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# Determination of Pore Pressure Using Divergences

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## Abstract

Pore pressure prediction is the most important process in the design of drilling wells. Much has been written on the topic; however, even today a high percentage of non-productive time in drilling activities is related to pore pressure and wellbore instability problems. Misleading prediction of pore pressure is linked to: misunderstandings of pore pressure origins, the limited scope of pore pressure models based on well logs and to miscalculations of the key parameters of pore pressure models. This paper depicts a new methodology to analyze pore pressure based on the normal compaction theory of sediments and the way of that normal behavior diverges when it is interrupted. The process consists of generating compaction tendencies parallel to the normal compaction trend and interpreting the parallel and transitional trends observed in the well or seismic logs to generate a divergent area. When the divergent area is defined, the pore pressure calculation can be done using any method based on normal compaction theory and well logs data. In addition, this methodology allows, under specific conditions, to determine pore pressure in reservoir rocks that do not follow compaction theory such as carbonates or sands. Finally, a case of study is presented to support the results of this methodology.

**Keywords:** Pore pressure, Geopressure, Abnormal pressure, Geomechanic, Overpressure, Divergences.

## INTRODUCTION

The analysis of abnormal pressures is an issue that has been studied for more than 50 years, however, even today a high percentage of Non-Productive Time (NPT) in drilling activities is related to pore pressure and wellbore instability problems (Hamid et al. 2016; Ong et al. 2015; York et al. 2009). The misleading prediction of geopressures is linked to misunderstandings of the pore pressure genesis for a particular area and to the limited scope of pore pressure models based on well logs and miscalculations of the key parameters of pore pressure models.

Swarbrick and Osborne (1998) describe several mechanisms that originates abnormal pressures, which must be taken into account for pore pressure prognosis during drilling well design. Furthermore, despite the broad causes of abnormal pressures in the earth's crust, the mathematical prediction models that use either well logs or seismic data only predict pore pressure generated by stress-related mechanisms; this is also called as "*compaction disequilibrium*" or "*undercompaction*". **Figure 1** shows a pressure-depth plot illustrating the existence of other pore pressure mechanisms, which must be taken into account to improve pressure predictions.

Actually, the prognosis of abnormal pressures focuses on shales behavior because they are more sensitive to undercompaction phenomena (Hottmann, and Johnson 1965; Bowers 2002). The most commonly used pore pressure models in industry are based on the normal compaction theory of clays described by Terzaghi and Peck (1948). In that theory, the pore pressure models consider the behavior of porosity (or porosity indicators such as sonic transit time, resistivity or interval velocity) with depth to define the compaction disequilibrium; this behavior is called normal compaction trend (NCT).

