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Pore Pressure Prediction from Well Logs and Seismic Data

Bikas Kumar,*, Sri Niwas[1], [b], Bikram K. Mangaraj[2], [c]

Summary

The subject of detection of abnormally high pressured zones from seismic has received a great deal of attention in exploration and production geophysics because of increasing activities in frontier areas or offshore and a need to lower cost without compromising safety and environment, and managing risk and uncertainty associated with very expensive drilling. An estimation of pore pressure can be obtained from seismic velocity as well as from well logs. Using interval velocity volume to estimate pre drill pore-pressure, but the seismic velocities need to be derived using methods having sufficient resolution for well planning purpose. Velocity field obtained using a conventional method based on the Dix equation. Parameters in the velocity- OBG-NCT-to- pore-pressure transform are estimated using seismic interval velocity and pressure data from nearby calibrated wells. The uncertainty in the pore pressure prediction is analyzed by examining the spread in the predicted pore pressure obtained using parameter combinations which sample the region of parameter space consistent with the available well data. Whenever we go for a virgin area, seismic would be more reliable since it is spatially well sampled and we can reached up to the bottom of the seismic volume. On the other hand pore pressure prediction from well logs is accurate at a particular point only, but they are spatially limited. It has also depth limitation. By bringing the two together secrets hiding in subsurface data can be revealed.

***Keyword**: Pore pressure, Interval velocity volume, OBG and NCT.*

Introduction

It is vital to the planning of drilling wells to have an estimate of the expected pressure regime to be encountered in the subsurface. Direct concerns are the safety of the personnel and equipment, in particular minimizing the associated risks. Furthermore, it facilitates more effective planning and ordering of the required material. With respect to the reservoir, the right drilling mud weight is important. If it is too low, a blow out might occur and conversely, if it is too high, the formation might be damaged by invasion of the drilling fluid.

In recent years the prediction of pore pressure has undergone various developments. Geoscientists, such as reservoir and processing geophysicists, are more involved in the application of processes to do predictions based on seismic in 3-D. Historically, it was only done on site in 1-D. The advancement of seismic processing allows a more and more accurate estimation of the velocities. The combination of the knowledge of engineers and geoscientists is extremely valuable in trying to predict the pressure cube. Besides extracting the forecast pressure profiles at future drilling locations from these volumes, they have an interpretation value. They allow scanning to provide alternative well locations, see how the pressure regime is distributed with respect to the structure and geology, and help with the identification of sealing or leaking faults. This last item is even better facilitated when used in combination with other now standard seismic attribute volumes that help to identify fluids and sands, such as those from AVO and elastic inversion (Covering, 2007).

It is the process of deriving as accurate as possible velocities from seismic processing which is one of the key factors in predicting reliable pressure. Obviously, this is where the processing geophysicists come in. On the other hand, this needs to be combined with an in-depth analysis of the well data, pressure data, and drilling data by an experienced person such as petrophysicist and drilling engineer. The role of the reservoir geophysicist is to integrate the subsurface information with the specially conditioned seismic data to achieve the most reliable results.

[a] *Student,* [b] *Professor, Department of Earth Sciences, IIT Roorkee, Uttarakhand, India,*
E-mail: kbikas100@gmail.com
[c] *Chief Geophysicist (S), INTEG, GEOPIC, ONGC Dehradun, Uttarakhand, India*

In this paper we describe the extensive pore pressure prediction (PPP) from three given wells namely Well-1, Well-2 and Well-3 and also from the 3-D marine seismic data acquired over the same area in the Arabian Sea, India. 3-D seismic data was available in the form of Pre Stack Time Migration (PSTM).

1.1 Concept of Pressure

Pore pressure or formation pressure, P, is defined as the pressure acting on the fluids in the pore space of a formation. Hydrostatic pressure, P_h, is the pressure caused by the weight of a column of fluid:

$$P_h = \rho_f gz \qquad (1)$$

where z, ρf and g are the height of the column, the fluid density, and acceleration due to gravity, respectively. The size and shape of the cross-section of the fluid column have no effect on hydrostatic pressure. The fluid density depends on the fluid type, concentration of dissolved solids (i.e., salts and other minerals) and gasses in the fluid column, and the temperature and pressure. Thus, in any given area, the fluid density is depth dependent. In the SI system, the unit of pressure is Pascal (abbreviated by Pa), and in the British system, the unit is pounds per square inch (abbreviated by psi). We note that 1 Pa=1.45x10-4 psi=1 N/m2. This is a rather small unit and for most practical applications, it is customary to use megapascals (MPa), where 1 MPa=106 N/m2.

