

REVIEW

Prediction of Formation Pressure Gradients of NC98 Field-Sirte Basin-Libya

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ABSTRACT

The prediction of formation pore pressure and fracture pressure gradients is a significant step towards the drilling plan. In this study, the formation pressures of twelve wells from NC98 field-Sirte Basin (Waha Oil Company) were calculated by employing empirical methods, Eaton's equations, that depend on the real drilling and well-logging data. Regarding the results, the normal pore pressure in the NC98 field in Sirte basin is 9.89 kPa/m (0.437 Psi/ft), and it is extending from the top of the wells in the investigated area to 2134 m (7,000 ft). A subnormal to normal pore pressure zone is noticed in the interval of 2134 m to 2743 m (7,000 ft. - 9,000 ft). Then, slightly subnormal to somewhat abnormal (overpressure) region is seen from 2743 – 3414 (9,000 ft. - 11,200 ft). Beyond to that depth and down to the top of the reservoir, the overpressure zone was clearly observed. Based on the results, the casing seating depth and the equivalent mud weight were simply determined for the area of study.

1. Introduction

One of the most significant factors for drilling preparation is the formation pore pressure. The pressure formed in pore spaces due to the presence of the fluids is known as formation pore pressure. Pore pressure is classified as subnormal (less than hy-

drostatic pressure "9.8 kPa/m or 0.433 psi/ft"), normal (equal to hydrostatic pressure), and overpressure (slightly more than hydrostatic pressure and less than overburden pressure). Thermal expansion, under compaction, mineral transformations, hydrocarbon generation,..., etc. are some of the reasons for having formation pore overpressure

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zones. The abnormal compaction results in disequilibrium compaction, which concludes with the changing trend of the overburden pressure (probably decreasing) with the depth, more pore spaces, and overpressure^[1]. Where the rapid sedimentation process and the presence of a no permeable system are the main reasons for creating overpressure zone^[2]. The ratio of the pore volume of the formation decreases with depth in the case of regular compacted or pressurized zones^[3]. Finally, the precise prediction of formation pore pressure is crucial to prevent drilling well blowouts, pressure kicks, and fluid influx.

Accurate prediction of formation pressures can benefit even the geologists historically to analyze the migration of the fluids from the mother rock (source rock) to the trap^[4]. The precise prediction of the overpressure zone can be proved by the alteration in the overburden pressure gradient curve. According to the results, the predicted pore pressure is inversely related to the overburden pressure and linearly related to the fracture pressure; however, fracture pressure is straightly linked with both of them. Also, it was noticed that the overburden pressure mainly affected by the depth of the formation. Where it is directly proportional to the depth^[5]. In the Gulf of Mexico, about 24 % of the drilling processes were ended up with loss circulation and flowing of water/gas, due to the wrong pre-drilling data^[6].

The common methods to predict the formation pressures depend on pre-drilling information (seismic data), during drilling information (well-logging/drilling data), and history information (known data data)^[7]. For wildcat wells, only seismic data may be available. For the development wells, the prediction of the formation pressure gradients depends on the well-logging and drilling data in the investigated area. The prediction of formation pressures in complicated geological regions raises the uncertainty of the applied prediction models^[8]. A long time ago, before the application of well-logging data to predict formation pore and fracture pressures, the characteristics of shale (mudrock) was employed. The predicted pressure from this technique represents pore pressure in shale. Alternatively, different ways included the centroid method introduced by Dickinson (1953)^[9], Bowers (2001)^[10] and the different models suggested by Yardley and Swarbrick (2000)^[11] as well as Meng et al., (2011)^[12] were employed.

In this study, Eaton's drilling and well logging methods are employed to predict formation pore pressure and fracture pressure gradients for NC98 field-Waha-Sirte Basin. The predicted formation pressure gradients were applied to determine the equivalent mud circulation, casing seating depths, and the number of required casings in this area. Besides, figuring out the most appropriate source of

data (drilling or well logging data) that can be used to predict pore and fracture pressure gradients.

The goals of this study are: (1) studying the applicability of Eaton's methods in the studied area, (2) determining of the proper source of data (well logging or drilling raw data) to predict formation pressure gradients, (3) predicting the minimum and maximum pore pressure, and fracture pressure gradients and (4) establishing one plot of the collective formation pressure results for the future development projects in this area.