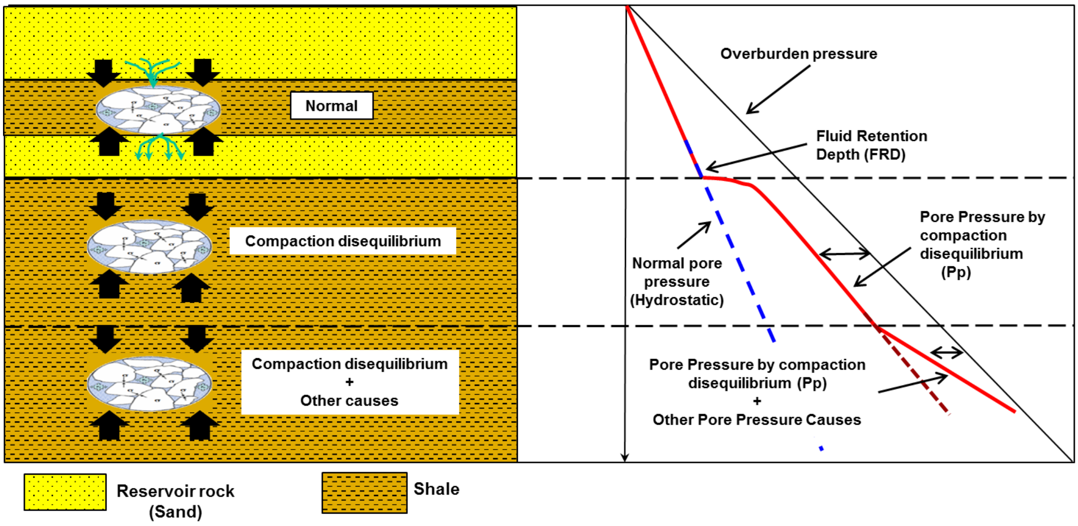

**Figure 1.** Pore pressure is because of combination of several mechanisms (Modified from Bowers 2002).

However, when we have reservoir type rocks (sands or carbonates), the prognosis of pore pressure using well logs or seismic data do not match altogether with recorded pore pressures (Green et al. 2016; Hoskin and O'Connor 2016). **Figure 2** describes pore pressure prognosis behavior in a shale and reservoir type rock (sands). The black dots on track No. 3 are pore pressure values measured in a reservoir type rock with a MDT tool. The continuous line A in track No. 3 represents the predicted pore pressure values determined from well logs using Eaton's model. This behavior is because the reservoir rock does not follow the compaction theory such as shales rocks do (Terzaghi and Peck 1938; Hottmann and Johnson 1965) and/or the generation of reservoir pore pressure is due to other pressure mechanism different to undercompaction.