The formation pressure gradient, expressed usually in pounds per square inch per foot (abbreviated by psi/ft) in the British system of units, is the ratio of the formation pressure, P (in psi) to the depth, z (in feet). It is not the true instantaneous gradient, dP/dz. In general, the hydrostatic pressure gradient, Pg (in psi/ft), can be defined by

$$Pg = 0.433 \times \text{fluid density (in g/cm3)} \qquad (2)$$

The overburden pressure, $S(z)$, at any depth is the pressure which results from the combined weight of the rock matrix and the fluids in the pore space overlying the formation of interest. This is expressed as

$$S = g \int_0^z \rho b(z)\,dz \qquad (3)$$

where ρ_b is the depth dependent bulk density given by

$$\rho_b = \phi\, \rho_f + (1-\phi)\, \rho_g \qquad (4)$$

where ϕ, ρ_f, and ρ_g are the fractional porosity, the pore fluid density, and the density of the matrix (grain density), respectively. The overburden pressure is depth dependent and increases with depth. In the literature, the overburden pressure has also been referred to as the geostatic or lithostatic pressure. (Dutta, 2002)

The effective pressure or differential pressure, σ, is the Pressure, which is acting on the solid rock framework. According to Terzaghi's principle (Terzaghi, 1943), it is defined as the difference between the overburden pressure, S, and the pore pressure, P:

$$\sigma = S - P \qquad (5)$$

It is σ that controls the compaction process of sedimentary rocks; any condition at depth that causes a reduction in σ will also reduce the compaction rate and result in geopressure

Fig.1 Showing the relationship between overburden pressure and the pore pressure i.e. Terzaghi's principle. (Terzaghi, 1943)

2. Methodologies Used

There are number of methods which are available for the pore pressure prediction over a single well or even in the case of seismic data. But we are focusing on only those methods which are currently running or the methods used in oil industry for the pore pressure prediction. We use the methods like Eaton's Resistivity, Bower's Sonic for the pore pressure gradient analysis and also using Eaton's approach for the Fracture gradient analysis. All the methods are listed below.

2.1 Eaton's Resistivity Approach

The Eaton Method is one of the more widely used quantitative methods. This method applies a regionally defined exponent to an empirical formula. His study has resulted in the development of four equations that may be used for the prediction of geopressure from well logs and drilling data. Equations are given for use with resistivity plots, conductivity plots, sonic travel-time plots, and corrected "d" exponent plots. All equations have the same theoretical basis.

In 1965, Hottman and Johnson presented a method for predicting geopressure by using resistivity and sonic log data. This technique has received wide acceptance even though the prediction charts were based only on data concerning Tertiary age sediments in the Gulf Coast area. It was specifically pointed out that these techniques were applicable only in areas where the generation of geopressures is primarily the result of compaction due to overburden stress.

In 1972, this author presented a theory on the effect of overburden stress gradients and geopressure prediction techniques. Compaction caused by overburden stress was described classically in a soil mechanics book by Terzaghi and Peck in 1948. With a vessel containing a spring and a fluid, they simulated the compaction of clay that contained water. Overburden stress was simulated by a piston. It was shown that the overburden stress, S, was supported by the stress in the spring, sigma, and the fluid pressure, p. Thus, the long- accepted equation of equilibrium was established.

$$\mathbf{S = \sigma + p}$$

it is obvious that if S is increased and the fluid is allowed to escape, sigma must increase while p remains as hydrostatic pressure. However, if the fluid cannot escape, p must also increase as S is increased. overpressured zones are often called "abnormal" pressure zones or "geopressure" zones. Eaton uses the following formula for the calculation of pore pressure gradient through resistivity.

$$\mathbf{PP = OBG - (OBG - PP_N)\ (R_o/\ R_N)^{x}} \qquad (6)$$

Where PP = Pore Pressure Gradient (ppg), OBG = Overburden Gradient (ppg), PP_N = Normal Pore pressure Gradient (ppg), R_o = Observed Resistivity (ohms-m), R_N = Normal Resistivity (ohms-m), x = Eaton Exponent (dimensionless), which is 1.2.