2. Description and Geology of NC98 Field-Waha-Sirte Basing:

NC98 is one of Waha Oil Company fields that are located in the southeastern section of Sirte basin that is found in the north-central part of Libya^[13]. Sirte basin is the newest developed basin in Libya with the largest petroleum reserve. The producible quantity of the hydrocarbon in this basin is estimated at 45 billion Bbl of oil and 33 trillion ft3 of gas. Geologically, the source rocks of the Sirte basin are Upper Cretaceous Rachmat and Sirte shale rocks and reservoir formations are formed in Cretaceous and Eocene to Miocene rift structures age. Structurally, 58 % of the reservoirs are sandstone rocks (clastic), and the rest are carbonates rocks^[14]. The lithology of Gialo - NC98 field is clearly shown in Fig. 1. The reservoir type is sandstone rock. The cap rock is mainly shale, salt mass, and claystone.

AGE	FORMATION	DEPTH (sub Sea B)	LITHOLOGY	DESCRIPTION
Pleist-Plio	Loose sand			Loose sand, Clay
				classic sediments, clay
				organic-rich shale
Miocene	Maradah	-1.550		Nubian quartzite's, Cenomanian dolomites, Evaporates, fossils, anhydrites
Oligocene	Diba			Sandstone, shale, sandy limestone.
Eocene	Upper	Augla	-2.300	Shale sequence, argillaceous limestone
		El Erg	-2.700	Fossils, argillaceous and chalky
		Gialo	-2.900	Carbonates, argillaceous and chalky limestone
	Medium	Jakherrah	-3.530	Limestone, shale intervals, anhydrite, fossils
			-3.800	
Eocene	Lower	Al Gata		Dolomite, anhydrite, fossils
			-4.950	
Paleocene	Upper	Kheir	-5.850	Marlstone, claystone, micritic limestone
		U. Sabil	-7.250	Dolomite, Anhydrite
			-8.440	
Paleocene	Lower	L. Sabil		Dolomite, Carbonates, shetrat shale
Cretaceous	Upper	Kalash	-9.640	Dense micritic limestone
		U. Sirte	-10.500	Shale, marlston
		Tagrfet	-10.750	Chalky carbonate, imbedded Shale carbonate.
		L. Sirte	-12.700	Shale, dolomite anhydrite, siltstone
		U. Salt	-13.350	Salt mass, Shale beds
		M C&A	-13.850	Dolomite, anhydrites, anhydrites mass
Pre-U Cret		L. Salt	-14.230	Salt mass, claystone
		T. Beds	-14.270	Shale, claystone, imbedded sandstone
		U. Nubian Sandstone	-14.418	Pay zone [Sandstone, quartz, claystone
		M. Shale MBR	-14.818	Claystone, imbedded w sandstone

Figure 1. The geology column of Gialo – NC98 (Waha Oil Company)^[15]

3. Methods

This procedure is applied in the drilling application to predict formation pore pressure, fracture pressure and overburden pressure gradients for the formation. Monitoring the well-logging data, drilling data, drilling fluid, and rock particles, can be employed to indicate the transition zone between normal and overpressure areas.

3.1 Overburden Pressure Prediction

The precise prediction of formation pressures is essential in terms of the cost and safety during the drilling process. Overburden pressure can be determined based on the pore pressure data^[16] by employing equation (1):

$$\sigma_{ob} = \sigma_v + \infty P_p \quad (1)$$

It is obvious from Equation (1) that the values of poroelasticity, vertical effective stress, and overburden pressure should be known to calculate formation pore pressure. The poroelasticity factor was experimentally proved as a constant ($\infty = 1$) by Terzaghi^[17]. As can be noticed in Equation (2), in addition, the calculation of the overburden pressure mainly depends on the formation bulk density.

$$\sigma_{ob} = \int \rho_b dD \quad (2)$$

Gardner and coworkers (1974) found that the calculation of formation bulk density could be done through some empirical correlation based on seismic and well logging data^[18]. Equation (3), as shown below, is directly employed to calculate the formation overburden pressure:

$$\sigma_{ob} = 0.433 \rho_b D \quad (3)$$

3.2 Pore Pressure Prediction

One of the important steps to prevent the possibility of having blowouts or mud loss during drilling step is the accurate prediction of formation pore pressure^[2]. Since there is no straightforward method to measure formation pore pressure in some formations such as shales, planning, and execution of new boreholes depends on indirect ways^[19]. Many methods such as Bowers^[20], and d-exponent^[21] are applied to predict the pore pressure in shales from indirect methods. The fundamental of the indirect techniques that are used to predict the abnormal pressure is based on the compaction of the studied formation. The abnormally pressured formations are less compacted and higher porous in comparison to formations of uniform lithology at the equivalent depth. So, formations with high porosity may be signified as overpressure areas. The indirect method proposed by Bingham (1969) depends on the hardness of the formation is known as the d-exponent method^[22]. The d-exponent equation was modified based on drilling raw data to d-corrected-exponent (dc-exponent) to standardize the calculated drilling rate of penetration. Jorden's and Shirley's model was modified to include the

term of mud weight^[23], as presented in equation (4):

$$dc - exponent = \frac{\log\left(\frac{ROP}{60 RPM}\right)}{\log\left(\frac{12 WOB}{10^3 d_{bit}}\right)} * \left(\frac{\rho_{normal}}{\rho_{actual}}\right) \quad (4)$$

In 1975, Eaton proposed a predictive method of pore pressure depending on the drilling data (dc-exponent) and well logging (sonic compressional transit time) data, respectively, as presented in equations (5) and (6)^[24]:

$$\frac{P_p}{D} = \frac{P_p}{D} - \left(\left(\sigma_{ob} - \frac{P_{pnormal}}{D} \right) \left(\frac{d_{c,observed}}{d_{c,normal}} \right)^{1.2} \right) \quad (5)$$

$$\frac{P_p}{D} = \frac{P_p}{D} - \left(\left(\sigma_{ob} - \frac{P_{pnormal}}{D} \right) \left(\frac{\Delta t_{normal}}{\Delta t} \right)^3 \right) \quad (6)$$

3.3 Fracture Pressure Prediction

Formation fracture pressure (PF) is the pressure at which the formation starts cracking and the mud loss circulation occurs. For an appropriate mud weight design, it is crucial to accurately predict fracture pressure gradient. There are different methods to determine fracture gradient. In practice, fracture pressure is calculated from leak-off tests (LOT). From the literature review, the most popularly applied method is the Ben Eaton's fracture gradient prediction approach (Eaton 1975), as shown in equation (7). Yoshida et al. (1996) announced that Eaton's pore and fracture pressure gradient equations are applicable worldwide. This examination showed Eaton's fracture gradient prediction approach is one of the best techniques to use^[19].

$$\frac{P_F}{D} = \frac{v}{1-v} \left(\frac{\sigma_{ob}}{D} - \frac{P_p}{D} \right) + \frac{P_p}{D} \quad (7)$$

The accurate prediction of overburden pressure gradient, pore pressure gradient and Poisson's ratio (Supplementary File-Poisson's Ratio calculation) of the studied area was essential to successfully apply Eaton's equation to calculate the fracture pressure gradient.

4. Results and Discussion

According to the combined dc-exponent results of the 12 investigated wells in the NC98 field, as shown in Fig. 2, we probably can say that the overpressure zone occurs. Where it starts with slightly decreasing in the dc-exponent data from 2,202 m to 3,048 m (7,223 ft - 10,000 ft), remarkably decreasing from 3,048 m to 3,658 m (10,000 ft to 12,000 ft), no deviation in the trend between 3,658 m and 4,572 m (12,000 ft and ~ 15,000 ft), and the data of dc-exponent is getting increased to the normal trend from 4,572 m to 4,952 m (15,000 ft - 16,250 ft). After that, the trend line reaches the equilibrium at the total depth (TD) 5,221.2 m (17,130 ft).

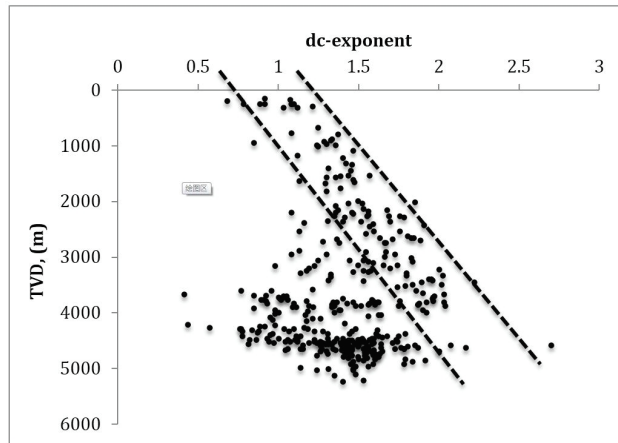


Figure 2. Modified dc-exponent values for the wells in the study area.