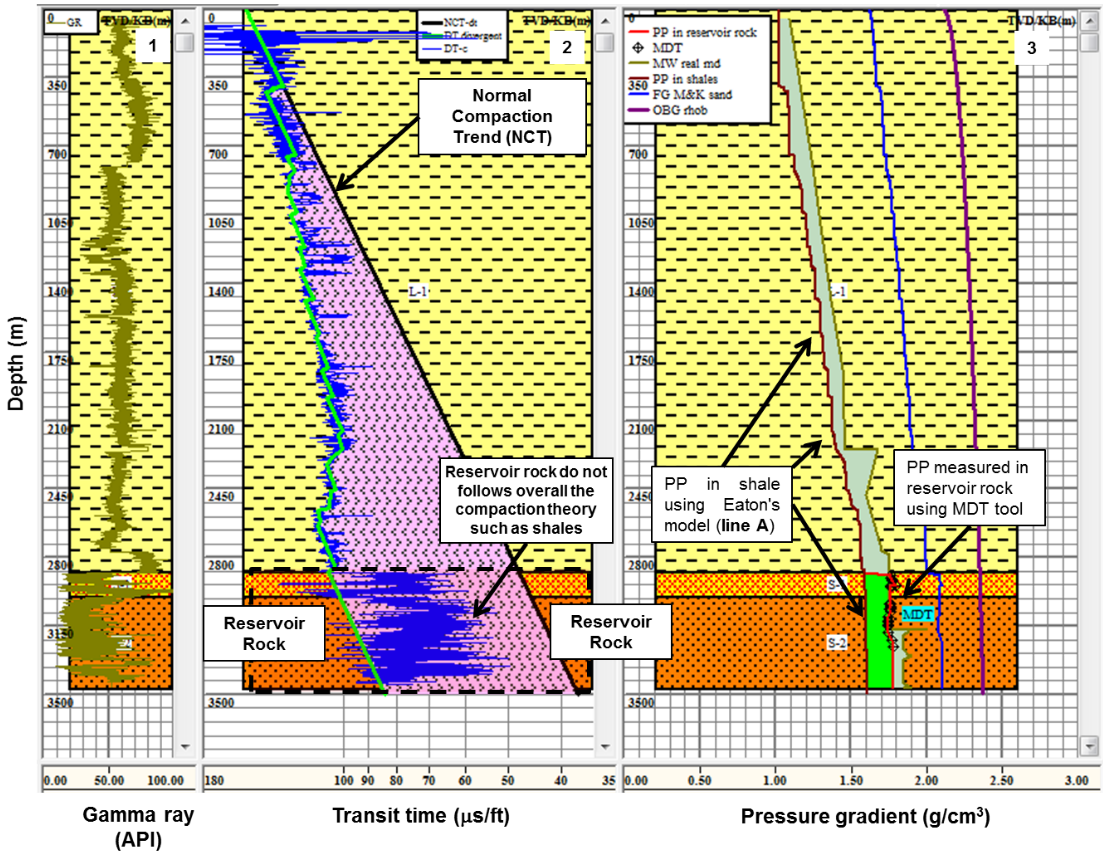

**Figure 2.** Behavior of pore pressure in shale and reservoir rock.

This work shows the methodology of the divergent area that allows under certain conditions to "*infer*" the pore pressure in reservoir rocks, such as carbonates or sands, eliminating the problem presented in figure 2 and allowing the use of pore pressure models based on the theory of normal compaction or on the behavior of effective stress.

## DIVERGENT AREA METHODOLOGY

The methodology is based on normal compaction trend of sediments and how it diverges when normal compaction is interrupted. The methodology states that if the overburden increases with depth and there is compaction disequilibrium at certain depth, the pore pressure must also increase starting in that depth. Terzaghi and Peck (1948) postulate that the overburden stress is shared by both, the fluid into the rock pores and the contact among grains; the intergranular contact stress is called effective stress (**figure 3**). In addition, they propose that if the pore fluid expulsion is interrupted, pore pressure increases because overburden stress increases. Hence, divergent lines and Terzaghi's model can be used to calculate pore pressure due to compaction disequilibrium as it increases when the overburden does (**figure 4**), as follows:

$$S = P_p + \sigma \tag{1}$$

$$\sigma = \mathrm{S} - P_p \tag{2}$$

$$\sigma_{an} = \sigma_n xDIV \tag{3}$$

$$\mathrm{DIV} = \left(\frac{\phi_n}{\phi_{an}}\right) \tag{4}$$

Where:

S = Overburden stress

Pp = Pore pressure

$\sigma$ = Effective stress

$\phi_n$ = Porosity from normal compaction trend

$\phi_{an}$ = Porosity from divergent lines

$\sigma_n$ = Normal effective stress = ($S-Pp_n$)

$\sigma_{an}$ = Abnormal effective stress = ($S-Pp_{an}$)

