to its greater lateral continuity of sands and related to its marine depositional environment with marked tidal influence.

The Freites formation is characterized by predominantly argillaceous sedimentation, represented by argillites of low resistivity with interleaved sandy intervals.

Mesa Las Piedras, is essentially sandy and is also characterized by the predominantly continental sedimentation.

Antecedents of Overpressure in the Mata Area

For the different wells of the Mata Area, a zone of overpressure was identified of approximately 2500 feet of thickness corresponding to the Freites Formation. In figure 4, shows a superposition of the acoustic log of the study well #2 (blue) with those of another two wells in the area (yellow and orange) to corroborate the regional character of the anomaly. The black line defines the normal trend of regional compaction of the area. The anomaly is observed where the values of ΔT diverge from this trend in the interval of 5000 to 7500 ft.

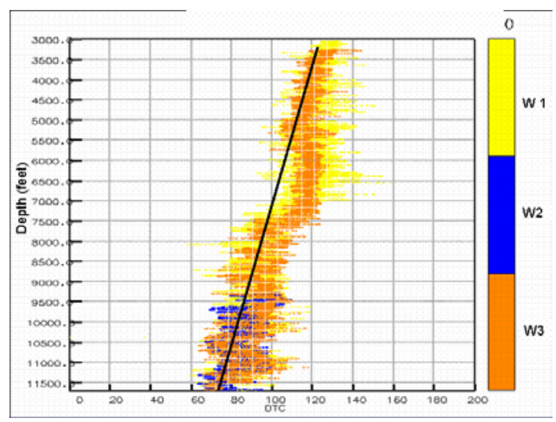


Figure 4: Plot of depth versus acoustic transit time for Wells #1, # 2 and #3.

Problems of instability and loss of circulation were present in all these wells and more severely in the neighboring well to that studied. For this reason, a study of the pore pressure gradients from the well logs and also a geomechanical study were made. An average pore pressure gradient for the geopressured zone of 0.72 psi/ft (equivalent to 13.8 lbs/gal) was estimated.

The gradients of pore pressure, gradients of collapse and gradients of fracture of this well, as well as the evolution of the weight of mud used during all the drilling are showed in the figure 4. In the section between 5000 and 7500 ft the mud weight used was greater at any moment than the pore pressure gradient, but there was a great defect with respect to the collapse gradient, thus was a deformation of the hole in this zone.

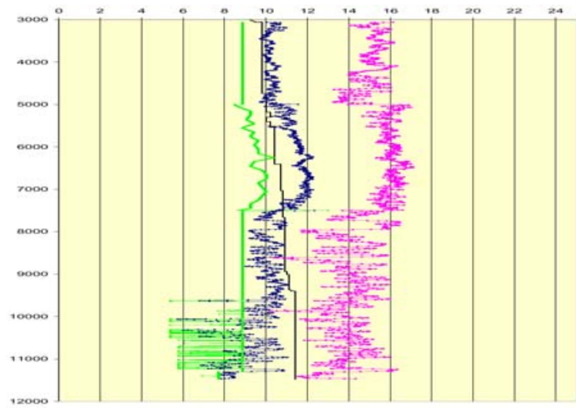


Figure 5. Pore pressure, collapse, fracture gradients, and mud weight for the study well.

Method of Seismic inversion

The seismic inversion can be defined as a numerical process that estimates the position of the reflector in the subsurface and the properties of acoustic impedance of the formations above and below a reflection interface. The result of the inversion of the VSP is an acoustic impedance log and an interval velocity log. One of the types of inversion applied to the VSP denominates Sparse Spike Inversion. This method estimates the reflectivity series that approximates the seismic data to a minimum number of sparse spikes. The results of the inversion have a high frequency content, maximizing vertical resolution.