2.2 Bower's Sonic Method

Bower's method uses the sonic velocity and empirically determined parameters to determine the vertical effective stress, which is then subtracted from the overburden (the vertical total stress) to determine the pore pressure. This method can be applied to predict pore pressures caused either by compaction disequilibrium or due to some source mechanism.

Only two empirical parameters are required when excess pressures are caused by compaction disequilibrium. The value of the two empirically determined parameters can be determined in a Compaction Trend Analysis or chosen by experience in offset wells. We need to know the value of the sediment's previous maximum effective stress, σ_{max}, to perform this analysis plus we need to establish the sediment's "unloading" velocity effective stress behavior, which is specified by the unloading parameter, U. The value of σ_{max} is calculated from the normal compaction response and the user- specified value of σ_{max}; and the value of U is empirically determined. Pore Pressure are calculated as follows

$$PP = OBG - \frac{(\sigma_{max})^{(1-U)}\left(\dfrac{\dfrac{10^6}{DT} - \dfrac{10^6}{DT_{ml}}}{A}\right)^{(U/B)}}{depth} \quad \text{and,}$$

$$\sigma_{max} = \left(\frac{\dfrac{10^6}{DT_{min}} - \dfrac{10^6}{DT_{ml}}}{A}\right)^{(1/B)}$$

Where PP = Pore Pressure Gradient (ppg), OBG = Overburden Gradient (ppg), DT = Sonic travel time (microsec/m), DTml = Sonic travel time corresponding to Vmax, A, B, U = Empirical values, Vmax = The velocity at which unloading occurred for sediments buried at depths greater than dmaxv, dmaxv = Depth at which unloading has occurred, depth = TVD in appropriate units.

2.3 Eaton's Fracture Gradient Analysis

Eaton's method requires pore pressure, Poisson ratio, and the overburden gradient that we have already analyzed in the previous step. The following equation is used in the calculation:

$$FG = PP + (OBG - PP)\ (\upsilon/\upsilon\text{-}1) \qquad (7)$$

Where, FG = Fracture Gradient (ppg), PP = Pore Pressure Gradient (ppg), OBG = Overburden Gradient (ppg), υ = Poisson's Ratio (dimensionless).

3. Results and Discussion

3.1 Pore Pressure Analysis from Well Data

This is shown in **Fig. 2.** There are four types of curves which are shown in the (a) all depicts the gradients. Since OBG is over gradient pressure which combines both pressure in the matrix as well as in pores. Therefore, it will be always maximum, which is also shown in the mentioned plates. Fracture gradient is just lagging behind the OBG, which indicating the behavior of geomechanical strength of particular formation. In this case we have both resistivity as well as sonic data therefore pore pressure gradient analysis has been performed by these two. Up to 1400m normal trend of pore pressure gradient is continuously increasing. It abruptly decreases at 1500m then again increasing afterwards. LOT data also showing the validation with fracture gradient Therefore there could be a possibility of high pressure zones. In part (b) the curves showing the absolute value of pore pressure as well as fracture gradient.

3.2 Pore Pressure Analysis from 3-D Seismic Data

The interval velocity cube which is used for the pore pressure analysis. It is used throughout in all the three wells in the form of interval velocity that we extracted from the cube for corresponding three wells. We apply the basic sequence pore pressure analysis for 3-D case and we use these cubes for the calibration of wells. 2-D section has been also generated for better visualization of pore pressure variation within a particular depth interval. The beauty of 3-D velocity cube is that in whole velocity cube we can extract pore pressure at any point and we can go up to the last extent of the data also its lateral resolution will be high. On the other hand in the case of well logs we can predict the variation of pore pressure at a point very accurately but predicting at some other point away from the well would not be accurate as much as we have in the case of seismic, the value will be the interpolation between three wells, its lateral resolution would be less and also it has depth limitation (upto log depth).

Analysis of Wells

This is shown in **Fig. 3**. It represents three linear tracks, the left hand track showing interval velocity curve, normal compaction trend (NCT) and also composite density curve. Interval velocity showing decreasing trend between 2600m to 5800m. This means that there is some anomalous zone which led to the deviation of interval velocity from its normal compaction trend (NCT). Also composite density curve showing decreasing trend within that interval since velocity is decreasing and it also can be verified with the porosity curve which is shown in extremely right hand track. The track which are present in the middle showing the increasing trend of pressure gradient within that particular interval is due to the presence of source rock i.e. shale and limestone from published well completion report. It is having the property of high porosity and less permeability. Therefore, pressure increases slightly.