$Pp_{an}$ = Abnormal pore pressure

$Pp_n$ = Normal pore pressure

DIV = Divergences

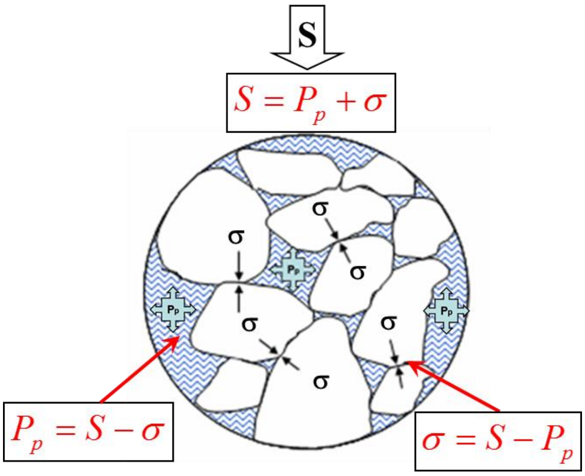

**Figure 3.** Illustration of Terzaghi's Model of overburden stress distribution in rock-grains and fluid.

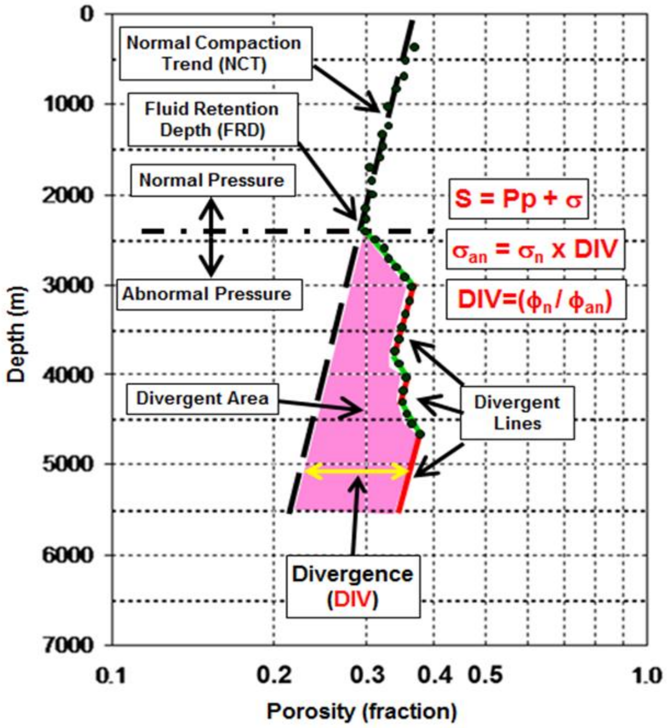

**Figure 4.** Divergent area coupled to Terzaghi's model.

The process consists of generating compaction tendencies parallel to the normal compaction trend, interpreting the parallel and transitional trends observed in the well or seismic logs to generate a divergent area following the next procedure:

a) Plot the porosity indicator (well log) against depth and define both the NCT and Fluid Retention Depth (FRD), **figure 5a.**

b) Draw lines parallel to NCT until well log is cover, **figure 5b.**

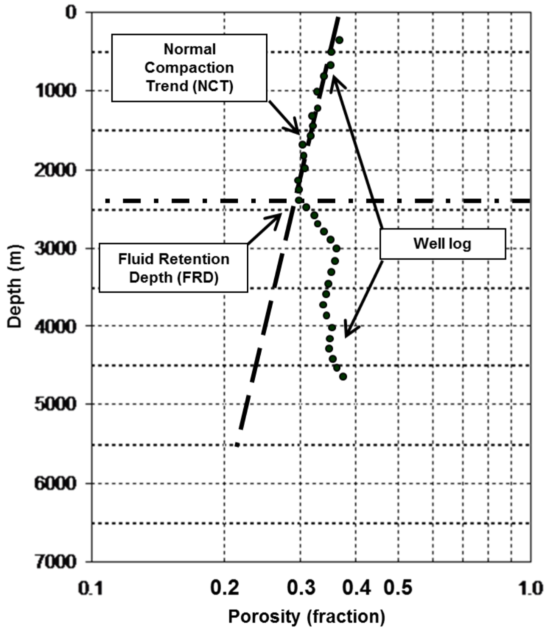

**Figure 5a.** Definition of NCT and FRD.

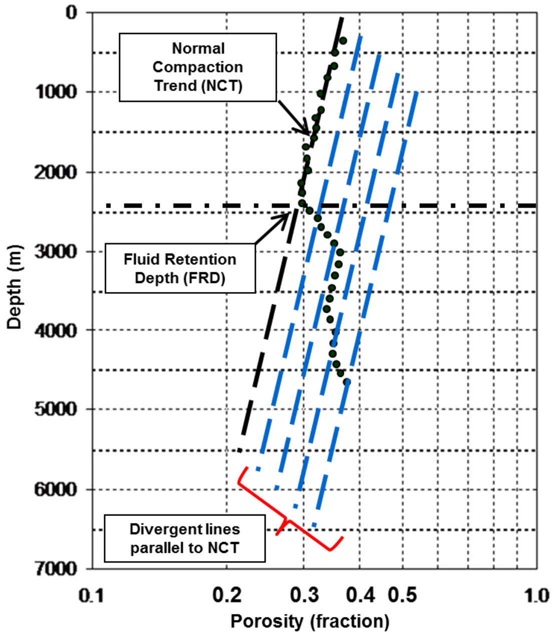

**Figure 5b.** Lines parallel to NCT until well log is cover.

c) On the well log, define the transitional and parallel lines (divergences) according with its behavior, as illustrated on **figure 5c.**