A recursive method of inversion of a single trace, which uses the supposition of sparse spikes is the Method of the L1 Norm. The basic theory of this method is discussed in the paper of Oldenburg et al (1983). According to the author, if a high resolution deconvolution is applied to a seismic trace, the estimated reflectivity can be considered like an average value of the original reflectivity valid only in a central range of a limited band of frequency. There is an infinite number of ways in which the lost components of frequency can be replaced. Oldenburg et al (1983) shows how to reduce the non-uniqueness of the solution providing more information to the problem. The following equation represents a stratified geologic model:

$$r(t) = \sum_{j=1}^{n} r_j \delta(t - \tau_j), \text{ donde } \begin{matrix} \delta = 0 & \text{si } t \neq \tau_j & \text{y} \\ \delta = 1 & \text{si } t = \tau_j & \end{matrix} \qquad (1)$$

Mathematically, this equation is considered like a constraint of the inversion problem. Now, the stratified earth model is equal to a function of blocky impedance, which is equal as well to a function of reflectivity of sparse spikes. In this method, the L1 norm is minimized which defines the sum of the absolute values of a seismic trace.

In order to consider the acoustic impedance, velocity and density information is required, which can be provided by the equation of Gardner (1974). This equation defines the relation between speed of the P wave and density as:

$$\rho = KV^{\mathbf{0.25}} \qquad (2)$$

Where V is the velocity obtained from the calibrated acoustic log using checkshots and K = 0.23 feet/sec or 0.31 m/sec. These are typical values for sedimentary rocks. It is needed to provide a calibration time with the velocities above and below the interface. Then, a scale factor is applied to the trace so that the amplitude of the spike in the time of the assigned calibration will be equal to the coefficient of reflection. This scaling, indeed converts the trace of sparse spikes to a trace of reflection coefficients.

Knowing these velocities, the density, and the coefficient of reflection of the following spike the impedance of the following interval and each subsequent interval can be calculated.

Also time-depth pairs have to be provided below the last level of checkshot registered to generate a good estimation of the low frequency behavior below the TD. This data could be obtained extrapolating the LF behavior of the VSP of another well in the area or from the surface seismic data. If this information is not provided, a constant regional velocity underneath the TD will be used.

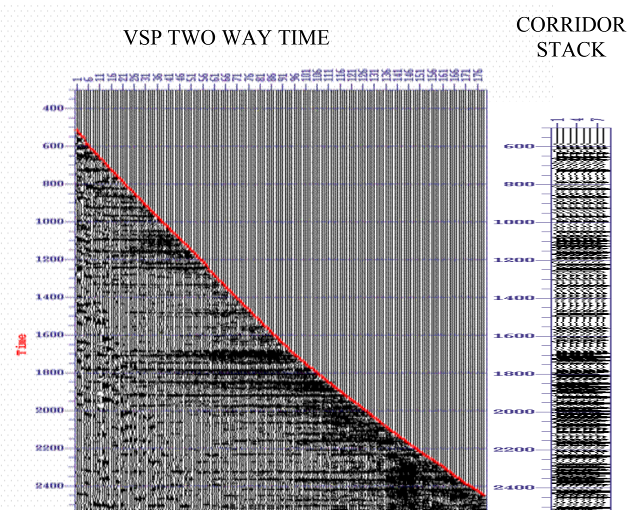
From the inversion of the VSP, the acoustic impedance below the TD can be estimated. This tool can be used to identify zones with abnormal pressures in the subsurface. The overpressures characterize those zones that have pore pressures higher than the normal hydrostatic pressure of pore fluids. They are caused by a particular zone that is beginning to be isolated or sealed. The behavior of the velocities in these zones diverges from the normal trend of compaction, diminishing its values from the top of the zone (Hottman and Johnson, 1965).

Results

The VSP inversion was applied to the study well in the interval where the VSP data was acquired in addition to other well logs. These logs helped to make an evaluation of logs previous to the inversion of the VSP with the purpose of comparing results. The processing of data Zero Offset VSP followed a standard processing sequence. The data of the VSP zero offset were processed with a passband filter of 5-10-88-115 Hz and with gain T of n = 1.18. The final result of the processing after the deconvolution and the corridor stack in two way time is showed in figure 5.

Before performing the inversion, a preliminary evaluation of the zone of overpressure from compressional □T measured in shale interval was made to detect top and base of the zone with abnormal pressure. The zone of overpressure was determined where the values of □T diverge from the normal trend of compaction. As it is observed in figure 6, the top was located at 4100 feet and the base at 6600 feet, corresponding to 1100 ms and 1700 ms respectively (two way time). This analysis was complemented with resistivity and gamma ray logs. These results indeed define an anomalous zone of 2500 ft that agrees with the same thickness identified in adjacent wells but that in this well is located shallower (1000 feet approximately) due to the dip of the area.