Fig. 4 showing the combined results of three wells together with Lithological column. It gives us better correlation that how pressure gradient varies where we encounter different lithology in a particular formation. Moreover on imposing the curves of pressure gradients from wells, we found that functional trend of pore pressure gradient curves are partially matching with the curves that we are obtained from the seismic. The reason behind is that, velocity in case of well logs is of very high frequency while in seismic it is very low frequency. Therefore two velocities will never match. Another reason could be the anisotropy factor. In seismic case, velocity may be different in x and y direction due to anisotropy but, in logging since it is one directional (vertical) therefore it would be same.

Pore Pressure Section

We generated 2-D section of pore pressure cube which is shown in **Fig. 5.** It is clearly showing high pressure zone within same range due to the presence of source rock i.e. shale and limestone from published well completion report.

4. Conclusion

A predrill estimate of pore pressure can be obtained from seismic velocity using a velocity-OBG-NCT-to–pore pressure transform. However, the seismic-interval velocity needs to be derived using a method capable of giving a spatial resolution sufficient for predrill well planning. Pore pressure is predicted from well logs as well as seismic data of the same region independently. It is found that high pressure zones are roughly sonic and we observed that pressure prediction from sonic is more reliable than resistivity. Since, resistivity log needs many corrections like temperature, borehole and it also depends on salinity of the formation fluid. Wells are calibrated with available LOT data. Pressure prediction from seismic data mainly depends on interval velocity. By using seismic data we can predict the pressure up to the bottom of seismic volume. This could not be achieved from well logs. From seismic we encounter high pressure zone which lies roughly in the interval of (2400-2600)m – (5600-6000)m i.e. increasing from Mahuva top. Functional trend of curves from well logs is partially matching with the curves from seismic. Broadly, both are showing similar kinds of trend.

5. Limitations

It is important to point out the limitations of the present analysis. In general, a different velocity-OBG-NCT-to–pore- pressure transform should be used for layers of different lithology or geological age. Usually, however, a single velocity-OBG-NCT-to-pore pressure transform is used which is the approach followed in this paper. The present study was carried out using conventionally available well data and 3-D PSTM seismic data over producing field. Accuracy of the result depends on accuracy of interval velocity used. Effect of fluid saturation and other structural features are reflected in P wave velocity at the time of acquisition of input data. Subsequent drop/rise in pressure due to production or fluid injection at reservoir level is not accounted for. Also centroid effect due to structural relief of reservoir bed and basin modeling for pressure taking structural framework was not addressed. Above study was mainly used for arriving at proper mud weight and casing policy for pre drill location over non producing field. Also we should predict the pore pressure to minimize the cost and risk which is associated with drilling rigs and also we could prevent drilling hazard such as rig blowouts.

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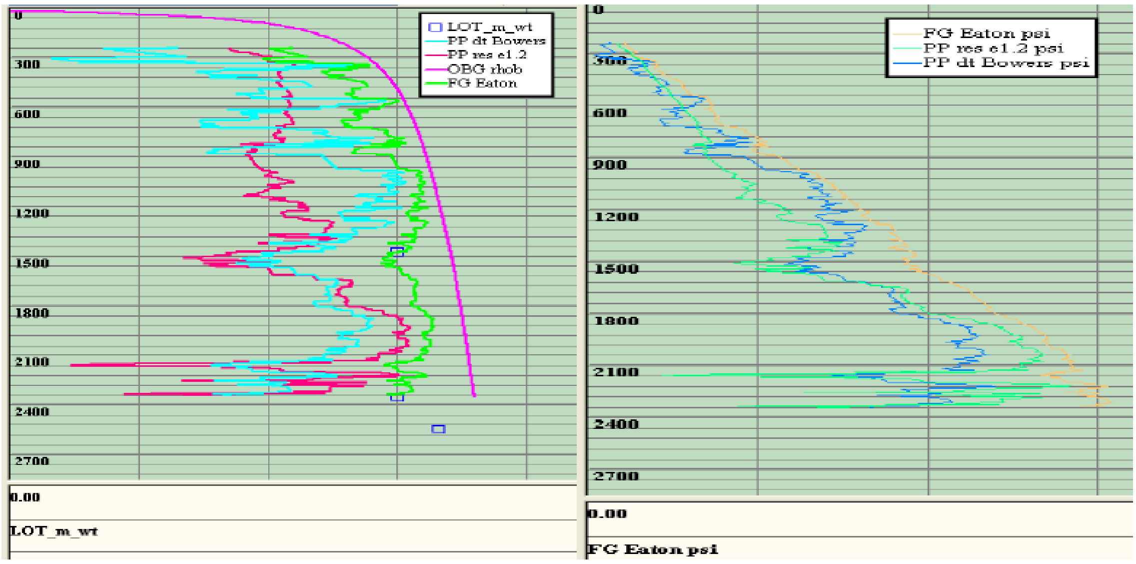