d) Define the divergent area and its divergent lines as shown on **figure 5d.**

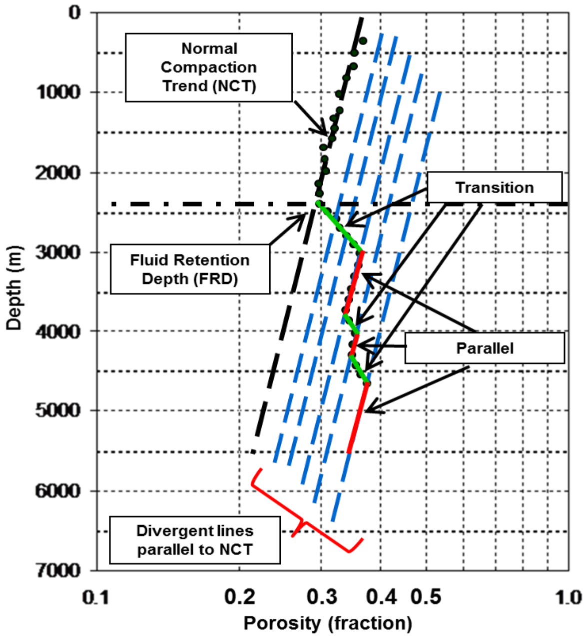

**Figure 5c.** Definition of transitional and parallel lines on the well log.

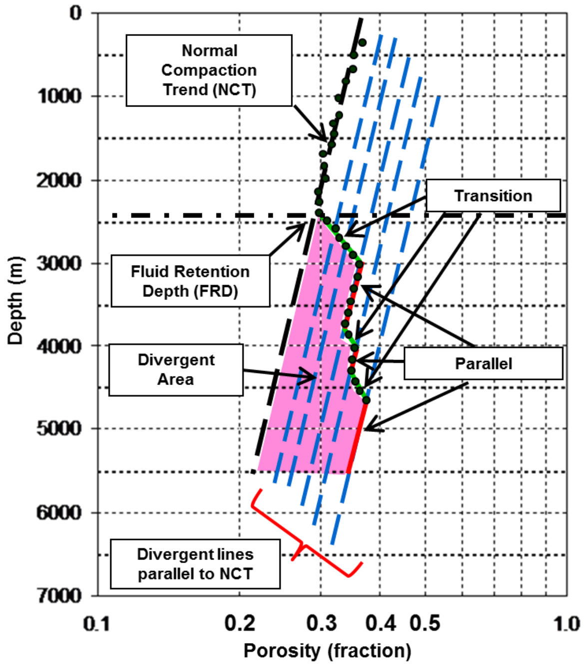

**Figure 5d.** Divergent area definition.

The methodology of divergent area can be applied to the reservoir rocks that do not follow the compaction theory as shales rocks do. Green et al. (2016) argue that one of the reasons that traditional prediction of pore pressure fails in carbonates is because the loss of porosity is not only controlled by effective stress but also by a variety of physical parameters such as depositional conditions, dissolution and diagenetic fabric history; the same occurs for sands according with Mouchet and Mitchell (1989). **Figure 6** shows an illustration of underprediction of pore pressure due to porosity affected by other parameters different to compaction (modified from Green et al. 2016).