Similarly to dc-exponent, the deviation in the sonic log trend of one of the studied wells starts from 2,164 m (7,100 ft), which is increasing with depth, as can be seen in Fig. 3, opposite to the dc-exponent trend manner, which approves the presence of the overpressure zone. In details, the slight increasing begins from 2,164 m to 3,828 m (7,100 ft to 12,558 ft), notably increasing from 3,828 m to 4,797 m (12,558 ft - 15,738 ft), and the trend line is decreasing from 4,797 m to 4,907 m (15,738 - 16,100 ft). After that, the trend line is almost not changeable up to the Total Depth (TD). Up to now, drilling and logging data are matching and mostly approving the existence of the abnormal pressure (overpressure) zone.

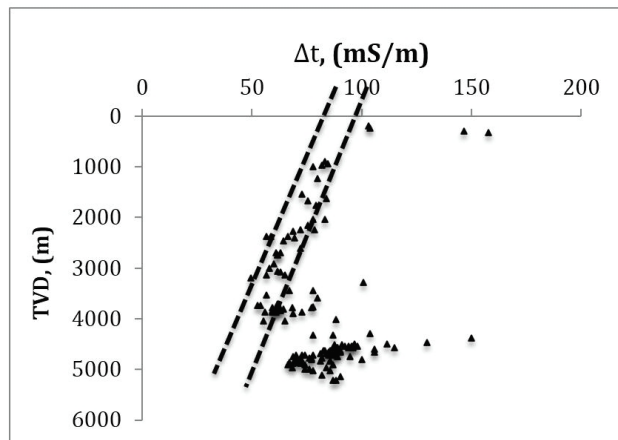


Figure 3. Sonic log records values for the wells in the study area.

The predicted pore pressure, fracture pressure, and overburden pressure gradients values from drilling raw data and well-logging records are presented in Fig. 4 and Fig. 5, respectively. Regarding the results, the overpressure zone can be clearly depicted from both drilling and

logging source of data. The drilling data, as shown in Fig. 4, reveals that the normal pore pressure in the NC98 field at Sirte basin is 9.89 kPa/m, and it is extending from the top of the well to 2,134 m (7,000 ft). After that, subnormal to normal pore pressure zone was noticed in the interval of 2,134 m to 2,743 m (7,000 ft. - 9,000 ft). Then, the marginally subnormal to relatively abnormal (overpressure) zone was seen from 2,743 m to 3,414 m (9,000 ft. - 11,200 ft). At the cap rock, the overpressure zone was apparently detected. For the well-logging source of data, as represented in Fig. 5 for one of the studied wells in the area of study, almost similar results to the drilling data were observed from the top to 2,919 m (9,578 ft). Slightly subnormal to marginal overpressure zone was noticed from 2,919 m to 3592 m (9,578 ft - 11,786 ft). However, beyond that depth to 3,749 m (12,300 ft), it became impossible to differentiate between pore pressure and fracture pressure gradients, which will make it difficult to determine the casing seating depth and equivalent mud weight (EMW) for this region based on well-logging data. Once before, the formation pore pressure of NC202, Sirte basin was estimated by applying both Eaton's and Bowers Methods. It was found that the Bowers method was more accurate than the Eaton's method. Because Eaton's technique used in that study depended on the well-logging data, which is affected by the shale content and the shale content cannot typically be determined for the carbonate rock. The shale content does not influence the Bowers method, as it depends on the pre-drill data^[25]. These outcomes agree with our results, as Eaton's drilling data formula concluded with better results than Eaton's well-logging method.

In general, the salt tectonics can change the formation compaction state, generating normal compaction pattern variations^[7]. The abnormal compaction results with disequilibrium compaction, which concludes with the changing trend of the overburden pressure (probably decreasing) with the depth, more pore spaces, and overpressure^[1]. Geologically, the subnormal to regular pore pressure interval in this area of study is mainly composed of Limestone, Chalky Limestone, Sandy Limestone, Dolomite, and evaporates. These formations are known with their total and effective porosity, which might be one of the reasons of having low to normal pore pressure area. However, the overpressure zone that is present in upper Sirte formation all the way down to lower salt formation T. beds (the cap rock) consists of shale and salt mass formations. These formations have high-disconnected porosity ratio that causes a noticeable increase in the pore pressure gradient. Proper prediction of pore and fracture gradient pressures is significant toward precise casing design^[26]. Overall, the results of the dc-exponent, sonic log, formation logging,

and drilling pore and fracture pressures are matched, which confirms that we have a high-pressure zone in the abovementioned interval depth.