Figure 6. VSP two way time and Corridor Stack



The input data to perform the inversion were the corridor stack and the interval velocity obtained from the calibration of checkshot with the acoustic log. In order to be able to predict the zone of overpressure from the inversion an intermediate VSP was simulated with 580 feet as deepest level above the overpressure zone. We compared the velocity log generated from the inversion to the existing measured velocity log in all the intervals of the well.

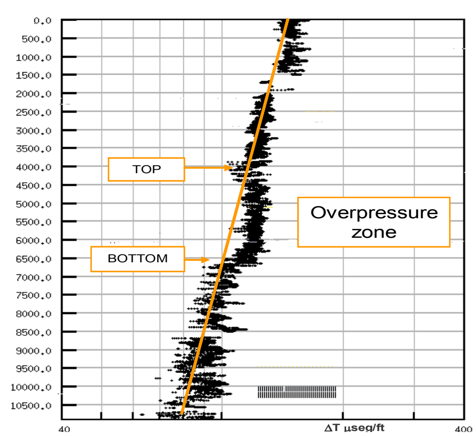


Figure 7: Plot of depth versus acoustic transit time in shale

In figure 8 we compare the original interval velocity log (left) with the results of the inversion (central and right panel). In the central and right panel are shown the corridor stack and the predicted reflectivity series. The blocky red curve represents the interval velocity until the TD and the blocky blue curve is the prediction of the interval velocity. The red curve on the right is the error curve, which measures the difference between the real depth and the depth predicted above the TD. The prediction of the depth is in the right axis of the graph.

There are two significant velocity changes at 1100 ms and 1700ms which would correspond to the top and the base of the overpressure zone identified in the well logs. These events only identify the zone of overpressure if the LF information is added underneath the TD, where the velocity diverges from the line of the normal trend of compaction, as shown in the central panel of figure 8. The top is pronounced like a diminution of the velocity, which stays constant approximately until a time of ~ 1500 ms, where it begins to increase gradually towards the base, in which the velocity comes back to the normal trend of compaction, which agrees with the behavior of the velocity in a zone of overpressure.

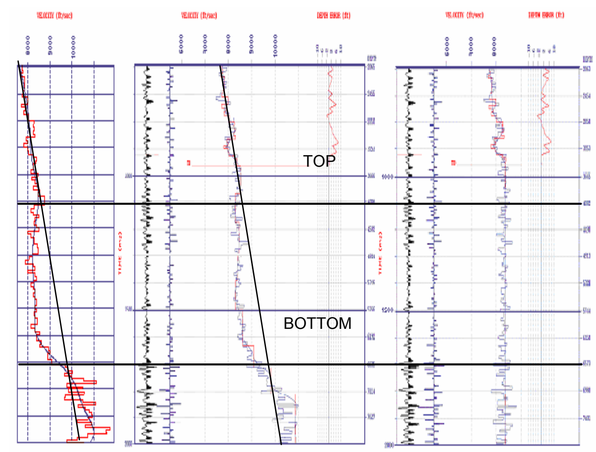


Figure 8. Left: Original Interval Velocities. Center: VSP Inversion with low frequency information below TD. Right: VSP Inversion without low frequency information below TD.

Without LF information (right panel), these same events are observed, but do not show a regional increase in the velocity; and the zone of overpressure cannot be determined. Also we can notice that there is a great similarity between the behavior of the original interval velocity curve and the one obtained from the inversion. The depth of prediction was of 4086 feet for top and 6635 feet for the base, producing a difference of 14 feet and 35 feet respectively, with respect to the depths identified in the acoustic log. Without adding to LF information, the top was predicted to a depth of 4082 feet and the base to 6575, with errors of 18 ft and 25 ft respectively. It can be seen quantitatively, the LF information, to a great extent did not alter the prediction of the depths and locally the events are located at similar depths in both cases (figure 8).

Figure 9 shows the velocity logs obtained by both inversions the values of ΔT (microsec/ft), over imposed to the true acoustic logs in time. We can see that the inversion with LF information has a good correlation in almost all the interval with the original log. However, for the inversion without LF information, the correlation is good until 2500 feet below the TD. Also, the base of this zone is observed, but only in the first case. In general, the values of the pseudo velocity logs are adjusted reproducing the most important high frequency interval velocity changes seen on the measured acoustic log.