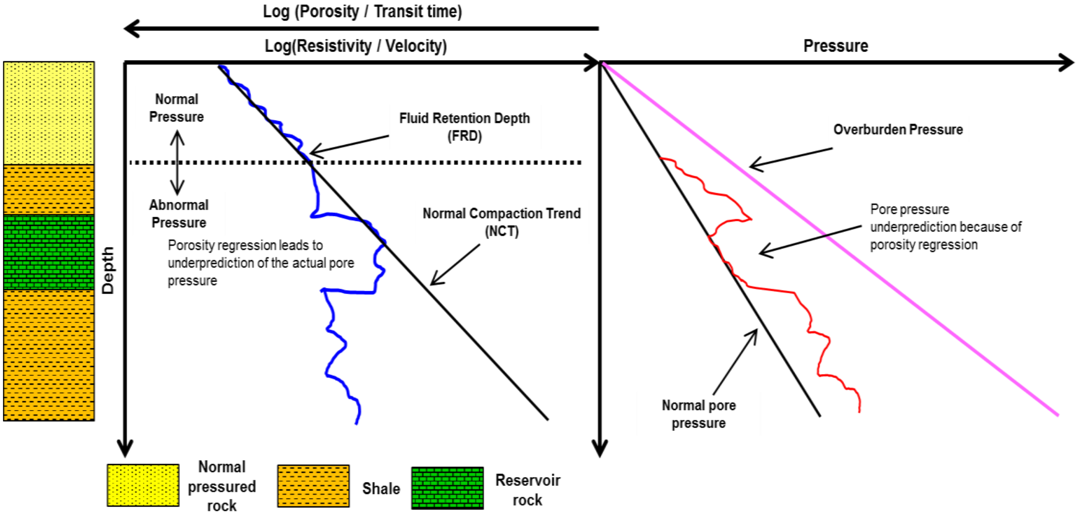

**Figure 6.** Underprediction of pore pressure due to porosity affected by other parameters different to compaction (modified from Green et al. 2016).

Shaker (2002) discuss that pore pressure in shales and in reservoir rocks (carbonates or sands) progresses in a cascade fashion to create a pressure envelope. In that case, pore pressure in reservoir rocks follow the hydrostatic gradient while in shales it progresses expontentially from top to bottom. **Figure 7** shows the pressure envelope following Shaker's statement (2002). Hence, considering the pressure envelope illustrated in figure 7, the methodology of divergences may be used to infer pore pressure in reservoir rocks like carbonates or sands. The divergence application consists in identify transitional behaviors of the porosity indicators (shale) and those that are parallel to normal compaction trend (reservoir rock) and then, build a divergent area as show in **figure 8.**