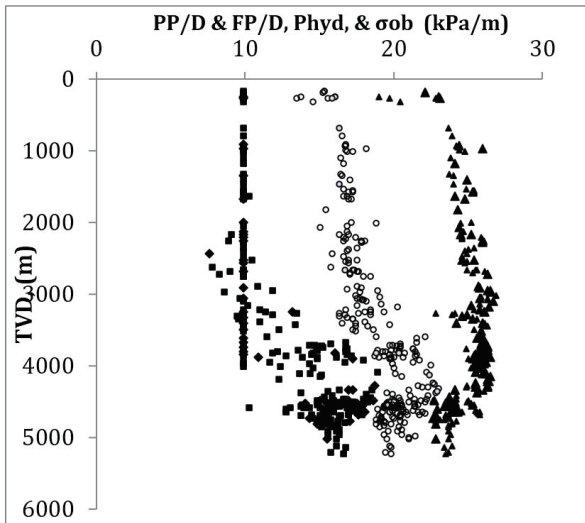


Figure 4. Predicted formation pressure gradients from drilling data

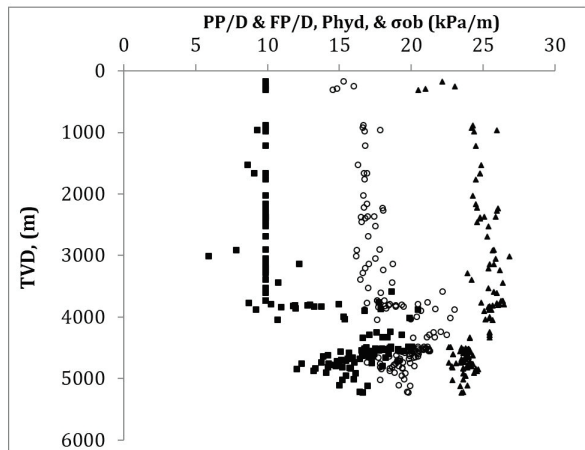


Figure 5. Predicted formation pressure gradients from well logging data

5. Casing Setting Depth

Besides formation pressure gradients, the seating depths and the number of casing strings also depend on geological conditions and the stability of freshwater aquifers. In deep wells, the principal concern is given to the control of abnormal pressure and of salt formations, which will tend to flow plastically^[26]. The objective of placing the casing in the borehole is to inhibit the collapse while drilling. It is also employed to prevent the contact between the drilling fluids and formation fluid; reduce damage to the subsurface environment from the drilling operation and extreme subsurface conditions. Besides, it provides a great

strength and safe flow of the fluids through the well. In the determination of casing places, monitoring the maximum pore pressure and minimum fracture pressure gradients of the formation related to the depth of the studied area are needed, as shown in Fig. 6.

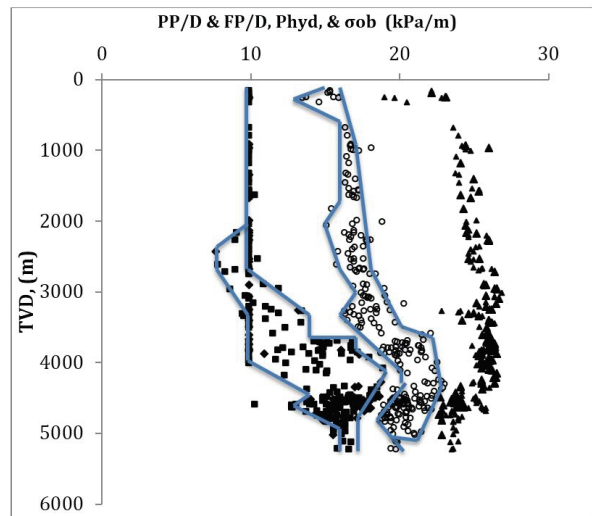


Figure 6. Estimating the minimum and maximum predicted formation pressure gradients from the drilling data

It is reasonable to employ the smallest fracture pressure trend line for casing depth design. After determining the minimum and maximum formation pressure gradients, the casing seating depth, the number of strings, and the EMW were easy to predict, as can be depicted from Fig. 7. Five casing strings are needed to prepare a casing design for this area. Besides, five mud weights are required to drill the wells appropriately in the studied field.