(a) 0-50 PPG

(b) 0-20000Psi

Fig.2. Pore pressure gradient analysis of Well

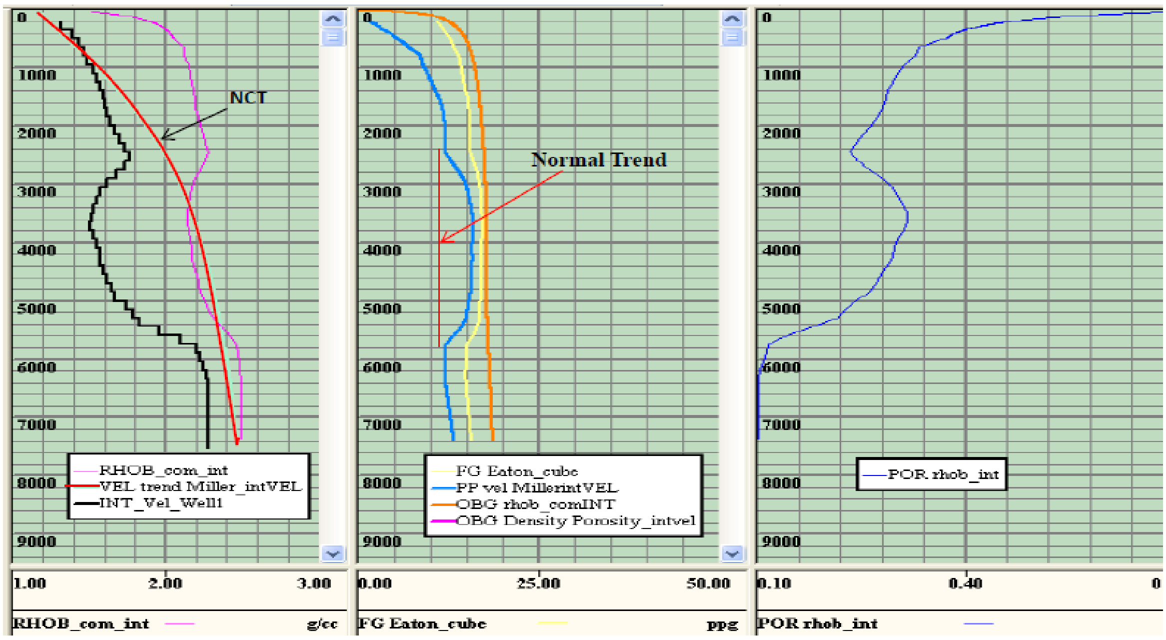

Fig. 3.Pore pressure gradient analysis of Well by using Interval Velocity

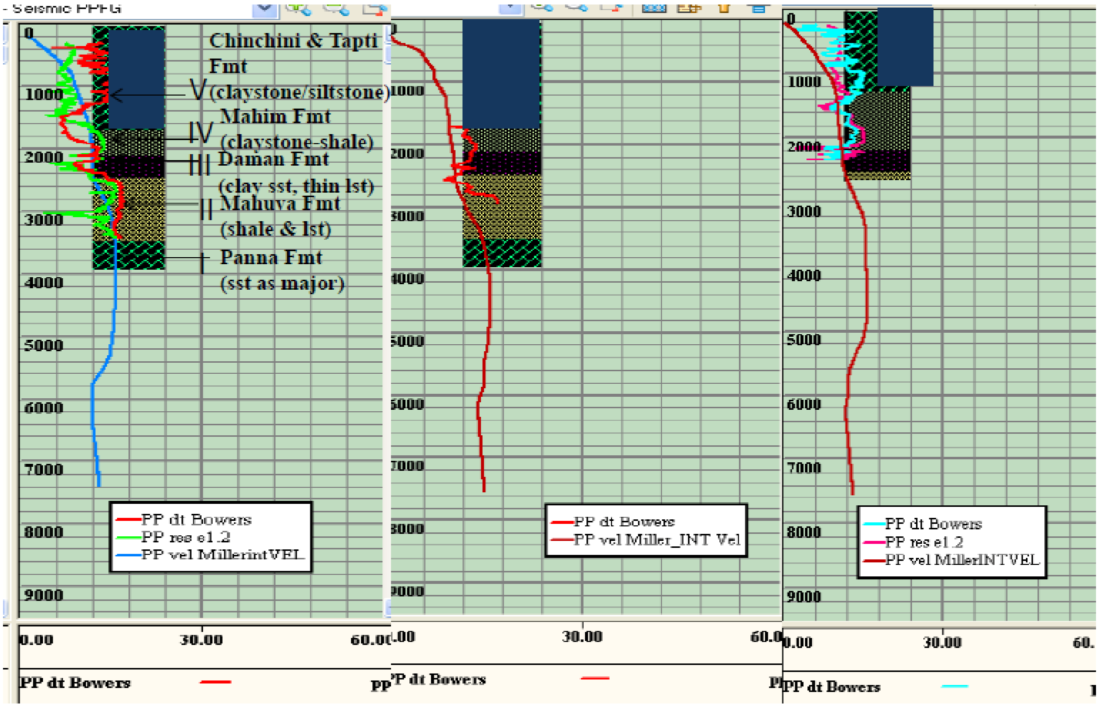