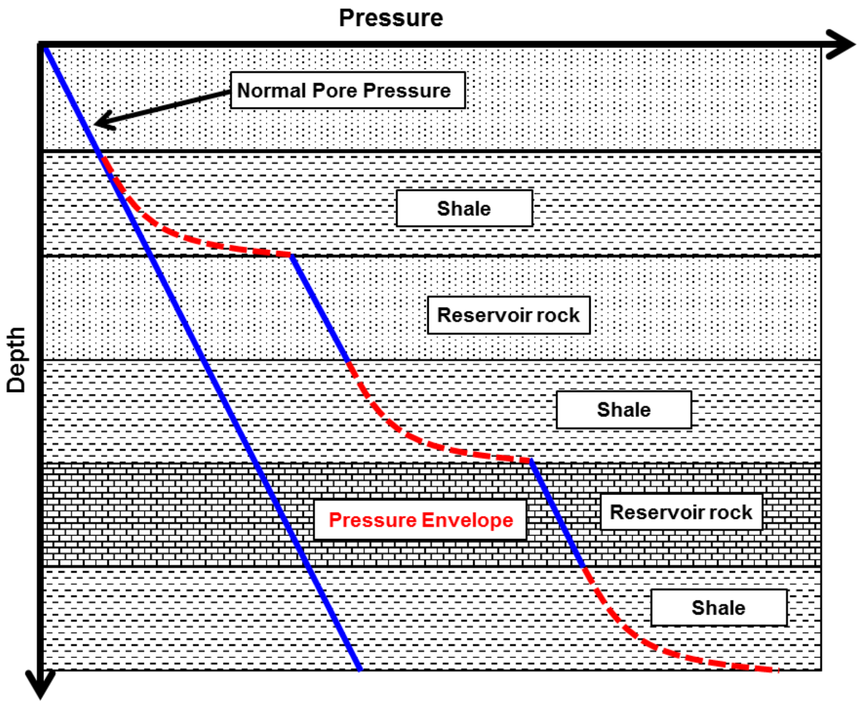

**Figure 7.** Illustration of pressure envelope (modified from Shaker 2002).

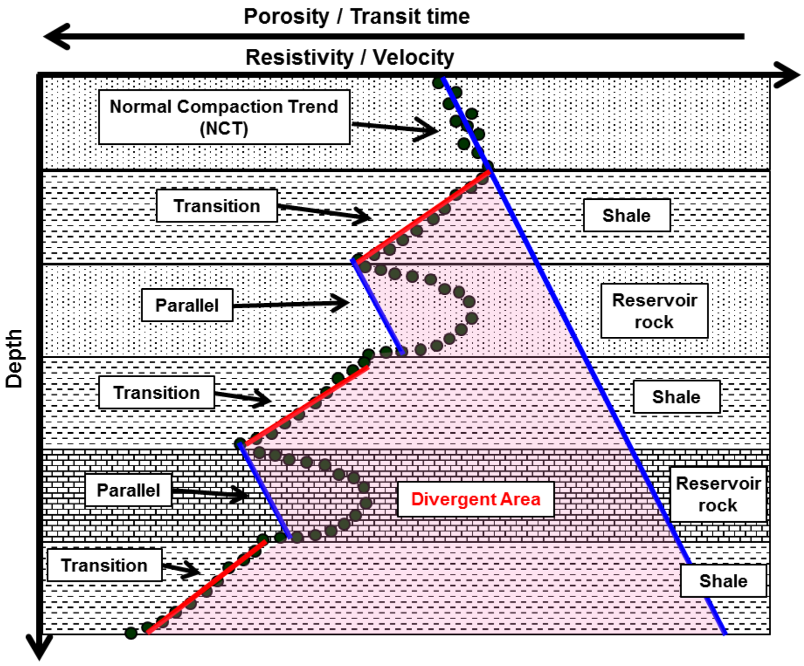

**Figure 8.** Divergent area to infer pore pressure in reservoir rocks.

Once the divergent area is defined, the pore pressure calculation can be done using a pore pressure model based on normal compaction theory, such as Eaton’s (1975), along with the use of either well logs and/or interval velocity from seismic.

## CASE ANALYSIS

The divergent area analysis of pore pressure was applied to an onshore well in Mexico as it is shown in **figure 9.** Track No. 1 displays the gamma ray log without shale points picks, which are not required when the divergent area is used. Track No. 2 present the analysis of "divergent lines" to identify transitional behaviors of the porosity indicators (shale rock) and those that are parallel to normal compaction trend (reservoir rock). When transitional and parallel behaviors are coupled to the normal compaction trend they build the divergent area. In addition, track No. 2 exhibits a reservoir rock with a porosity regression that without use of the divergent area, may lead to an underprediction of the pore pressure. Furthermore, the methodology of divergences replaces the shale point analysis for pore pressure prediction; instead, we can use the well logs directly. Track No. 3 expose the pore pressure analysis of the well, where we can observe how the pore pressure increases steadily and uniformly, properly describing the effect of the overburden pressure.