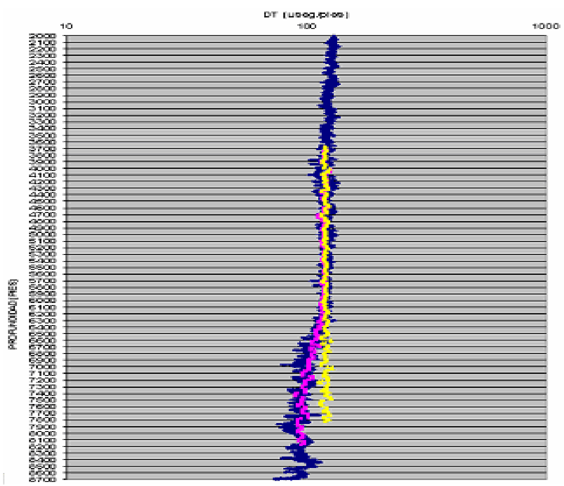


Figure 9. Blue curve: Calibrated Acoustic Log. Magenta curve: Pseudo Acoustic Log with low frequency information below TD. Yellow curve: Pseudo Acoustic Log without low frequency information below TD.

In figure 10 we compare the behavior of the previous cases with the true velocity curve in the time domain. The dotted red lines indicate some events with excellent correlation.

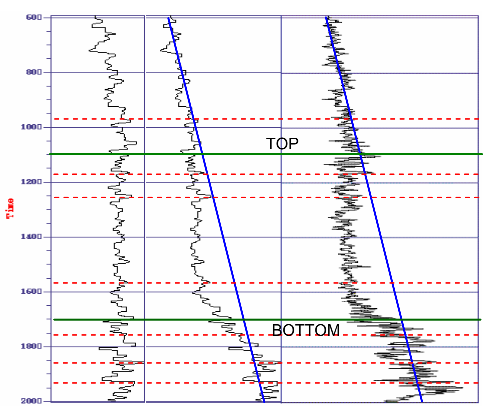


Figure 10. Time domain velocity curves. Left: VSP inversion without low frequency information below TD. Center: VSP inversion with low frequency information below TD. Right: Measured Velocity Log.

Estimation of pore pressures

By applying the method of Hottman and Johnson (1965), the formation pressures with these three velocity logs were estimated. At a depth of 5000 ft for example, the difference of ΔT between the normal trend of compaction, ΔTn, was determined, and the value of real ΔTan. This value was introduced in the chart of the FPG to obtain this value, which was measured manually and then multiplied by the depth in study. The pressure of formation to this depth is 3750 psi. From the inversion pressure value of 3400 psi was obtained, showing 9 % of error in the prediction of the fluid pressure, which, to be a gross analysis produced a good result of prediction. Also we should consider the fact that a discrimination of the velocity of sands was not made to calculate the pore pressures, producing a different trend of compaction to the real one. Perhaps, making a more detailed calculation of the FPG and using nearby well information, we could have more reliable results to determine the weight of the mud.

Bandwidth effect

Also these VSP data were filtered with a passband filter of 5-10-70-95 Hertz. The new VSP inversions lose resolution proportionally to the bandwidth reduction. it is clear that the wider bandwidth produce higher resolution.

Conclusions

From the inversion of Zero Offset VSP data, zones with abnormal pore pressure below the intermediate TD of the well can be determined. The determination of these zones of overpressure is only obtained by adding LF information below the TD. Without LF information changes of impedance are obtained locally, but the real regional trend is not followed.

Due to its higher frequency content, the VSP inversion reproduce the events of high frequency related to lithological changes very well, and can differentiate, for example, the velocity changes due to non-clastic low velocity rocks and the velocity changes due to overpressure.

Adding LF information to the VSP inversion, allowed values of ΔT from the predicted interval velocities to be obtained, producing estimated values of the measured acoustic log ahead of the bit until approximately 4000 feet below TD.

The best approach for use of the inversion is to integrate these results with information from neighboring wells and a 3D pore pressure volume to build a model of pore pressure before continuing to drill the well.

The prediction of zones with abnormal pressures helps with mud weight design and casing plans to prevent potential drilling problems and unplanned increases in cost.

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