Fig.4. Pore pressure gradient analysis of three wells together by using interval velocity and also results from wells is superimposed.

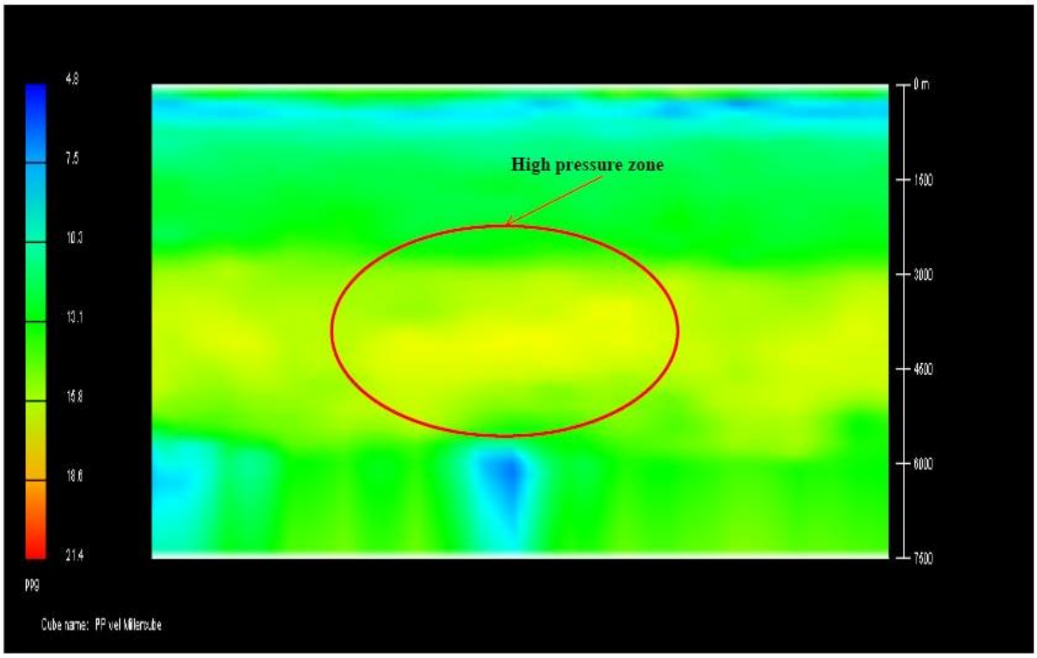

Fig. 5. Analysis of Pore pressure along a 2-D section generated from pore pressure cube