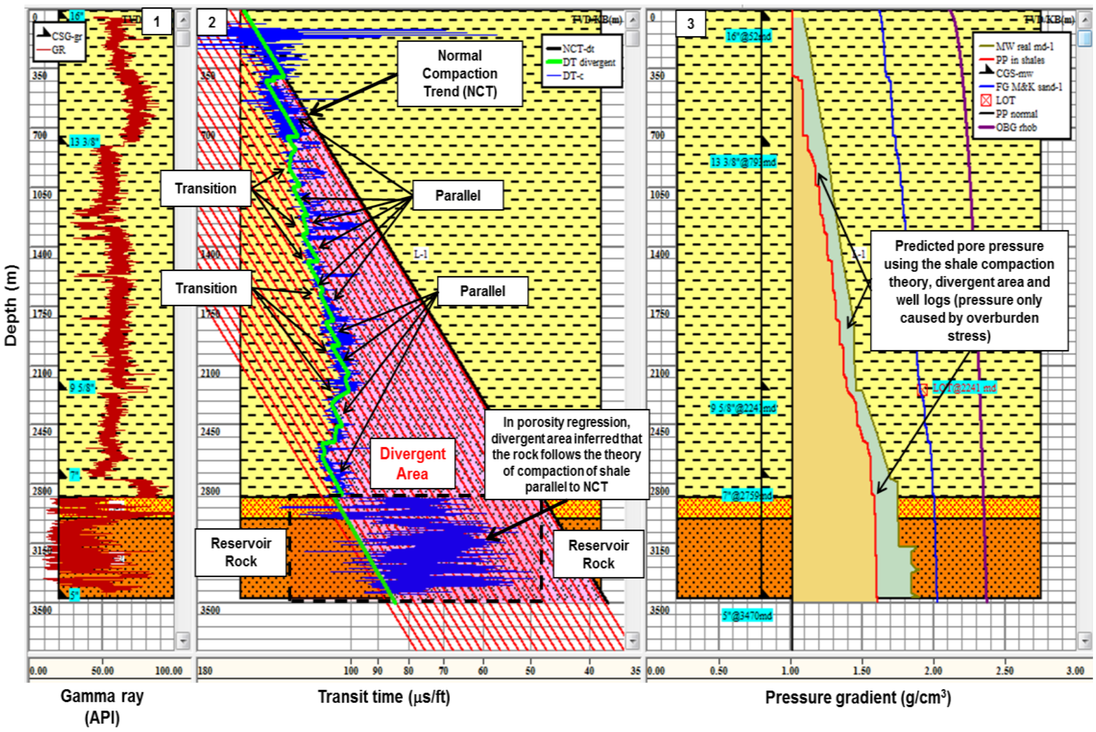

**Figure 9.** Pore pressure analysis using the shale compaction theory, divergent area and well logs in Mexican onshore well.

## CONCLUSIONS

- The NCT represents the porosity loss with depth thus any wells would have a unique NCT for pore pressure prediction using the compaction theory of shale.
- As burial depth increases, porosity reduces until a depth known as Fluid Retention Depth (FRD). Therefore, for the same well the FRD must be the same regardless of the well log used to identify it.
- The methodology of divergences allows developing a pore pressure prognosis based on the behavior of well logs due to normal compaction of sediments, avoiding the use of lithological logs and the selection of shale points.
- The methodology of divergences may be applied to the reservoir rocks that do not follow the compaction theory of clays.
- When the divergent area is defined, the pore pressure calculation could be done using both, a pore pressure model based on normal compaction theory of shale and well logs or the interval velocity from seismic.
- The methodology of divergences is properly coupled to the compaction theory of shales and to the pore pressure analysis based on well logs and seismic, i.e., if the overburden stress increases with depth and there is compaction disequilibrium, the pore pressure must increase with depth.

## ACKNOWLEDGMENTS

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## *NOMENCLATURE*

*CSG = Casing depth*

*DIV = Divergences*

*DRES = Deep Resistivity*

*DT = Sonic Transit Time*

*FG = Fracture gradient*

*FRD = Fluid Retention Depth*

*GR = Gamma Ray*

*LOT = Leak Off Test*

*MDT = Modular formation Dynamic Tester*

*MW = Mud Weight*

*NCT = Normal Compaction Trend*

*NPT = Non-Productive Time*

*OBG = Overburden gradient*

$Pp$ = *Pore pressure*

$Pp_{an}$ = *Abnormal pore pressure*

$Pp_n$ = *Normal pore pressure*

*RHOB = Bulk density*

$S$ = *Overburden stress*

$\phi_{an}$ = *Porosity from divergent lines*

$\phi_n$ = *Porosity from normal compaction trend*

$\sigma$ = *Effective stress*

$\sigma_{an}$ = *Abnormal effective stress*

$\sigma_n$ = *Normal effective stress*

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