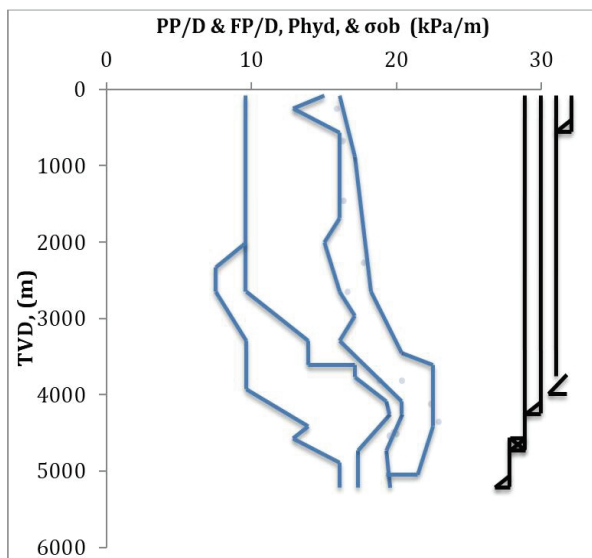


Figure 7. Estimating casing seating depths

Table 1. Predicted and actual mud weight and casing seating depths from drilling data

Casing #	Predicted Casing Depth	Predicted drilling fluid density	Actual drilling fluid density	Actual Bit Size used	Actual Casing Seating depth
	m	g/cm ³	g/cm ³	in (cm)	m
1	500	1.01	1.03	26 (66.04)	315
2	3703	1.37	1.04	17.5 (44.45)	2400
3	3917	1.82	2.15	12.25 (31.115)	3993
4	4644	1.88	1.88	8.5 (21.59)	4484
5	5224	1.71	1.62	5.9375 (15.08)	5224

6. Validation of Predicted and Real Field Data

In this section, the predicted and real Equivalent Mud Weight (EMW) and casing seating depths employing Eaton's Drilling results were compared, as can be seen in Table 1. Waha Company used about 1,379 kPa to 2,758 kPa (200 psi - 400 psi) as sustained pressure to ensure overbalance-drilling process. The gathered predicted results of 12 well were compared with the actual results of the deepest studied well in this research. Both the predicted and actual data show that five casing strings and drilling fluids are needed to drill a well in this area. It is evident that the predicted and real results are comparable, which confirms the accuracy of applying Eaton's drilling method to predict the formation pore and fracture pressure gradients, drilling fluid weight and casing seating depths.

7. Conclusion

The range of the formation pore pressure value is from less than hydrostatic pressure (normal pore pressure) to critically abnormal pressure (up to 90 % of the overburden pressure). The overall results provided that the drilling data are more reliable to be employed for predicting formation pressure gradients than the well-logging data. The predicted formation pressure gradients graph clearly shows the casing seating depths as well as the maximum and the minimum mud weight gradients that can be employed. So, the figure of the gathered data can be used as a reference for future drilling processes in the NC98 field-Sirte basin. Finally, all of the goals of this study were clearly addressed.

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Nomenclature

- Cr = rock matrix compressibility,
- Cb = bulk compressibility of rock.
- D = depth (m)
- d_{bit} = bit diameter, (cm),
- d_{c,normal} = normalized dc-exponent value.

- d_{c,observed} = actual dc-exponent value.
- Pp_{normal} = normal formation pore pressure (kPa).
- P_F = formation fracture pressure (kPa).
- ROP = Penetration Rate (m/h),
- RPM = Round per minute,
- WOB = Weight on the bit (lb),
- σ_{ob} = overburden stress, kPa
- ρ_{normal} = Normal Hydrostatic Gradient (g/cm³),
- ρ_{actual} = Current mud Weight (g/cm³).
- Δt_{normal} = normalized sonic transit time.
- Δt = the actual obtained sonic transit time using sonic log tool.
- σ_v = effective vertical stress, kPa
- ∞ = Biot's constant, (0 < ∞ < 1) = (1 - Cr/Cb)
- ν = Poisson's ratio =
$$\nu = \frac{0.5 \times \left(\frac{\Delta ts}{\Delta tc}\right)^2 - 1}{\left(\frac{\Delta ts}{\Delta tc}\right)^2 - 1}$$

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